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Research article

Coal consumption-environmental sustainability nexus in developed and developing major coal-consuming economies

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ABSTRACT

Coal is crucial for economic progress but equally baneful to the environment. Thus, the coal consumption-environmental sustainability nexus attracted the attention of both policymakers and scholars. This study evaluates the coal consumption-environment nexus in developed and developing countries over the period 2000–2020. We used panel data econometric techniques and the Augmented Anderson–Hsiao (AAH) two-step GMM estimator to assess and compare the impact of coal consumption on CO_2. The findings revealed that the consumption of coal aggravates environmental pollution and hinders environmental sustainability. Thus, this study confirms the environment-destroying effect of coal consumption. However, the findings reveal that the negative consequence of coal consumption on the environment is more for the sample of developed countries than that of developing countries. This suggests that coal use harms the environment developed economies than the developing countries. Specifically, we found that the carbon emissions emanating from a one percent (1%) increase in coal consumption of the developed countries is about six-fold more than that of the developing countries. Therefore, this study suggests a gradual phase-out, rather than sudden phase-out, of coal consumption with greater emphasis on developed countries. The implementation of the coal phase-out policy and the removal of fossil fuel subsidies should start with the developed countries or be made more stringent in such countries than the developing economies. The developed countries should relinquish a greater proportion of their coal consumption than the developing countries.

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1. Introduction

The utilization of energy constitutes a fundamental necessity for the progression and maturation of any economic system. So, the drive for economic progress and industrialization increases the demand for energy in many countries across the world. Primarily, every economic system relies on coal to satisfy its growing energy requirements. This preference stems from the fact that, within the category of fossil fuels, coal is acknowledged as the primary [1], sufficient, and cost-effective [2] energy source globally. It is globally distributed with a greater reserve and relatively lower price compared to other sources of fossil fuel. Hence, coal has been a reliable energy source and the most economical of conventional fuels, which helps to match the world energy requirement, and its usage is crucial for economic development, and economic upliftment.

However, according to the Trends in Global CO_2 Emissions Reports, approximately 90% of carbon dioxide emissions result from the burning of fossil fuels and heat generation [3]. These factors include energy demand and production, energy efficiency, and fuel composition. The nations examined in this investigation utilize over 82% of the global coal consumption, contributing to more than 66% of the worldwide CO_2 emissions [3–5]. In 2016, coal declined in consumption by 458 Mt which is the largest recorded since 1971 according to IEA records because of growth in gas usage in electricity generation from China, the US, and the UK [3,6]. In 2014, coal contributed 30% of global primary energy needs and 41.1% of the world's electricity generation [7]. Coal stands as a principal energy source for numerous nations, and in 2015, it constituted 65.5% of global electricity generation and commercial heat, 82.7% for OECD countries, and 56% for China [3]. While in South Africa, Colombia and Mongolia exports of coal had exceedingly increased in 2016 by 1.3%, 7.1%, and 78.3% respectfully. For global importations grew by 1.5% (1331.3 Mt) in the same period. While the overall global coal consumption in energy units has declined by 1.9% (105.7 Mt), China has experienced a decrease of 1.8%, the United States of America by 7.8%, OECD countries by 5.3%, and non-OECD countries by 0.9%. This decline is attributed to concerns related to air pollution and shifts in economic growth models [3]. Specifically, China has advocated and developed the concept of Green GDP in their 13th five-year Plan to reduce carbon emissions by 40%–59% in the year 2020 and 60%–65% in 2030 about 2005 [8]. According to Ref. [9], CO_2 emissions (million tons) from China, India, Japan, Saudi Arabia, South Africa, Russia, and the USA are 10,720, 2470, 1260, 510, 420, 1760, and 5180 respectively in 2015. Hence, the ongoing enhancement and escalation in energy usage result in a global surge in carbon dioxide (CO_2) emissions, driven by swift economic expansion [6].

Globally, coal is the dominant source of energy generation which constitutes about 36% of fuel for power generation and more than 41% of total electricity generation in 2021 [10]. Again, coal consumption increases by 6% to 160 EJ in 2021– the highest since 2014, and the coal consumption in both Europe and North America has increased in 2021 after over a decade of consecutive decline [10]. Anticipations indicate a probable surge in coal consumption exceeding 50%, necessary to fulfil global electrification targets by the year 2030 [11].

However, the high demand for coal constitutes a threat to environmental sustainability. Extant studies have shown that it is not a mere coincidence that the major coal consumers such as China, India, and the United States are equally leading carbon emitters in the world [12–17]. It is equally established that coal consumption contributes immensely, more than other fossil fuels to the global carbon emissions [18,19]. Thus, numerous environmental problems are attributed to the extensive consumption of coal [8,18,20].

Consequently, the increase in coal consumption poses a significant challenge to attaining the sustainable development goal related to climate change initiatives and the commitments outlined in the Paris Agreement, which targets to check climate change to a pre-industrial level of 1.5 °C. Therefore, high coal consumption makes it difficult to achieve the pivotal aim of the COP26 held in Glasgow, which reaffirmed the Paris Agreement and set a target of ensuring net zero global carbon emissions by 2050 [20]. The IPCC emphasized the necessity for effective management of the primary origin of carbon dioxide emissions originating from energy consumption to realize the objectives outlined in the sustainable development goals related to clean energy and climate action.

Having identified the adverse ramifications of coal usage on the environment, the critical emphasis of the COP26 is phasing out coal consumption from the energy consumption group of nations across the world and transitioning to clean and renewable energy to achieve environmental sustainability. However, it is challenging to phase out coal consumption because of its enormous contribution to the gross domestic product (GDP) and prosperity of many nations. It is a cheaper source of energy. For instance, industrialized nations largely depend on coal as a source of domestically produced energy source due to the volatility of oil prices in the world market and political instability in some major oil-producing countries [21]. In addressing the reliability of the supply of crude oil by importing countries and volatile regions of the Middle East where high concentrations of oil and gas reserves supply sources are domiciled, the importing countries of this commodities (Oil and Gas) are making concerted efforts to search for alternative cheaper domestic energy supply. Coal is the most economically abundant of fossil fuels and has been identified as a source to meet the demand for a secured energy source. Coal is abundant and one of the most economically viable fossil fuels and assumes a remarkable part in matching the demand for secured energy and world coal deposits/reserves are estimated to last for the next 147 years, in comparison with gas and petroleum products which are estimated to last for 63 and 41 years respectively [3,4].

Accordingly, the elimination of coal from the energy consumption mix is a viable approach for achieving environmental sustainability. However, it may simultaneously result in a downturn in the economic growth and development of numerous countries worldwide. The profound repercussions of this phase-out policy are extensive, affecting all sectors of economies heavily reliant on coal for power generation. The adverse effects of an abrupt cessation of coal consumption on businesses and households are noteworthy. The policy is anticipated to render coal firms obsolete and precipitate reduced production in coal-dependent industries, resulting in a decline in overall output and an upswing in unemployment. Furthermore, it is poised to induce an escalation in public (both domestic and foreign) debt due to the expenses associated with transitioning from non-renewable to renewable energy sources. Managing the intricacies of compensation and restructuring will pose considerable challenges for countries characterized by low financial development and weak economic and political institutions. Consequently, the implementation of the policy is anticipated to be arduous owing to barriers in the market and technology, regional disparities in economic advancement, and policy misalignment. In addition, the quality of government and administration structured to design and execute policymaker programs, policies and deliver services efficiently and effectively also has a connection with carbon dioxide emissions and GHGs. More so, the government machinery responsible for formulating and implementing environmental regulations could operate with superfluous bureaucracy and long queuing times in most cases. It should be noted that the organizational framework for environmental governance especially in developing nations is inefficient with pitiable governance to mitigate CO_2 emissions. The weak institutions could prevent the design and implementation of good environmental policies and the adoption of the coal phasing-out policy.

The phasing out of coal consumption and full transition to affordable clean energy is not however impossible. Instead, it ought to be executed gradually, aligning with the developmental stage of each respective nation. Since the countries of the world are at different levels of development, which was achieved largely using coal for energy generation, the complete abrupt phase-out of coal consumption will critically harm many developed and developing nations and aggravate world poverty. Hence, it is crucial to assess the connection between coal consumption and environmental sustainability in economies at varying levels of development. This is of significance as comprehending the diversity in the relationship between coal usage and the environment will offer insights and direction for the implementation of diverse climate policies, particularly the gradual removal of coal from the energy consumption spectrum.

Hence, the present evaluate the relationship between coal consumption and environmental sustainability among the primary coal consumers globally. The present research contributes to the available literature on the association between coal consumption and the environment in many ways. Firstly, it employs a panel of countries recognized as major coal producers and consumers globally, departing from prior studies that focused on individual major coal producers and consumers. This approach addresses the challenge of generalizing findings to countries that recently adopted the phase-out policy during COP26. Secondly, the study compares the influence of coal usage on environmental deterioration in developing countries with that in developed countries, recognizing the variations in levels of development and coal consumption among these nations. This allows for an exploration of the diverse magnitudes of the influence of coal usage on the environment based on the heterogeneity of countries in terms of their development levels. Thirdly, the study introduces a governance index to account for the quality of governance in the coal consumption-environment model. Recognizing differences in institutional frameworks and capacities among countries to implement an energy transition is crucial, as it can significantly influence environmental sustainability. The omission of this institutional factor, common in many existing studies, may lead to variable omission bias and an overestimation of the effect of coal consumption on carbon emissions. Lastly, the current study utilizes the AAH estimator, a state-of-the-art estimation technique, to evaluate the nexus between coal consumption and the environment. This technique is advantageous in handling short panels with cross-sectional dependence, a prevalent feature of panel data due to increasing globalization and trade. Previous studies often employed less efficient techniques, such as fixed and random effects models and system GMM in the presence of cross-sectional dependence.

The subsequent sections of the paper include a literature review, methodology, results and discussion, and the conclusion and policy implications, presented from section 2 to section 5, respectively.

2. Literature review

2.1. Theoretical literature

The theoretical nexus between coal use and environment can be deduced from the ecological modernization theory which states that advancement in human society – further modernization facilitates the technological innovations in production and consumption processes which can reduce the use of material and energy (including coal), facilitate the internalization of environmental cost and thus promote environmental sustainability [22,23]. With modernization, economic actors introduce innovations that can promote environmental sustainability. The proponents of the ecological modernization theory also posit the dematerialization thesis. Dematerialization refers to a production and consumption process characterized by a reduced utilization of resources compared to conventional and more materialistic production and consumption methods.

The dematerialization in terms of energy transition from hard to soft energy path was considered [24]. The rigid energy approach is deemed economically inept and ecologically detrimental because it relies on resource and energy-intensive manufacturing utilizing coal along with oil energy. A soft energy path leads to a decline in material and energy intensity of production and consumption, which can result in the enhancement of the quality of the environment [24,25]. Accordingly, innovative production techniques can foster economic advancement while maintaining a low utilization of resources, promoting sustainable progress. In line with the ecological modernization theory, the consumption of coal could make production inefficient and can cause ecological damage. Moreover, the dematerialization thesis of the ecological modernization theory was also demonstrated by the environmental Kuznet Hypothesis – EKC [26,27]. Therefore, it is the nexus between environmental sustainability and coal consumption is well-established in the theoretical literature.

2.2. Empirical literature

Several empirical studies were carried out concerning the coal consumption-CO_2 nexus. The first aspect of the relationship considered is the causality between carbon emissions and coal consumption. The causal relationship between the utilization of coal and the release of CO_2 is thoroughly explored in the field of environmental sustainability studies. For example [12], conducted an empirical analysis investigating the connection between coal consumption and CO_2 emissions concerning economic growth, employing both a demand-side and supply-side framework in China, which is globally recognized as the largest producer and consumer of coal. The vector error correction mechanism showed that there is a one-way causal relationship from coal consumption to output both in the immediate and extended periods in the context of supply-side analysis. On the demand side, on the other hand, the relationship is from income to coal consumption. The interrelation between coal consumption and CO_2 emissions (pollutants) is found to be reciprocal both in the long and short term. The deduction drawn is that it would be challenging for China to enact a policy aimed at reducing greenhouse gas emissions solely through the curtailment of coal consumption.

Moreover [13], presented empirical proof of the reciprocal causal connection between the coal-CO_2 emissions relationship in China and India. Additionally [11], examined the long-term and short-term causal association between coal consumption and CO_2 emissions on GDP growth in the leading 10 coal-consuming nations over the period 1992–2009, employing Pedroni and Koa cointegration examinations and Granger causality. The findings reveal the existence of a prolonged association between GDP growth, overall coal consumption, and CO_2 emissions. The Granger causality test demonstrated that neither overall coal consumption nor CO_2 emission exhibited a causal link with GDP growth, while a short-term positive mutual causal connection between overall coal consumption and CO_2 emission was identified. Nevertheless [28], determined that there exists no causal relationship between coal consumption and various quantiles of "carbon emissions in the People's Republic of China.

A limited number of investigations have also assessed the influence of coal consumption on carbon emissions. For instance Ref. [29], presented empirical evidence of the adverse effect of coal usage on environmental conditions in BRICS and Turkey, respectively. The research by Ref. [30] indicated that the utilization of coal and a reduced reliance on fossil fuels are linked to increased CO2, while the adoption of renewable energy is correlated with decreased emissions in developed economies. In the same vein [31,32], studied the case of South Africa and Russia respectively, and established that the consumption of coal and other natural resources drives environmental degradation through the associated increase in carbon dioxide emissions. Similarly [33], investigated the interconnections between coal consumption, CO_2 emissions, FDI, economic growth, and urbanization in South Africa and confirmed a high speed of convergence under the period of investigation on outlined series and the existence of a LR equilibrium relationship between the variables for 1970 to 2017. The ARDL equilibrium relationship indicated coal consumption and economic growth contributed a larger volume to the emitter of CO_2 emissions in both the short and long range. Another study [34] looked at how Turkey's energy policies affect the relationship between coal, industrialization, and agriculture in relation to the climate goals of sustainable development. They used three models, one for economic reasons and the other two for environmental reasons. The study found that Turkey's environmental and economic performance followed the environmental Kuznets curve. Coal consumption, along with other factors, had a positive and statistically significant relationship with the ecological footprint in both the short and long term. In South Africa, there exists an inverted U-shaped pattern between energy consumption and environmental deterioration [35].

Another facet of the coal-environment nexus that attracted the attention of scholars is the impact of coal rent on environmental pollution. Another study [36] found that coal rent has a two-way effect on CO_2 emissions in India [29]. It also looked at the connections between coal rent, GDP growth, and CO_2 emissions in BRICS nations employing a pooled mean group with dynamic autoregressive distributed lag (PMGARDL). It found that both coal usage and coal rents have a big but adverse effect on CO_2 emissions. Likewise [37], submitted that regulating coal consumption by rent increases CO_2 emissions in E7 economies.

Some studies also explored the relevance of governance in the coal-environment nexus. However, in the measures of how governance affects CO2 emission in countries under survey by applying FMOLS and DOLS estimations, the empirical results indicated that governance enhances environmental quality. The findings suggested that good governance effectively enhances and protects environmental quality [15].

From the foregoing, the extant literature has established the diverse influence of coal consumption on the environment and economic growth. However, the issue is still contentious and there are numerous limitations of the extant studies that necessitate this study. First, the previous studies concentrated on a few individual countries such as China, the US, South Africa, and India. Yet, many other countries depend largely on coal for energy generation to promote industrialization and economic growth. Second, the extant studies failed to compare the coal consumption-environment nexus for developed and developing economies. It is important to do such a comparison to be able to provide the useful insight necessary for the implementation of the coal phase-out policy advocated during COP26. Third, the previous studies used econometric techniques which do not account for certain characteristics of panel data. Thus, their findings might be unreliable or less efficient for policy inferences in the current dispensation of the global economy.

Therefore, the present study attempts to bridge this gap in the literature by evaluating the impact of coal consumption on environmental sustainability in a panel of 59 major coal-dependent economies across the world.

3. Methodology

The econometric analysis for this study follows the procedure of the second-generation panel data techniques. The process commenced with initial examinations, encompassing summary statistics, correlation analysis, and tests for multicollinearity, CD, PURT, and panel-cointegration tests, followed by the estimation of the regression models.

3.1. Data

Using annual data for 59 major coal-consuming countries reported by the BP Statistical Review of World Energy (BP-SRW) [10] for the years 2000 and 2020, this study examined the connection between coal consumption and CO2 emissions. These nations were further categorized into 27 developed countries (DVC) and 32 developing countries (DIC) based on the WB classification utilizing gross national income per capita (World Bank, 2022). This categorization was employed to enhance consistent, robust, and reliable practical policy implications and specific recommendations. Economic growth data (GDP per capita (constant 2015 US$), CO2 emission (metric tonnes per capita), urban population (% of total population), FDI, and net inflows (% of GDP) were gathered from the WB-WDI. Coal consumption information was sourced from the BP-SRW, 2022. The data for the human capital index were acquired from PWT10, and governance was calculated using six WGI, obtained from the WB indicators, measured by indicators ranging from −2.5 to 2.5 [38]. The IMF provided the Financial Development Index, and globalisation data were sourced from the KOF in 2021.

3.2. Econometric techniques

The econometric process in this investigation commenced with pre-estimation tests, crucial for selecting suitable estimation methods. The test considered in this study includes the CD test, PURT and cointegration tests, then, the estimation techniques. These tests are important for the examination of the characteristics of the variables. The techniques are discussed as follows.

3.3. Cross-sectional dependency (CD) test

The common feature of panel data in recent times is cross-sectional dependence. It occurs when a common factor makes the cross-sectional units (the countries in this case) interdependent. The factors which cause the problem of CD in panel data include contiguity, and globalization. Due to the current wave of globalization, any time series panel data could be susceptible to the presence of CD. For instance, considering the geographical, social, and economic interconnectedness of the countries used in this study, it crucial to examine the existence of CD in the data. Thus, ignoring the problem of CD could lead to prejudiced and unpredictable results [39,40] Therefore, to ensure the robustness of the test, this study engaged four different CD tests. The tests are most appropriate for this study which used panel data with relatively large cross-sectional units (59 countries) as compared to the period (21 years). The H_0 for CD tests is absence of CD. The statistical decision concerning the test result is based test statistics.

3.3.1. Panel stationarity tests

Following the CD test, we examined the stationarity characteristics of all the variables using Pesaran [41] –CADF test. The CADF test captures the issue of CD and avoids invalid regression estimates. Equation (1) specifies the CADF model.

$$\Delta y_{it} = \beta_i + \delta_i y_{i,t-1} + \lambda_i \overline{y}_{t-1} + \sum_{j=0}^{p} \gamma_{ij} \Delta \overline{y}_{t-j} + \sum_{j=1}^{p} \theta_{ij} \Delta y_{i,t-j} + u_{it} \tag{1}$$

Where $\Delta y_{i,t-j}$, and $\overline{y}_{t-1}$ characterize the differenced and lags of the variable being tested. This study also employed the cross-sectional CIPS test by Pesaran [41] for a robustness check. The CIPS test also accounts for CD.

3.3.2. Panel cointegration test

Another crucial pre-estimation examination conducted in the present study is the panel cointegration test. It is employed to scrutinize the existence of enduring relationships among the variables. The Westerlund cointegration method (2nd-Gen cointegration test), accommodating CD [42], was utilized. Equation (2) outlines the formula for the test.

$$G_t = \frac{1}{N} \sum_{i=1}^{N} \frac{\delta_i}{SE(\widehat{\delta}_i)} \text{ and } G_a = \frac{1}{N} \sum_{i=1}^{N} \frac{T\delta_i}{1 - \sum_{j=1}^{k} \widehat{\delta}_{ij}} \tag{2}$$

$$P_t = \frac{\widehat{\delta}_i}{SE(\widehat{\delta}_i)} \text{ and } P_a = T\widehat{\delta}$$

The H_0 of the test is “no cointegration”. While the alternate hypothesis is that “there is cointegration”

3.4. Model specification and estimation

This study investigates the influence of coal consumption on environmental sustainability, as gauged by carbon emissions. Thus, following extant theoretical and empirical studies [16,17,21,25,33,35,43–49], the empirical model of this study is specified in equation (3).

$$\ln CO_{2it} = \alpha_0 + \beta_1 \ln GDPPC_{i,t} + \beta_2 \ln GDPPCSQR + \beta_4 \ln COAL_{i,t} + \beta_4 FD_{i,t} + \beta_4 GLOB_{i,t} + \beta_4 HCI_{i,t} + \beta_4 GOV_{i,t} + \beta_5 URB_{i,t} + \beta_4 FDi_{i,t} + u_{i,t} \tag{3}$$

Where $i = 1, 2, \ldots.59$, Major coal consuming countries, $t = 2000, 2001, 2003, \cdots\cdots\cdots, 2020, .$

CO_{2it} = CO_2 emission (metric tonnes per capita), $GDPPC_{it}$ = the per capita GDP, $GDPPCSQR_{it}$ = the squared GDP per capita, $COAL_{it}$ = Coal consumption, FD_{it} = Financial Development index, $GLOB_{it}$ = KOF Globalization index, GOV_{it} = Governance index,

URB_{it} = urban population, FDI_{it} = Foreign Direct Investment. The subscript i and t symbolizes the country and time respectively while u_{it} is the stochastic error term. All the variables, except URB and FDI were used in their logarithm forms. The URB and FDI were not log-transformed because URB was in percentage while FDI is measured in net inflows which contains negative values. The natural log of the variables was used to harmonize the units of measurement and remove the influence of possible outliers in the data. The justification for the incorporation of the variables in the model is premised on their significant nexus with environmental degradation established in the extant studies adopted for the model specification.

To estimate the regression model, the AAH estimator, as suggested by Chudik and Pesaran, was utilized [39]. The AAH serves as a form of GMM estimator that facilitates the utilization of internal instruments derived from the regressors (self-instrumenting). This solves the problems associated with the issues of appropriateness of the instruments. It is specifically most efficient for short panels (N > T). This makes it efficient for short and dynamic panel data models. The AAH estimator is more preferable compared to the [50] First-difference estimator and the [51] system GMM, primarily because it is applied with fewer restrictive conditions. Additionally, the estimates derived from AAH remain valid in the presence of correlated error terms and are asymptotically efficient. Given the nature of our data, where n $n\ (59) > T(21)$, the use of the AAH estimator is deemed appropriate.

4. Results and discussion

4.1. Descriptive statistics

The primary goal of the present study is to evaluate coal consumption-environmental degradation nexus in both developed and developing coal-consuming nations worldwide. Consequently, the variables incorporated in this study encompass carbon emissions assessed in terms of CO_2 emissions PC (CO_2), real GDPPC at constant 2015 US$ (GDP) as an indicator of economic growth, coal consumption (COAL), the financial development index (FD) gauged based on the efficiency, depth, and accessibility of financial markets and institutions, the KOF-globalization index (GLOB) measured in terms of aggregate economic, political, and cultural globalization, the human capital index (HCI), the Governance Index (GOV) calculated from the world governance indicators, urbanization quantified by urban population as a percentage of total population (URB), and FDI net inflows as a percentage of GDP (FDI). The data is sourced from various references, as specified in the methodology section of this study.

The descriptive statistics (Table 1) present a lot of interesting facts and distributional characteristics of the variables across the samples. For example, the mean (average) CO_2 emissions per capita amount to 3611.421, 7885.081, and 5.52, respectively, for the overall sample, high-income nations, and low-income nations. This indicates huge carbon dioxide emissions globally, with the developed countries as the major emitters. On average, the CO2 emissions in developed nations exceed those of the considered developing countries by more than a thousand times in this study.

Table 1
Summary statistics.

Variables	Observations	Mean	Standard deviation	Minimum	Maximum	Skewness	Kurtosis
Full sample							
CO2	1239	3611.421	13633.045	.17	88413.195	4.268	21.664
GDP	1239	18943.432	18869.196	653.809	78732.555	.989	2.866
COAL	1239	54.344	219.854	.1	1969.1	6.958	54.797
FD	1239	1.316	4.487	.047	40.9	6.643	49.67
GLOB	1239	64.966	22.82	.173	91.406	−1.731	5.557
HCI	1239	42.806	251.111	1.593	2015.554	7.393	56.143
GOV	1239	.822	.823	.096	3.874	2.679	9.141
URB	1239	64.327	25.845	.632	100	−1.139	3.641
FDI	1239	10.526	21.605	−40.081	108.42	2.541	8.38
Developed countries							
CO2	567	7885.081	19307.86	3.003	88413.195	2.62	9.169
GDP	567	28786.597	20358.303	2000	78732.555	.196	2.077
COAL	567	31.865	90.75	.1	573.3	4.721	25.633
FD	567	2.413	6.464	.1	40.9	4.352	22.121
GLOB	567	66.835	31.909	.173	91.406	−1.536	3.489
HCI	567	18.45	31.957	2.142	90.728	1.635	3.694
GOV	567	1.269	1.037	.413	3.874	1.657	3.907
URB	567	62.01	30.876	.632	98.079	−1.238	3.048
FDI	567	18.17	29.424	−40.081	108.42	1.404	3.427
Developing countries							
CO2	672	5.52	4.7	.17	29.146	1.906	7.933
GDP	672	10638.261	12504.175	653.809	61173.906	2.149	7.101
COAL	672	73.311	285.386	.1	1969.1	5.564	33.942
FD	672	.389	.167	.047	.787	.371	2.435
GLOB	672	63.389	9.823	36.106	84.469	−.25	2.748
HCI	672	63.357	338.459	1.593	2015.554	5.391	30.075
GOV	672	.444	.182	.096	.846	.492	2.504
URB	672	66.283	20.491	23.59	100	−.282	2.05
FDI	672	4.077	6.313	−2.757	58.519	4.102	23.345

Furthermore, the mean of coal consumption is 54.344, 31.865, and 73.311 for the full sample, developed economies, and developing nations respectively. This shows that an enormous quantity of coal has been consumed by the sample countries over time. But, the developing countries, on average, the developing countries consumed more coal than their developed counterparts across the world. This could be a result of the fact that developing countries largely depend on coal for electricity generation. The summary statistics equally show variations in the average values of other key variables such as GDP, governance, and FD, among others, across the samples.

Additionally, the variations in all the variables across the entire sample and the subsets of developed and developing nations are evident in the standard deviations of the variables. For instance, the standard deviation (SD) is substantial (exceeding 2) for the overall sample (13633.045), developed nations (19307.86), and developing nations (4.7). This implies notable fluctuations and distinctions in the levels of CO2 emissions within and among the subgroups and countries over time. The significant standard deviations of CO2 indicate substantial variations and alterations in the extent of environmental degradation globally and across different periods. Therefore, it is relevant to scrutinize the factors influencing environmental degradation using both a universal sample and subsets of developed and developing nations. Additionally, the standard deviations of most variables across all samples are considerable (exceeding 2), signifying significant dynamics of the variables within the samples over time.

Simultaneously, the skewness reveals mixed skewness, signifying that the distribution of certain variables is right-skewed while others are left-skewed. Additionally, some of the variables display leptokurtosis (long-tailed), while GDP exhibits platykurtosis (short-tailed) with a kurtosis less than 3. Consequently, the data suggests the presence of outliers. This rationalizes the log transformation of the variables to mitigate the impact of the outliers in the regression analysis. Subsequently, the AAH technique [39] was employed for the analysis.

In summary, the summary statistics indicate substantial fluctuations, and dynamism of the variables over the period considered. The statistics demonstrate the noteworthy dynamics in the levels of environmental degradation, coal consumption, economic growth, governance, and other crucial macroeconomic variables across all the sets of nations. Therefore, it is crucial to consider the full sample and subsets of developed and developing countries in the analysis.

4.2. *Correlation and multicollinearity test*

The analysis of correlation is performed to examine the existence of multicollinearity within the dataset, with the results outlined in Table 2. The results reveal a mixed correlations (+-) among the variables. Moreover, estimates indicate predominantly weak

Table 2
Pairwise correlations coefficients and Variance inflation factor (VIF).

Entire sample										
Variables	Mean VIF	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) LNCO2	4.87	1.000								
(2) LNGDP		−0.158	1.000							
(3) LNCOAL		0.033	−0.017	1.000						
(4) LNFD		0.640	0.102	0.222	1.000					
(5) LNGLOB		−0.902	0.490	0.029	−0.559	1.000				
(6) LNHCI		0.738	−0.124	0.025	0.502	−0.696	1.000			
(7) LNGOV		0.816	0.168	0.127	0.722	−0.665	0.632	1.000		
(8) URBAN		−0.581	0.753	−0.106	−0.323	0.781	−0.416	−0.355	1.000	
(9) FDI		0.878	−0.289	−0.031	0.605	−0.868	0.666	0.733	−0.627	1.000
Developed countries										
Variables	Mean VIF	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) LNCO2	30.50	1.000								
(2) LNGDP		−0.820	1.000							
(3) LNCOAL		−0.001	0.160	1.000						
(4) LNFD		0.595	−0.390	0.137	1.000					
(5) LNGLOB		−0.975	0.865	0.064	−0.608	1.000				
(6) LNHCI		0.993	−0.845	−0.040	0.609	−0.988	1.000			
(7) LNGOV		0.977	−0.736	−0.055	0.625	−0.961	0.973	1.000		
(8) URBAN		−0.918	0.897	0.150	−0.527	0.942	−0.932	−0.881	1.000	
(9) FDI		0.916	−0.797	−0.102	0.574	−0.894	0.914	0.886	−0.872	1.000
Developing countries										
Variables	Mean VIF	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) LNCO2	2.99	1.000								
(2) LNGDP		0.748	1.000							
(3) LNCOAL		−0.013	−0.204	1.000						
(4) LNFD		0.286	0.509	0.393	1.000					
(5) LNGLOB		0.460	0.622	0.208	0.625	1.000				
(6) LNHCI		0.245	0.369	0.032	0.200	0.294	1.000			
(7) LNGOV		0.295	0.586	0.224	0.721	0.732	0.247	1.000		
(8) URBAN		0.593	0.852	−0.328	0.262	0.486	0.304	0.411	1.000	
(9) FDI		0.192	0.456	−0.048	0.385	0.274	0.052	0.430	0.388	1.000

correlations (coefficients below 0.6) among the majority of variables. Nevertheless, some exceptions are noted, where certain variables demonstrate robust correlations, particularly within specific subsets. We reported the mean VIF for each sample. The estimates show that the VIF of the entire sample (4.8) and the subsample of developing countries (2.99) is less than 5. Hence, there is an absence of multicollinearity among the variables for both the overall sample and the panel of developing countries. Conversely, the VIF of the panel of developed countries (30.5) suggests the existence of multicollinearity, a condition that can potentially compromise the model estimates and result in deceptive inferences regarding the statistical significance of the variables. However, we used the AAH estimator which is robust to multicollinearity, and other econometric problems such as heteroskedasticity, and endogeneity.

5. Results of CD tests

Cross-sectional dependence arises when unobservable common factor(s) induce substantial cross-sectional correlations [41,52]. The consideration of cross-sectional dependence (CD) holds significance in the selection of statistical methodologies for panel data analysis. Disregarding the concern of cross-sectional dependence (CD) may result in imprecise and untrustworthy estimates, incorrect statistical deductions, and misleading insights into the connections among the variables under scrutiny. CD arises from various factors, including globalization, spatial (neighbourhood) effects, geographical location, and economic integration among the countries forming the panel. Consequently, the dataset employed in this study is vulnerable to CD challenges, as it encompasses all principal factors contributing to CD. As the countries were chosen from diverse regions globally, it becomes imperative to rigorously assess the presence of CD in the data. The outcomes of the CD tests detailed in Table 3 indicated the existence of CD in the data. Consequently, we opted for 2nd-generation panel data techniques, which accommodate CD for stationarity (unit root), cointegration tests, and regression analysis.

5.1. Results of unit root tests

Table 4 contains the results of the PURT (CADF and CIPS) at both levels and the first difference. The estimates of the CADF revealed that for the entire sample, Globalization (GLOB), governance index(GOV), and foreign direct investment (FDI) are stationary at levels while carbon emission (CO2), coal consumption (COAL), financial development index (FD), human capital index, and urbanization are stationary at first difference. Moreover, in addition to GLOB, GOV, and FDI, the CADF result shows that GDP and FD are stationary at levels for subsamples of developed and developing countries respectively. Similarly, the estimates of the CIPS confirm the mixed order of integration of the series for the entire sample and subsamples. Hence, the outcomes of the second-generation PURT suggests that a shock, will have a lasting impact on most variables – I(1), whereas certain variables will experience a transitory effect from a shock (positive or negative) and remain stationary at the level.

Table 3
Results of cross-sectional dependence (CD) tests.

	Breusch-Pagan LM	Pesaran (2004) scaled LM	**Bias-corrected scaled LM**	Pesaran (2015) CD
Entire sample				
LNCO2	16362.14***	250.456***	248.981***	7.409105***
LNGDP	26057.05***	416.187***	414.712***	138.0247***
LNCOAL	14167.06***	212.9319***	211.4569***	4.804963***
LNFD	11244.18***	162.9664***	161.4914***	47.84333***
LNGLOB	24464.06***	388.9555***	387.4805***	132.8912***
LNHDI	27577.15***	442.1726***	440.6976***	136.8433***
LNGOV	8805.475***	121.2775***	119.8025***	7.274575***
FDI	3731.102***	34.53292***	33.05792***	14.27449***
URB	23801.26***	377.6251***	376.1501***	105.5268***
Developed countries				
LNCO2	3751.529***	128.3447***	127.6697***	21.10863***
LNGDP	5283.751***	186.1747***	185.4997***	60.37589***
LNCOAL	2794.376***	92.21927***	91.54427***	30.08181***
LNFD	1773.991***	53.70732***	53.03232***	13.80821***
LNGLOB	4820.315***	168.6834***	168.0084***	65.33948***
LNHDI	5775.147***	204.7212***	204.0462***	73.32847***
LNGOV	2009.146***	62.58269***	61.90769***	3.148603***
FDI	1016.386***	25.11338***	24.43838***	4.649262***
URB	4328.714***	150.1291***	149.4541***	40.97028***
Developing Countries				
LNCO2	4654.72***	132.0395***	131.2395***	25.65951***
LNGDP	7963.056***	237.0793***	236.2793***	78.59215***
LNCOAL	4595.099***	130.1465***	129.3465***	20.54196***
LNFD	4088.217***	114.053***	113.253***	47.36766***
LNGLOB	7502.468***	222.4556***	221.6556***	67.26183***
LNHDI	7844.968***	233.33***	232.53***	62.68266***
LNGOV	2544.442***	65.03811***	64.23811***	5.148865***
FDI	1017.903***	16.57043***	15.77043***	10.95665***
URB	2328.314***	253.912***	104.441***	62.24301***

Table 4
Results of Unit root tests.

	CADF test			CIPS Test		
	Levels		First Diff	Levels		First Diff
Entire sample	(N = 59, T = 21)					
lnCO2	−1.726		−2.779***	−2.708***		−4.443***
lnGDP	−1.970		−1.705	−1.492		−3.096***
lnCOAL	−1.657		−3.364***	−2.759***		−5.038***
lnFD	−1.783		−3.365***	−2.584**		−4.617***
lnGLOB	−2.268***		−3.149***	−2.682***		−4.499***
lnHCI	−0.682		−1.040	−1.983		−3.204***
lnGOV	−2.293***		−2.880***	−2.893***		−4.444***
FDI	−2.159**		−3.600***	−3.379***		−5.153***
URB	−1.097		−1.326	−1.474		−2.519
Critical values	10%	5%	1%	10%	5%	1%
Level	−2.020	−2.080	−2.190	−2.52	−2.58	−2.69
1st Difference	−2.010	−2.080	−2.200	−2.53	−2.59	−2.72
Developed countries			(N = 27, T = 21)			
lnCO2	−1.510		−3.325***	−2.598**		−4.351***
lnGDP	−2.169**		−1.752	−1.465		−3.703***
lnCOAL	−2.304***		−3.975***	−2.613*		−4.880***
lnFD	−1.967		−3.294***	−2.394		−4.796***
lnGLOB	−2.153**		−3.297***	−2.589**		−4.946***
lnHCI	−1.851		−1.452	−2.736**		−3.722***
lnGOV	−2.067*		−2.668***	−2.703**		−4.466***
FDI	−2.184**		−3.255***	−3.445***		−5.105***
URB	−2.066		−2.436***	−3.425***		−3.316***
Critical values	10%	5%	1%	10%	5%	1%
Level	−2.070	−2.150	−2.300	−2.58	−2.66	−2.81
1st Difference	−2.070	−2.150	−2.300	−2.58	−2.67	−2.83
Developing countries			(N = 32, T = 21)			
lnCO2	−1.899		−2.882***	−2.778***		−4.378***
lnGDP	−1.681		−1.852	−2.213		−2.741**
lnCOAL	−1.974		−3.118***	−2.816***		−4.584***
lnFD	−2.288***		−4.070***	−3.301***		−4.821***
lnGLOB	−2.272***		−3.235***	−2.731***		−4.314***
lnHCI	−0.293		−0.532	−1.530		−2.287
lnGOV	−2.138**		−3.130***	−2.923***		−4.386***
FDI	−2.200**		−3.929***	−3.719***		−5.043***
URB	−0.725		−0.173	−1.104		−1.905
Critical values	10%	5%	1%	10%	5%	1%
Level	−2.040	−2.110	−2.230	−2.54	−2.61	−2.73
1st Difference	−2.030	−2.110	−2.250	−2.54	−2.62	−2.76

5.2. Result of cointegration test

The outcomes of the CADF and CIPS panel stationarity assessments reveal the non-stationarity of certain variables. It becomes pertinent, therefore, to examine the LR relationship among the variables and estimate their LR effect on environmental sustainability. This is achieved with the application of the Westerlund panel cointegration test., which captures CD. The test results contained in Table 5 show that the Gt statistics for the entire sample (α = −2.321, P = 0.000), developed countries (α = −2.335, P = 0.000), and

Table 5
Results of Cointegration tests.

	Entire sample			Developed countries			Developing countries		
Westerlund (2007) panel cointegration test									
Statistic	Value	Z-value	Robust P-value	Value	Z-value	Robust P-value	Value	Z-value	Robust P-value
Gt	−2.321	4.588	0.000	−2.335	3.174	0.000	−1.720	0.061	0.000
Ga	−3.045	5.861	0.980	−1.061	5.615	1.000	−1.864	5.386	0.900
Pt	−8.493	1.238	0.630	−3.837	2.293	0.900	−3.823	2.767	0.400
Pa	−2.063	2.684	0.800	−1.490	2.288	0.700	−0.698	3.200	0.700
Gengenbach, Urbain, and Westerlund (2015) error correction-based cointegration test									
	Entire sample			Developed countries			Developing countries		
Statistics	Coef	T-bar	P-value	Coef	T-bar	P-value	Coef	T-bar	P-value
ECT	−1.341	−3.41	0.01	−1.195	−3.33	0.05	−1.464	−3.481	0.01

developing countries (α = −1.720, P = 0.000), are statistically significant at 1%, indicating the rejection of the H_0 in all the samples of countries (full, developed, and developing). This shows the existence of LR nexus among the variables in all the models. The presence of cointegration is also confirmed by Gengenbach, Urbain, and Westerlund's error correction-based cointegration test, which is reported in the lower portion of Table 5. The EC-coefficients (ECT) of the test for the entire sample (T-bar = −3.41, P-value = 0.01), developed countries (T-bar = −3.33, P-value = 0.05), and developing countries (T-bar = −3.481, P-value = 0.01) are statistically significant, signifying the rejection of the null hypothesis. Therefore, there is LR equilibrium nexus among the variables considered.

5.3. Regression results

We have examined the characteristics of the series using descriptive statistics, stationarity tests, and the cointegration test. The results established the presence of CD, unit root, and LR relationship among the variable. Hence, we employed the AAH estimator to assess the impact of coal consumption, economic growth, governance, financial development, and other crucial macroeconomic variables on environmental degradation, quantified by carbon dioxide emissions. The models were estimated for both the overall sample of countries and the subgroups of developed and developing countries. The findings from this advanced panel data regression technique are displayed in Table 6. Columns 1, 2, and 3 of the table encompass the regression estimates for the full sample, developed and developing nations, respectively. This enables a robustness check and easy comparison of the parameter estimates of each variable for the different samples of countries considered in this study. Hence, the findings are discussed in the context of each explanatory variable as follows.

Economic growth and environmental sustainability: The regression result indicates that economic growth, represented by GDP per capita has a significant negative impact on carbon dioxide emissions in the context of the entire sample, where all the countries are in the panel. The elasticity parameter estimates shows that a one percent increase (decrease) in economic growth will result in about a 1.4357 percent decrease (increase) in carbon emissions. To evaluate the EKC hypothesis, we included the square of the GDP in the model. The coefficient estimates indicate a positive and significant elasticity between the GDP squared and carbon emission. Then, the corresponding negative and positive elasticity coefficient of GDP and GDPSQR reveal that a U-shaped relationship exists between economic growth and environmental degradation in the case of the full-sample panel of countries considered in this study. This suggests that the EKC hypothesis is not applicable within the scope of the nations examined in this study. These results align with empirical observations, as many nations are inclined to prioritize and embrace prolonged economic growth, potentially compromising environmental sustainability.

Moreover, the sample is dominated by developing economies that are still aspiring for further development. In such cases, the increase in economic growth will be less pollution-driven than when the countries reach an advanced stage of development. So, an increase in economic growth will lead to a reduction in carbon emissions to a certain (turning) point after which the increase in economic growth will increase environmental pollution. These findings are in line with the submissions of [25,44,45] who found U-shape economic growth-environment nexus for China and India and argued that the EKC hypothesis does not apply to all economies, particularly the developing economies. This is also confirmed in the case of the sub-panel of developing countries presented in column 3 of Table 6.

Table 6
Estimates of Chudik-Pesaran (2022) AAH (AAH) two-step GMM.

	(1)	(2)	(3)
VARIABLES	ChudikP_Entire sample	ChudikP_Developed countries	ChudikP_Developing countries
lnGDP	−1.4357***	0.3749***	−1.0577
	(0.4892)	(0.05483)	(0.7409)
lnGDPSQR	0.9893***	0.1874***	0.6815*
	(0.2484)	(0.02742)	(0.3926)
lnCOAL	0.1192***	0.1944***	0.03111*
	(0.009715)	(0.03155)	(0.01730)
lnFD	−0.1721***	−0.08702***	−0.1414***
	(0.009654)	(0.02194)	(0.03728)
lnGLOB	1.1631***	0.3563**	0.8277***
	(0.04583)	(0.1757)	(0.1591)
lnHCI	−1.9616***	1.1502	−0.4709***
	(0.08545)	(0.7646)	(0.1507)
lnGOV	0.1806***	0.9852***	−0.2092***
	(0.03389)	(0.2533)	(0.07045)
URB	−7.945e-04	−0.09416***	0.01884***
	(0.003836)	(0.01732)	(0.005389)
FDI	−2.076e-04**	0.001774***	−0.002391*
	(9.510e-05)	(5.215e-04)	(0.001318)
Constant	−4.7825***	2.0047***	−5.8792***
	(0.2538)	(0.5586)	(0.6272)
Observations	1239	567	672
Number of cid	59	27	32

Robust standard errors, presented in parentheses, indicate significance levels of 1%, 5%, and 10%, denoted by ***, **, and *, respectively.

In contrast, the elasticity coefficients of GDP and GDPSQR exhibit positivity and statistical significance within the sub-panel of developed countries. This consistently indicates a positive correlation between economic growth and environmental pollution in developed nations. These countries, characterized by extensive industrialization, emerge as significant contributors to global carbon emissions. Their development heavily relies on fuel consumption, and endeavors towards environmental sustainability often fall short of offsetting the ecological impact of economic activities within these nations.

Coal consumption and environmental sustainability: The coal consumption coefficient holds statistical significance and exhibits a positive relationship for both the overall sample and the subgroups of developed and developing countries. The elasticity coefficients suggest that a percent rise in coal consumption corresponds to a 0.1192%, 0.1944%, and 0.03111% increase in carbon emissions for the entire sample, developed countries, and developing countries, respectively. This suggests that the consumption of coal aggravates environmental pollution. The result reveals that the negative consequence of coal consumption on the environment is more in developed countries than the developing countries. Countries across the world are heavily using coal to meet up with their energy demand. Globally, coal is a major source of energy, constituting about 30% of power generation, and 40% of electricity, and it is the second-largest source of energy [29]. This exerts an adverse impact on the environment by elevating the release of carbon dioxide into the atmosphere. The finding resonates the reality because of the predominant use of coal for energy in developed and developing countries. For instance, the three (3) highest consumers of total coal, China, India, and the United States are, at the same time, the three (3) biggest emitters of carbon dioxide in the world [3,4]. The findings are in tandem with the dematerialization thesis of the ecological modernization theory. Also, the findings corroborate the submissions of [16,34,35] who reported that coal consumption damages the environment.

Financial development and environmental sustainability: Financial development is also examined as a factor influencing environmental pollution in this investigation. The regression results reveal that the elasticity coefficient of environmental pollution, represented by per capita carbon dioxide emissions, with respect to financial development is both negative and statistically significant across the entire panel, as well as within developed and developing countries. This suggests an inverse relationship between financial development and carbon emissions, signifying that heightened financial development plays a crucial role in fostering environmental sustainability. The magnitude of the coefficient indicates that a percent increase in the financial development index will lead to 0.1721, 0.08702, and 0.1414 percent decline in the carbon emissions for the case of the full panel, developed, and developing countries respectively. This supports the view that the development of the financial market and institutions encourages foreign direct investments, and facilitates trade and transfer of technology, which promote environmental sustainability.

Globalization and environmental sustainability: The estimates about the nexus between globalization and carbon emissions are positive and statistically significant for the entire sample and all the sub-panels of developed and developing countries considered in this study. This implies a positive relationship between globalization and environmental pollution. Globalization has led to an increase in production and trade, which increases energy consumption, especially fossil fuels, and the exploitation of natural resources substantially. Thus, globalization increases carbon emissions and ecological footprint across the globe, leading to further environmental degradation. Further, the estimates indicate that the elasticity parameters of carbon emissions for globalization are 1.1631, 0.3563, and 0.8277 for the full-panel, developed, and developing countries respectively. This suggests that the debilitating effect of globalization is more for the developing countries than their developed counterparts The plausible reason for the imbalance in the globalization-environmental pollution nexus against the developing countries compared to the developed countries is as a result of the fact that the former have less stringent environmental regulations than the latter. So, developed countries use stringent environmental regulations to substantially minimize the negative impact of globalization on their environment. Similar findings were submitted by Refs. [43,46,47] who found that globalization fosters environmental degradation.

Human capital and environmental sustainability: We also included the human capital index as a determinant of environmental sustainability. The findings revealed that human capital is negatively and significantly associated with environmental degradation for the entire sample and the sub-panel of developing countries. The parameter estimates demonstrate that a percent rise in HCI will result in a 1.9616 percent, and 0.4709 percent decline in carbon emission for the entire sample and sub-sample of developing countries respectively. This implies that higher human capital development reduces environmental pollution. With improvements in human capital, people become more knowledgeable about the adverse consequences of environmental pollution. The awareness will increase demand for a better environment through improved sanitation and prudent use of the environment, leading to a decline in environmental degradation. These findings are in tandem with the submission of [49] who found a negative association between human capital and ecological footprints in Pakistan and South Africa respectively. However, the parameter estimate of the human capital in the case of developed countries is statistically insignificant, indicating that human capital development does not significantly impacted CO_2 emissions in the developed nations. This reveals the fact that human capital is so high in developed countries that a further marginal increase in the human capital index would not affect environmental pollution.

Governance and environmental sustainability: The elasticity coefficients of carbon emissions concerning the quality of governance are statistically significant and positive for full-sample ($\beta = 0.1806$, P-value <0.01), and subpanel of developed countries ($\beta = 0.9852$, P-value <0.01) but negative for the subpanel of developing countries ($\beta = -0.2092$, P-value <0.01). This shows that better governance will bring about an increase in carbon emissions, especially in developed economies. An increase in economic growth could be the channel through which improve governance may drive CO_2. Better governance will foster economic growth, which will in turn increase production and energy consumption. The attendant effects will be an increase in carbon emission, this explains the reason the developed countries constitute major carbon emitters in the world. However, in the case of developing countries, better governance will improve institutions, including environmental regulations, and promotes the transfer of technology, thereby reducing carbon emission.

Urbanization and environmental sustainability: Urbanization is another explanatory variable we considered in this study. The coefficient of urbanization was negative and insignificant ($\beta = -7.945\text{e-}04$, P-value >0.1) for the entire sample, negative and statistically significant ($\beta = -0.09416$, P-value <0.01) for the developed countries, and positive and significant ($\beta = 0.01884$, P-value <0.01) for the developing countries. These estimates infer that urbanization fosters the decline in carbon emissions in the case of developed economies but results in an increase in carbon emissions in developing countries. The plausible explanation for this interesting finding is not farfetched. In the case of developed countries, the need for sustainable cities and eco-friendly development is a top agenda, thus urbanization led to more environmental consciousness among policymakers and individuals. On the other hand, urban areas are industrial hubs in the developing countries. Consequently, urbanization increases industrial waste, the combustion of fossil fuels, and the destruction of the environment due to construction. Hence, the positive nexus between urbanization and carbon emission in developing countries. Similar findings were shared by other studies [34,48,53].

Foreign direct investment and environmental sustainability: We also considered the impact of foreign direct investment on carbon emissions. The parameter estimates are −2.076e-04, 0.001774, and −0.002391 for the entire sample, developed, and developing countries respectively. All the coefficients are statistically significant, indicating that foreign direct investment (FDI) is a significant driver of carbon emission. However, the result revealed a negative nexus between FDI and carbon emission for the entire sample and developing countries, but a negative relationship between FDI and carbon emission for the developed countries. This is intuitively plausible because FDI inflow to developing countries encourages technological transfer, which reduces environmental pollution. Contrarily, the inflow of FDI into developed countries increases production, boosts economic activities, and increases carbon emissions. This shows that our findings support the pollution hallo hypothesis for the developing countries and the entire sample but reinforced the pollution-haven hypothesis for the developed economies.

6. Conclusion and policy implications

Coal has become a necessary evil in the world. It is crucial for economic progress but equally baneful to the environment. So, the coal consumption-environmental sustainability nexus attracted the attention of both policymakers and scholars. The current study used second-generation panel data techniques and the AAH technique to evaluate the coal consumption-environment nexus in major coal-dependent countries.

The findings confirm that higher levels of coal consumption are associated with higher levels of carbon emissions. This suggests that the consumption of coal aggravates environmental pollution and hinders environmental sustainability. Thus, this study confirms the environment-destroying effect of coal consumption. However, the findings reveal that the negative consequence of coal consumption on the environment is more for the sample of developed countries than that of developing countries. This implies that coal consumption by developed economies is more harmful to the environment than coal consumption by developing countries. Specifically, we found that the carbon emissions emanating from a one percent (1%) increase in coal consumption of the developed countries are about six-fold more than that of the developing countries.

The policy implication of these findings centers on the energy transition (hard to the soft path) policy, environmental tax, and coal phase-out agenda aimed at entrenching the dematerialization of production and consumption. The coal phase-out policy framework is beneficial to the global environment. Nonetheless, the implementation of the coal phase-out policy and the removal of fossil fuel subsidies should start with the developed countries or be made more stringent in such countries than the developing economies. Better still the developed countries can be compelled to relinquish a greater proportion of their coal consumption than the developing countries. Therefore, this study suggests that gradual phase-out, rather than abrupt phase-out of coal consumption should be implemented with greater emphasis on developed countries.

However, the limitation of this study is the use of a sample of selected coal consumers. The need to surmount the challenges of environmental sustainability is a global concern, and the coal phase-out policy is a global strategy. Also, the study did not compare the coal-environment association between the major coal consumers. Hence, a sample of many countries will enable researchers to compare the dynamics of the coal-environment nexus across different subregions of the World. Thus, further studies on coal consumption and environmental sustainability with a large (macro) panel and comparative analysis of the nexus are imperative for holistic policy inferences concerning the global agenda on the coal phase-out.

Data availability statement

Data is sourced from World Bank-WDI available at World Bank Open Data | Data and BP Statistical Review of World Energy available at Statistical Review of World Energy | Energy economics | Home (bp.com)

CRediT authorship contribution statement

Abdulkareem Alhassan: Formal analysis, Data curation, Conceptualization. **Ilhan Ozturk:** Writing – original draft, Supervision. **Mohammad Fahmi AL-Zyoud:** Methodology. **Festus Victor Bekun:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Y. Lei, L. Li, D. Pan, Study on the relationships between coal consumption and economic growth of the six biggest coal consumption countries: with coal price as a third variable, Energy Procedia 61 (2014), https://doi.org/10.1016/j.egypro.2014.11.1185.
[2] S.L. Satti, M.S. Hassan, H. Mahmood, M. Shahbaz, Coal consumption: an alternate energy resource to fuel economic growth in Pakistan, Econ Model 36 (2014), https://doi.org/10.1016/j.econmod.2013.09.046.
[3] International Energy Agency, International Energy Agency (IEA) World Energy Outlook 2022, 2022.
[4] I. Citaristi, International energy agency—IEA, The Europa Directory of International Organizations (2022) 2022, https://doi.org/10.4324/9781003292548-126.
[5] D. Liu, International energy agency (IEA), in: The Palgrave Encyclopedia of Global Security Studies, 2021, https://doi.org/10.1007/978-3-319-74336-3_587-1.
[6] S. Zou, T. Zhang, CO2emissions, energy consumption, and economic growth nexus: evidence from 30 Provinces in China, Math Probl Eng 2020 (2020), https://doi.org/10.1155/2020/8842770.
[7] H. Heubaum, F. Biermann, Integrating global energy and climate governance: the changing role of the International Energy Agency, Energy Policy 87 (2015), https://doi.org/10.1016/j.enpol.2015.09.009.
[8] J. Chai, M. Du, T. Liang, X.C. Sun, J. Yu, Z.G. Zhang, Coal consumption in China : how to bend down the curve? Energy Econ 80 (2019) https://doi.org/10.1016/j.eneco.2018.12.016.
[9] J.G.J. Olivier, K.M. Schure, J.A.H.W. Peters, TRENDS IN GLOBAL CO 2 and TOTAL GREENHOUSE GAS EMISSIONS 2017 Report Trends in Global CO2 and Total Greenhouse Gas Emissions: 2017 Report, 2017 [Online]. Available: www.pbl.nl/en.
[10] bp, Statistical Review of World Energy, 2022.
[11] U. Al-Mulali, I. Ozturk, The investigation of environmental Kuznets curve hypothesis in the advanced economies: the role of energy prices, Renewable and Sustainable Energy Reviews 54 (2016), https://doi.org/10.1016/j.rser.2015.10.131.
[12] H. Bloch, S. Rafiq, R. Salim, Coal consumption, CO 2 emission and economic growth in China: empirical evidence and policy responses, Energy Econ 34 (2) (Mar. 2012) 518–528, https://doi.org/10.1016/j.eneco.2011.07.014.
[13] B. Lin, Z. Li, Is more use of electricity leading to less carbon emission growth? An analysis with a panel threshold model, Energy Policy 137 (2020), https://doi.org/10.1016/j.enpol.2019.111121.
[14] Q. Wang, X. Song, Y. Liu, China's coal consumption in a globalizing world: insights from Multi-Regional Input-Output and structural decomposition analysis, Science of the Total Environment 711 (Apr. 2020), https://doi.org/10.1016/j.scitotenv.2019.134790.
[15] L.C. Liu, L. Cheng, L.T. Zhao, Y. Cao, C. Wang, Investigating the significant variation of coal consumption in China in 2002-2017, Energy 207 (2020), https://doi.org/10.1016/j.energy.2020.118307.
[16] T.S. Adebayo, A.A. Awosusi, F.V. Bekun, M. Altuntaş, Coal energy consumption beat renewable energy consumption in South Africa: developing policy framework for sustainable development, Renew Energy 175 (2021), https://doi.org/10.1016/j.renene.2021.05.032.
[17] F.V. Bekun, A.A. Alola, B.A. Gyamfi, P.A. Kwakwa, G. Uzuner, Econometrics analysis on cement production and environmental quality in European Union countries, International Journal of Environmental Science and Technology 20 (4) (2023), https://doi.org/10.1007/s13762-022-04302-9.
[18] R. Kurniawan, S. Managi, Coal consumption, urbanization, and trade openness linkage in Indonesia, Energy Policy 121 (2018), https://doi.org/10.1016/j.enpol.2018.07.023.
[19] V.G.R. Chandran Govindaraju, C.F. Tang, The dynamic links between CO2 emissions, economic growth and coal consumption in China and India, Appl Energy 104 (2013), https://doi.org/10.1016/j.apenergy.2012.10.042.
[20] C. Hepburn, Y. Qi, N. Stern, B. Ward, C. Xie, D. Zenghelis, Towards carbon neutrality and China's 14th Five-Year Plan: Green COVID-19 recovery, sustainable urban development and clean energy transition Authors' declaration. www.lse.ac.uk/GranthamInstitute, 2022.
[21] Y. Wolde-Rufael, K. Menyah, Nuclear energy consumption and economic growth in nine developed countries, Energy Econ 32 (3) (2010), https://doi.org/10.1016/j.eneco.2010.01.004.
[22] M.T. Clement, J. Schultz, Political economy, ecological modernization, and energy use: a panel analysis of state-level energy use in the United States, 1960-1990, Sociological Forum 26 (3) (Sep. 2011) 581–600, https://doi.org/10.1111/j.1573-7861.2011.01263.x.
[23] A. Razzaq, Y. Wang, S. Chupradit, W. Suksatan, F. Shahzad, Asymmetric inter-linkages between green technology innovation and consumption-based carbon emissions in BRICS countries using quantile-on-quantile framework, Technol Soc 66 (Aug. 2021) 101656, https://doi.org/10.1016/J.TECHSOC.2021.101656.
[24] A.B. Lovins, Soft Energy Paths: towards a Durable Peace, 2022.
[25] I. Khan, F. Hou, H.P. Le, S.A. Ali, Do natural resources, urbanization, and value-adding manufacturing affect environmental quality? Evidence from the top ten manufacturing countries, Resources Policy 72 (2021), https://doi.org/10.1016/j.resourpol.2021.102109.
[26] K. Ehrhardt-Martinez, E.M. Crenshaw, J.C. Jenkins, Deforestation and the Environmental Kuznets Curve: A Cross-National Investigation of Intervening Mechanisms *, 2022.
[27] V. Suri, D. Chapman, Economic Growth, Trade and Energy: Implications for the Environmental Kuznets Curve, 1998.
[28] K. Cheng, H.P. Hsueh, O. Ranjbar, M.C. Wang, T. Chang, Urbanization, coal consumption and CO2 emissions nexus in China using bootstrap Fourier Granger causality test in quantiles, Lett Spat Resour Sci 14 (1) (Apr. 2021) 31–49, https://doi.org/10.1007/s12076-020-00263-0.
[29] F.F. Adedoyin, M.I. Gumede, F.V. Bekun, M.U. Etokakpan, D. Balsalobre-lorente, Modelling coal rent, economic growth and CO2 emissions: does regulatory quality matter in BRICS economies? Science of the Total Environment 710 (Mar. 2020) https://doi.org/10.1016/j.scitotenv.2019.136284.
[30] E. Kohlscheen, R. Moessner, E. Takáts, Growth, coal and carbon emissions: economic overheating and climate change, SSRN Electronic Journal (2021), https://doi.org/10.2139/ssrn.3832005.
[31] T.S. Adebayo, Trade-off between environmental sustainability and economic growth through coal consumption and natural resources exploitation in China: new policy insights from wavelet local multiple correlation, Geological Journal 58 (4) (2023), https://doi.org/10.1002/gj.4664.
[32] O. Kanat, Z. Yan, M.M. Asghar, Z. Ahmed, D. Kirikkaleli, M. Murshed, How Do Natural Gas, Oil, and Coal Consumption Contribute to Environmental Degradation? An Empirical Investigation in Russia (2021), https://doi.org/10.21203/rs.3.rs-673735/v1.
[33] U. Joshua, G. Uzuner, Festus, V. Bekun, "Revisiting the Causal Nexus between Coal Energy Consumption, Economic Growth, and Pollutant Emission: Sorting Out the Causality", 2007, 10.1007/s11356-020-09265-3/Published.
[34] U. Joshua, F.V. Bekun, The path to achieving environmental sustainability in South Africa: the role of coal consumption, economic expansion, pollutant emission, and total natural resources rent, Environmental Science and Pollution Research 27 (9) (2020), https://doi.org/10.1007/s11356-019-07546-0.
[35] C. Magazzino, F.V. Bekun, M.U. Etokakpan, G. Uzuner, Modeling the dynamic Nexus among coal consumption, pollutant emissions and real income: empirical evidence from South Africa, Environmental Science and Pollution Research 27 (8) (Mar. 2020) 8772, https://doi.org/10.1007/s11356-019-07345-7. –8782.
[36] M. Bhattacharya, S. Rafiq, H.H. Lean, S. Bhattacharya, The regulated coal sector and CO2 emissions in Indian growth process: empirical evidence over half a century and policy suggestions, Appl Energy 204 (2017), https://doi.org/10.1016/j.apenergy.2017.07.061.
[37] B.A. Gyamfi, F.F. Adedoyin, M.A. Bein, F.V. Bekun, D.Q. Agozie, The anthropogenic consequences of energy consumption in E7 economies: uxtaposing roles of renewable, coal, nuclear, oil and gas energy: evidence from panel quantile method, J Clean Prod 295 (2021), https://doi.org/10.1016/j.jclepro.2021.126373.
[38] Indicators of Governance and Institutional Quality New Data on Governance • TI's 2005 Corruption Perceptions Index • WBI Worldwide Governance Indicators • World Bank Investment Climate Survey Database • 'Doing Business': Regulations and Their Enforcement • International Budget Project • Public Integrity Index • Freedom House: Civil Liberties and Political Freedoms • Reporters without Borders: Worldwide Press Freedoms Index A User's Guide to Governance Indicators, 2022.
[39] A. Chudik, M.H. Pesaran, An augmented Anderson–Hsiao estimator for dynamic short-T panels, Econom Rev 41 (4) (2022), https://doi.org/10.1080/07474938.2021.1971388.
[40] A. Chudik, M.H. Pesaran, A Bias-Corrected Method of Moments Approach to Estimation of Dynamic Short-T Panels, vol. 2017, Federal Reserve Bank of Dallas, Globalization and Monetary Policy Institute Working Papers, 2017, https://doi.org/10.24149/gwp327, 327.

[41] M.H. Pesaran, A simple panel unit root test in the presence of cross-section dependence, Journal of Applied Econometrics 22 (2) (2007), https://doi.org/10.1002/jae.951.

[42] J. Westerlund, Estimating cointegrated panels with common factors and the forward rate unbiasedness hypothesis, Journal of Financial Econometrics 5 (3) (2007), https://doi.org/10.1093/jjfinec/nbm006.

[43] S. Sabir, M.S. Gorus, The impact of globalization on ecological footprint: empirical evidence from the South Asian countries, Environmental Science and Pollution Research 26 (32) (Nov. 2019) 33387–33398, https://doi.org/10.1007/s11356-019-06458-3.

[44] A.N. Ajmi, R. Inglesi-Lotz, Revisiting the Kuznets curve hypothesis for Tunisia: carbon dioxide vs. Ecological footprint, Energy Sources, Part B: Economics, Planning, and Policy 16 (5) (2021) 406–419.

[45] V. Yilanci, M.S. Gorus, Does economic globalization have predictive power for ecological footprint in MENA counties? A panel causality test with a Fourier function, Environmental Science and Pollution Research 27 (32) (2020), https://doi.org/10.1007/s11356-020-10092-9.

[46] D. Kirikkaleli, T.S. Adebayo, Z. Khan, S. Ali, Does globalization matter for ecological footprint in Turkey? Evidence from dual adjustment approach, Environmental Science and Pollution Research 28 (11) (Mar. 2021) 14009–14017, https://doi.org/10.1007/s11356-020-11654-7.

[47] D.M. Ibrahiem, S.A. Hanafy, Dynamic linkages amongst ecological footprints, fossil fuel energy consumption and globalization: an empirical analysis, Management of Environmental Quality: An International Journal 31 (6) (2020), https://doi.org/10.1108/MEQ-02-2020-0029.

[48] A. Alhassan, O. Usman, G.N. Ike, S.A. Sarkodie, Impact assessment of trade on environmental performance: accounting for the role of government integrity and economic development in 79 countries, Heliyon 6 (9) (Sep. 2020), https://doi.org/10.1016/j.heliyon.2020.e05046.

[49] P.T. Iorember, G. Jelilov, O. Usman, A. Işık, B. Celik, "Correction to: the influence of renewable energy use, human capital, and trade on environmental quality in South Africa: multiple structural breaks cointegration approach, Environmental Science and Pollution Research 28 (11) (2021), https://doi.org/10.1007/s11356-020-11860-3 (Environmental Science and Pollution Research, (2021), 28, 11, (13162-13174), 10.1007/s11356-020-11370-2),".

[50] M. Arellano, S. Bond, The Review of Economic Studies, Ltd. Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application T O Employment Equations, 1991.

[51] R. Blundell, S. Bond, Initial Conditions and Moment Restrictions in Dynamic Panel Data Models, 1998.

[52] M.H. Pesaran, Testing Weak Cross-Sectional Dependence in Large Panels, 2012.

[53] F.V. Bekun, Race to carbon neutrality in South Africa: what role does environmental technological innovation play? Appl Energy 354 (Jan. 2024) 122212 https://doi.org/10.1016/J.APENERGY.2023.122212.