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Investigating the role of energy mix and sectoral decomposition on environmental sustainability in selected European countries

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ABSTRACT

This study investigates the interactions between per capita CO_2 emissions, economic growth, energy consumption (renewable and nonrenewable), agricultural, industrial, and services value-added, and trade openness across a panel of 23 European countries from 1995 to 2022. The empirical analysis is based on panel data econometric approaches (fixed effects, fully modified ordinary least squares, dynamic ordinary least squares, quantile regression models). Empirical findings reveal that economic growth and renewable energy consumption negatively impact CO_2 emissions across all models, highlighting its role as a crucial mitigating factor in reducing air pollution. Conversely, fossil fuel energy consumption and trade openness positively influence CO_2 emissions, underscoring the urgent need to transition towards more sustainable sources and trade strategies. Agriculture, industry, and services value-added are also significantly associated with air pollution, indicating areas requiring targeted interventions to curb emissions effectively. These empirical insights contribute to the literature and provide actionable plans for policymakers.

1. Introduction

The study explores the interrelationship between air pollution and several economic and energy-related variables across 23 selected European countries. In light of escalating climate change concerns, investigating the nexus between energy consumption, economic progress, sectoral value added, openness, and environmental quality is paramount. More specifically, this research seeks to contribute significantly to this ongoing debate by investigating how energy sources, ranging from renewable to nonrenewable, influence CO_2 emissions and economic advancement across Europe. Evidence-driven research is crucial as Europe grapples with pressing environmental concerns and strives to align with global sustainability goals. By enlightening the drivers of CO_2 emissions and economic growth across diverse European areas, the study tries to equip policymakers with facilitating the design and implementation of targeted policies to promote environmental sustainability while fostering economic growth.

The contributions of the study are three-fold. First, the current study explores the influence of detailed energy mix consumption on air pollution across EU nations. This disaggregated analysis investigates the impact of energy consumption on CO_2 emissions, considering the diverse energy types utilized across various sectors. Renewable and nonrenewable categories enable the determination of the percentage of sustainable energy derived from sources like wind, solar, hydropower, and nuclear, as opposed to finite resources like coal, oil, and natural gas. This data holds significant importance for sustainability efforts, supporting policymakers and energy stakeholders in evaluating progress toward a more sustainable energy blend and determining necessary measures to promote alternative energy adoption.

Second, the agricultural industry is often characterized as contributing to gas emissions due to unsustainable farming practices. These practices usually fail to enhance productivity and ensure food security (Li et al., 2014). Still, there is a widespread belief that agriculture could be crucial in reducing air pollution or ecological footprint (Manikas et al., 2020). Globally, it is responsible for approximately 20 % of CO_2 emissions, with methane contributing around 70 % and nitrogen oxide accounting for approximately 90 % (World Bank, 2016). Hence, a vital challenge is enhancing agricultural productivity while mitigating environmental degradation. Unlike previous research, which typically focuses solely on agricultural value-added contributions, this analysis extends its scope to encompass critical sectors such as industry (including construction) and services. By examining the impact of these sectors on CO_2 emissions alongside renewable and nonrenewable energy factors, this paper offers a holistic understanding of the complex

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dynamics driving carbon emissions in the EU. As far as our knowledge extends, this study is a pioneering effort in the broader context of environmental economics, specifically within EU-level CO_2 emission analysis.

Third, many studies have aimed to research the impact of economic growth, energy usage, trade activities, and agriculture on CO_2 emissions. However, many of these studies face limitations due to traditional empirical methodologies and generalized measurement approaches. Addressing these concerns, the importance of employing innovative econometric techniques to ensure unbiased analysis results is underscored (Sharif et al., 2021). The present study utilizes nonlinear and asymmetric specifications examining specific parameter variations within the conditional probability distribution of the environmental degradation variable. The current analysis primarily relies on econometric panel methods that address cross-sectional dependence and heterogeneity issues.

After this introductory section, the subsequent part (Section 2) reviews prior literature. Section 3 outlines the methodology employed and describes the utilized data. Section 4 illustrates the empirical findings of the analysis. Section 5 deliberates on these findings, while Section 6 wraps up with suggested policy recommendations.

2. Literature review

Understanding the complicated relationship between economic activities, energy consumption, and environmental sustainability is crucial to mitigating climate change and forward-moving to sustainable development. Most previous empirical studies examine the dynamics of CO_2 emissions across diverse countries and focus on the pivotal roles of income status, energy mix consumption, agriculture, industry, services, and trade openness (see Appendix, Table A). The majority of the studies have focused their interest on the effect of economic growth on air pollution (Mardani et al., 2019; Kostakis et al., 2023). Also, there is another strand in the literature that has included the effect of globalization and trade openness on environmental degradation (see inter alia Aluwani, 2023; Khurshid et al., 2022; Balsalobre-Lorente et al., 2019; Jebli and Youssef, 2015). However, our focus in this study is on the impact of the energy mix and sectoral decomposition on air pollution. Below, the first subsection examines the impact of renewable and nonrenewable energy consumption on CO_2 emissions. Following this, we explore the complicated role of sectoral decomposition in contributing to or mitigating air pollution.

2.1. Renewable and nonrenewable energy consumption

Several researchers have investigated the complex relationship between energy and CO_2 emissions across different countries and regions in a series of studies. For instance, Liu et al. (2017a) employed panel data analysis and observed a negative (positive) impact of renewable (nonrenewable) energy consumption on CO_2 emissions in the ASEAN-4 countries from 1970 to 2013. Similarly, Aydoğan and Vardar (2020) investigated the E7 countries (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey) during 1990–2014 and found a positive relationship between air pollution and fossil fuel energy consumption. Conversely, a negative relationship between CO_2 emissions and renewable energy consumption was observed. Moreover, Khan et al. (2022) examined data from 22 developing and developed countries spanning from 1991 to 2010, focusing on per capita CO_2 emissions, agriculture, forestry, and fishing value-added, cereal yield, renewable energy consumption, GNI per capita, industry and manufacturing value-added, and trade. Their results revealed a negative association between economic growth, energy consumption, and CO_2 emissions. Qiao et al. (2019) studied G20 countries from 1990 to 2014. Employing several econometric approaches (*cointegration, vecm, granger causality*), they found that renewable energy consumption is a mitigating factor of environmental degradation across all economies. Similarly, Nwaka et al. (2020) conducted a comprehensive study from 1990 to 2015 across 15 ECOWAS countries. They revealed that renewable energy has a negative relationship with total CO_2 emissions. Jebli and Youssef (2015) found that renewable energy exhibits a weak and negative impact on CO_2 emissions in Tunisia over the period 1980–2009. Waheed et al. (2018) employed ARDL in Pakistan (1990–2014) and estimated that there are adverse and significant effects on CO_2 emissions from renewable energy consumption in the long run, suggesting that increasing renewable energy can effectively improve air quality. Also, Chiu-Lan Chang (2022) confirmed the renewable energy-led growth hypothesis in BRICS countries, but surprisingly, it does not exist in N-11 economies. Similar results were found by Wang et al. (2023) for 38 sub-Saharan African countries in 2000–2019 and Kostakis (2024) in selected ASEAN economies over the period 1996–2018.

2.2. Agriculture, industry, and services value added

The outcomes concerning the influence of agriculture on CO_2 emissions diverge considerably, attributed to the diverse characteristics of different countries, varying periods, and methodological approaches employed. Two strands in the literature exist concerning the correlation between agriculture and CO_2 emissions. The first strand suggests that agriculture contributes to CO_2 emissions and air pollution. For instance, Liu et al. (2017b), estimated that agriculture positively affected air emissions in the BRICS nations from 1992 to 2013. Similarly, Waheed et al. (2018), utilizing ARDL and VECM approaches, observed that agricultural production positively and significantly impacted CO_2 emissions, indicating a potential area for targeted interventions to address emissions in the agricultural sector. Hafeez et al. (2020) investigated environmental degradation and emissions dynamics in economies participating in the OBORI initiative from 1980 to 2017. They focused their interest on energy demand, total energy use, finance, agriculture, forestry, fishing value-added per worker, and forest area. Employing Westerlund cointegration analysis and Panel causality tests, they found that agriculture contributes to increased environmental degradation, while forest expansion positively influences environmental quality. Agboola and Bekun (2019) analyzed data from Nigeria covering the period from 1981 to 2014. Using the Bayer and Hanck cointegration technique and Granger causality tests, their study found that agricultural activities contribute to CO_2 emissions. Similarly, Balsalobre-Lorente et al. (2019) applied DOLS, FMOLS, cointegration, and causality tests to BRICS nations from 1990 to 2014, discovering a positive correlation between agriculture and air pollution.Similar results have been confirmed by Aydoğan and Vardar (2020), Khan et al. (2022), Khurshid et al. (2022), Balogh (2022) and Aluwani (2023).

The alternative perspective asserts that agriculture leads to a reduction in CO_2 emissions. Jebli and Youssef (2017) conducted an extensive study across five North African countries from 1980 to 2011. Utilizing DOLS, FMOLS, cointegration, and causality tests, they identified a bidirectional relationship between CO_2 emissions and agriculture. Their long-term parameter estimates indicated that increased agricultural value-added was linked to a reduction in CO_2 emissions. Asumadu-Sarkodie and Owusu (2017) conducted a study in Ghana from 1971 to 2011. They used Partial Least Squares Regression and SIMPLS regression models and revealed that a 1 % increase in the crop production index reduced carbon dioxide emissions by 0.71 %. Raihan (2023) conducted a study in Vietnam covering 1984 to 2020, using the ARDL bounds test, VECM, FMOLS, and Toda-Yamamoto empirical approaches. Empirical results showed that improving agricultural value enhances environmental quality and reduces CO_2 emissions.

Moreover, certain studies examine the concerns surrounding industrial energy usage and CO_2 emissions through the lens of industrial value addition. Industrial value addition measures the extent, pace, effectiveness, and composition of industrial progress. Dong et al. (2020) undertook a detailed investigation focusing on China's economic

Table 1
Documentation of variables and sources.

Variable	Definition	Measurement	Source	Expected sign
$CO2_{it}$	Carbon dioxide emissions	Metric tons per capita	WDI	
$NREN_{it}$	Nonrenewable energy consumption	Quad Btu per capita	EIA	+
REN_{it}	Renewable energy consumption	Quad Btu per capita	EIA	-
AVA_{it}	Agriculture, forestry, and fishing, value added (% of GDP)	Value added (% of GDP)	WDI	+/-
AVI_{it}	Industry (including construction), value added (% of GDP)	Value added (% of GDP)	WDI	+/-
AVS_{it}	Services, value added (% of GDP)	Value added (% of GDP)	WDI	+/-
GDP_{it}	Gross domestic product	Constant 2015 US$, per capita	WDI	+/-
TO_{it}	Trade openness	Ratio between the sum of exports and imports and the GDP	WDI	+/-

Notes: WDI: World Development Indicators; EIA: Energy Information Administration

growth and carbon emissions from 2000 to 2017. They explored various sectors, including agriculture, industry, construction, transportation, retail, accommodation, and other industries' value-added contributions to GDP and CO_2 emissions. Using the STIRPAT decomposition model and the Tapio decoupling model, the study revealed an inverse relationship between value-added contributions from sectors like agriculture, industry, and transportation and GDP and carbon emissions. Conversely, a positive correlation was noted between the value-added contributions from construction, retail, accommodation, and other industries to GDP and carbon emissions. The study highlighted a dynamic pattern of decoupling and coupling between economic growth and carbon emissions across China's major industries.

Other researchers have also examined the impact of service sector value-added on CO_2 emissions. Rafiq et al. (2016) studied 53 countries, including 30 low-to-medium-income and 23 high-income nations, from 1980 to 2010. They analyzed factors such as CO_2 emissions, total population, GDP per capita, industrialization, and the contributions of the service and agricultural sectors to environmental degradation. Employing panel unit root tests with structural breaks, the Westerlund (2007) test, the Bai and Perron (2003) cointegration test, and Granger causality tests, their findings showed that industrialization increased pollution, while service and agricultural value-added were associated with reduced emissions.

Likewise, Jebli et al. (2020), found that for low-income countries, the industrial value-added statistically significantly and positively influences emissions. Conversely, in lower-middle-income countries, both industrial and service value added had positive effects, whereas within upper-income countries, services added were associated with reduced CO_2 emissions.

Singh (2021) analyzed data from 21 European countries (2000–2018) and found bidirectional causality between CO_2 emissions and each sector. Piaggio et al. (2015) employed input-output analysis, multiplicative decomposition, and additive decomposition to explore the dynamics of total carbon dioxide emissions in Uruguay. Their research revealed significant insights into the role of services in contributing to carbon emissions. More specifically, they found that transport-related sectors predominantly generate direct emissions from services. Also, the pollution from the service subsystem substantially impacts the overall economy. Interestingly, the study highlighted that almost all pollution attributed to the service subsystem originates from non-transport-related sectors. Xu and Lin (2016) conducted a comprehensive study across 30 Chinese provinces from 2000 to 2013 and suggested a U-shaped and an inverted U-shaped relationship between CO_2 emissions and the manufacturing and industrial sectors, respectively.

Ramos et al. (2018) examined sectoral value-added data from 11 economic sectors in Portugal from 1996 to 2013, finding both inverted-U and N-shaped relationships. Their analysis indicated that nearly all sectors contributed to increased CO_2 emissions, highlighting the broad impact of different sectors on Portugal's air pollution landscape during this period. Murshed et al. (2020) investigated 12 OPEC countries from 1992 to 2015 and discovered that income from the transportation sector decreased CO_2 emissions in the short term, whereas income from the construction sector increased CO_2 emissions. Interestingly, income from the tourism sector was associated with reduced CO_2 emissions.

2.3. Research gap

The current literature provides valuable insights into the relationships between economic activities, energy consumption, and CO_2 emissions, yet significant gaps remain. While existing studies form a strong basis for understanding these connections, there is a notable lack of research specifically examining how the agricultural sector in various European countries interacts with CO_2 emissions. Complementary, wide-ranging research on how other economic sectors, like industry and services, influence CO_2 emissions across Europe is lacking. Thus, by addressing these gaps and introducing a novel approach incorporating the agriculture, industry, and service sectors into our models, we can better understand the factors driving CO_2 emissions in Europe. Addressing these gaps will provide a more comprehensive understanding of the factors driving CO_2 emissions and inform evidence-based policy interventions for European environmental sustainability.

3. Data and methodology

Initially, the dataset encompassed the 27 EU countries and the United Kingdom. However, due to missing data values, five countries (Cyprus, Estonia, Czech Republic, Poland, and Lithuania) had to be omitted from the analysis. The countries in the study include Austria, Belgium, Bulgaria, Croatia, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Luxembourg, Malta, Netherlands, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom. Table 1 presents a documentation of variables along with their definitions, measurements, and data sources. The variables include CO_2 emissions (metric tons per capita), nonrenewable energy consumption (quad Btu per capita), renewable energy consumption (quad Btu per capita), agriculture, forestry, and fishing value added (% of GDP), industry (including construction) value added (% of GDP), services value added (% of GDP), gross domestic product per capita (Constant 2015 US$), and trade openness (the ratio between the sum of exports and imports and GDP). The measurements and sources of these variables are detailed, with data primarily sourced from the World Development Indicators (WDI) and the Energy Information Administration (EIA).

The selection of indicators for this study is grounded in their relevance to understanding the multifaceted dynamics of environmental sustainability and economic development. CO_2 emissions per capita reflect the carbon footprint associated with economic activities. Economic growth, represented by GDP, is a fundamental indicator of a country's economic performance and potential influence on environmental outcomes. Trade openness is included to examine how the degree of a country's integration into the global economy can affect environmental sustainability. The value-added by agriculture, industry, and services sectors is crucial for understanding the sectoral contributions to environmental quality. Finally, renewable and nonrenewable energy consumption indicators are selected to capture the differing effects of energy sources on air pollution. By examining these specific indicators, the study aims to comprehensively analyze the interactions between economic activities, energy use, and environmental quality, thus offering valuable insights for policymaking and sustainable development strategies.

Table 2 presents the average summary statistics for the sample of countries.

The descriptive statistics provide a snapshot of the dataset. For CO_2 emissions, the maximum value observed is 183.54, with a mean of 14.84 and a standard deviation of 34.41. The median value is 6.76, indicating that the distribution is skewed to the right, as evidenced by the higher mean than the median. Similarly, for GDP per capita in constant dollars, the mean value is 31,663 dollars. Trade as a percentage of GDP exhibits a mean value of 113 %, indicating a significant trade openness for this group of European countries. Renewable energy consumption, as expected, is deficient in per capita levels, while the nonrenewable energy consumption average is around 2.67 quad btu. The last three variables, AVA (Agriculture Value Added), AVI (Industry Value Added), and AVS (Services Value Added), represent different economic sectors' contributions. AVA has a mean of 2.66, AVI has a mean of 23.51, and AVS has the highest mean of 62.43, indicating that services contribute the most to the economy. These variables show varying degrees of contribution and variability within the dataset, providing insights into the economic structure and activity across different sectors.

In the empirical analysis, this study employs annual data from 1995 to 2022 to investigate the relationship between CO_2 emissions, economic growth, nonrenewable energy consumption, renewable energy consumption, agriculture, industry (including construction), services value-added, and trade openness in 23 European countries. The model can be constructed based on the following formula:

$$\begin{aligned}\ln CO2_{i,t} &= \beta_0 + \beta_1 \ln GDP_{i,t} + \beta_2 \ln REN_{i,t} + \beta_3 \ln NREN_{i,t} + \beta_4 \ln AVA_{i,t} + \beta_5 \\ &\quad AVS_{i,t} + \beta_6 AVI_{i,t} + \beta_7 TO_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{1}$$

where, t denotes the time (1995 to 2022), i denotes the 23 countries, $\varepsilon_{i,t}$ denotes a stochastic error, respectively. $\ln CO2_{i,t}$ is the log-transformed CO_2 emissions per capita, $\ln GDP_{i,t}$ is the log-transformed income per capita, $\ln REN_{i,t}$ is the log-transformed renewable energy consumption per capita, $\ln NREN_{i,t}$ is the log-transformed nonrenewable energy consumption per capita, $\ln AVA_{i,t}$ is the log-transformed agriculture value added (% of GDP), $\ln AVI_{i,t}$ is the log-transformed industry (including construction) value added (% of GDP), $\ln AVS_{i,t}$ is the value of the log-transformed service added (% of GDP), and $\ln TO_{i,t}$ is the log-transformed trade openness variable.

The particular set of countries comprises 23 selected European countries. That makes them to become more integrated. Thus, cross-section dependence should be tested. Failing to address this issue and assuming independence between cross-sections can lead to inaccurate, inconsistent, and biased results from estimators (Sarafidis and Wansbeek, 2012). To detect cross-section dependence, the study utilizes four CD tests (CD, CDW, CDW+, and CD*).[1] Null hypotheses state that there is no weak cross-sectional dependency between cross-sections, so any shock in one variable of the countries does not affect the others. The next step is to examine the homogeneity of the slope coefficients between the countries of interest (Pesaran and Yamagata, 2008; Blomquist and Westerlund, 2016; Bersvendsen and Ditzen, 2021). The classical panel data model is as follows:

Table 2
Summary statistics.

	Max	Mean	SD	Median
$CO2_{it}$	183.54	14.84	34.41	6.76
GDP_{it}	112,417	31,663	21,244	30,688
TO_{it}	393.14	113.00	67.88	88.22
REN_{it}	0.00	0.00	0.00	0.00
$NREN_{it}$	0.03	2.27	3.00	13.01
AVA_{it}	20.48	2.66	2.38	2.08
AVI_{it}	40.21	23.51	5.25	23.50
AVS_{it}	80.38	62.43	6.66	62.33

Notes: Renewable energy values are not zero but close to zero.

$$y_{i,t} = a_i + \beta'_{1,i} x_{1i,t} + \beta'_{2,i} x_{2i,t} + e_{i,t} \text{for} i = 1, 2, ..., n \text{and} t = 1, 2, ..., t \tag{2}$$

where i and t indicate the cross-section dimension and the time period, respectively. Null hypothesis is formulated as:

H_o: $\beta_{2i} = \beta_2$ for some i,

against the alternative.

H_o: $\beta_{2i} \neq \beta_2$ for some $i \neq j$,

Based on delta approach, the test statistic assumes that $e_{i,t}$ and $e_{j,t}$ are independently distributed for $i \neq j$ and/or $t \neq s$. However, it allows for a heterogeneous variance. The test statistic is given by:

$$\tilde{\Delta} = \frac{1}{\sqrt{n}} \left(\frac{\sum_{i=1}^{n} \tilde{d}_i - k_2}{\sqrt{2k_2}} \right) \tag{3}$$

Under the null hypothesis, slope coefficients are homogeneous across cross-sectional units. We should use the appropriate unit root tests to examine the stationarity hypothesis of the panel series employed in the present study. Using first-generation panel unit root tests that rely on cross-sectional independence and do not allow for a heterogenous cross-sectional slope coefficient in modeling is inappropriate as these methods can lead to inaccurate conclusions.[2] To address these issues, this study employs the cross-sectionally augmented Dickey-Fuller (CADF) panel unit root tests developed by Pesaran (2007). Therefore, in the following step of analysis, the cross-sectional augmented Dickey-Fuller (*CADF*) and cross-sectional IPS (*CIPS*) unit root tests developed by Pesaran (2007) should be utilized. CIPS test is a modified IPS test specified as follows:

$$CIPS = \frac{1}{n} \sum_{i-1}^{n} CADF_i \tag{4}$$

where *CADF* is the individual augmented Dickey-Fuller test that is described below:

$$\Delta y_{i,t} = a_i + \rho_i y_{i,t-1} + \beta_i \bar{y}_{t-1} + \sum_{j=0}^{k} \gamma_{i,j} \Delta \bar{y}_{t-1} + \sum_{j=0}^{k} \gamma_{i,j} \Delta y_{t-1} + e_{i,t} \tag{5}$$

where a_i, k and $\bar{y}_t$ are the constant, the lag specification and the temporary defined cross-sectional average respectively. The null hypothesis assumes that variables lack stationarity. Should the variables be integrated, they might demonstrate cointegration over a long period. After that, this study employs several panel cointegration approaches, specifically the demeaned options of Pedroni (1999; 2004), Kao (1999), and the bootstrapping Westerlund (2005), to assess the possible long-run relationships between the variables in the model. As mentioned earlier, the cointegration tests can give robust results in possible heterogeneity and cross-sectional dependence following the bootstrapping and demeaning options.

After establishing a long-term equilibrium relationship between the variables, the econometric analysis progresses by employing cointegration models. In our study, we utilize first and second generation

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[1] Pesaran (2015); Juodis & Reese (2022); Fan et al. (2015); Pesaran and Xie (2021).

[2] Under cross sectional dependency, first generation panel unit root tests have lower power and may lead to spurious outcomes.

models, starting with the fixed-effects (FE), fully modified ordinary least squares (FMOLS), and dynamic ordinary least squares (DOLS). More specifically, the current study estimates the fixed effects with Driscoll and Kraay (1998) standard errors (FE-DK) technique that provides robust estimates in the presence of heteroskedasticity, cross-sectional, and serial dependence (Sarkodie and Strezov (2019)). Moreover, we employ three alternative estimations since our data is an extended and heterogeneous panel dataset. First, the fully modified ordinary least squares (FMOLS) estimator suggested by Phillips and Hansen (1990) addresses endogenous and serial correlation errors. Second, the dynamic ordinary least squares (DOLS) estimator proposed by Saikkonen (1991) and Stock and Watson (1993) is employed as it addresses endogeneity while giving normally distributed estimators. Last, this study uses the innovative Machado and Silva (2019) quantile regressions (MMQR) method to find the distributional and heterogenous effects across quantiles while addressing cross-sectional dependence.

As a final step, to ascertain the causal relationship between the predicted variable and different predictors, the study also incorporates the recent Granger causality method proposed by Juodis et al. (2021). The uniqueness of this technique arises due to the null hypothesis assumption. Meanwhile, individual effects and autoregressive parameters may vary among individuals, with the Granger-causation parameters uniformly set to zero, indicating homogeneity (Xiao et al., (2023)). The null hypothesis posits no causal relationship between variables across all cross-sections, while the alternative hypothesis suggests the potential for a causal relationship among variables within specific groups.

4. Empirical results and discussion

Starting with the observations of cross-sectional dependence as illustrated in Table 3 (panel A), the empirical findings (CD, CDw, CDw+, and CD*) reject the assumption of weak cross-sectional independence for all variables examined. Additionally, in Panel B, the outcomes of slope homogeneity tests indicate rejection of the null hypothesis of slope homogeneity, indicating the presence of cross-country differences in coefficients.

Given these findings, the panel unit root test should be based on the second-generation estimation technique (CADF), which accounts for country-specific heterogeneity in the data. The results of panel unit root tests are reported in Table 4.

The CADF test reveals that only renewable energy consumption exhibits stationarity at levels across countries. Conversely, the remaining variables are non-stationary at the 0.05 or 0.1 significance level. However, all variables demonstrate stationarity at the 1 % significance level when differenced once. Consequently, we can infer that the variables are integrated at order one I(1). This section presents the findings regarding the cointegration relationship among the variables under consideration.

Table 4
Panel unit root tests.

Variables	CADF	Variables	CADF
LnCO2	1.100	ΔlnCO2	−2.909***
lnGDP	−2.198	ΔlnGDP	−2.295***
lnREN	−3.066***	ΔlnREN	−9.507***
lnNREN	2.955	ΔlnNREN	−3.161***
lnTO	−1.823	ΔlnTO	−2.175**
lnAVA	−0.210	ΔlnAVA	−7.054***
lnAVI	3.474	ΔlnAVI	−2.787***
lnAVS	2.698	ΔlnAVS	−2.544***

Notes: ***, and ** denote 1 %, and 5 % significance level, respectively. Δ denotes the first difference operator. All the variables in level were tested with intercept and trend. Pesaran's CADF test presents Z t-bar values.

Table 5 reports the results of the applied cointegration tests and shows evidence of a long-run relationship between CO_2 emissions, real gross domestic product, renewable energy consumption, nonrenewable energy consumption, agriculture value-added, industry (including construction), services value-added, and trade openness. Since variables are cointegrated, we can estimate the long-run relationships between the variables of interest. Table 6 presents regression models utilizing different estimation techniques to explore the dynamics between various variables, particularly their impact on CO_2 emissions.

Empirical evidence shows that economic growth and renewable energy consumption are linked to lower CO_2 emissions, supporting the idea that transitioning from fossil fuels to alternative energy sources can enhance environmental quality and sustainability. These findings are consistent with studies by Aydoğan and Vardar (2020), Khan et al. (2022), and Liu et al. (2017b), but they contradict the findings of Qiao et al. (2019) and Raihan (2023). Nonrenewable energy consumption is positively correlated with higher CO_2 emissions, aligning with studies by Liu et al. (2017a), Liu et al. (2017b), and Nwaka et al. (2020), which have shown that fossil fuel consumption leads to greater environmental degradation. Regarding trade openness, empirical results indicate a positive relationship with CO_2 emissions. That means that more open trade economies are linked to higher air pollution. This result is consistent with the findings of Khurshid et al. (2022) but opposes the findings of Aluwani (2023).

Furthermore, regarding the structure of the economies, findings confirm that agriculture, industry (including construction), and services value-added are significantly associated with increased CO_2 emissions. These results for agriculture align with Liu et al. (2017b), Hafeez et al.

Table 3
Cross-section dependence (Panel A) and slope homogeneity tests (Panel B).

Panel A: Cross-section dependence				
Variables	CD	CD_{W}	CD_{W+}	CD_{W^*}
LnCO2	53.35***	0.93	941.73***	-1.15
lnGDP	69.66***	-2.06**	1104.36***	-1.59
lnREN	38.72***	0.78	706.40 ***	-2.93 ***
lnNREN	44.39***	2.39 **	877.53 ***	-1.24
lnTO	70.97***	-1.83*	1127.00 ***	-3.29 ***
lnAVA	62.17***	-0.06	997.27 ***	4.67 ***
lnAVI	45.78***	-2.55 ***	807.00 ***	-1.59
lnAVS	57.74***	-1.80 *	917.76 ***	-2.65 ***
Panel B: Slope homogeneity tests				
Statistic			Δ	Δ_{adj}
			11.696***	14.577***
p-value			0.000	0.000

Notes: ***, ** and * denote 1 %, 5 % and 10 % significance level, respectively. CD (Pesaran, 2021; Pesaran, 2015); CD_{W} (Juodis and Reese, 2022); CD_{W+} (Fan et al., 2015) CD_{W^*} (Pesaran and Xie, 2021). Δ denotes the first difference operator.

Table 5
Panel cointegration tests.

Pedroni (1999; 2004) with constant and trend					
Statistics	Modified Phillips-Perron *t*	Phillips-Perron *t*	Augmented Dickey-Fuller *t*		
Sample value	3.4115***	-2.3709 ***	-2.3043**		
p-values	0.0003	0.0089	0.0106		
Kao (1999) with constant					
Statistics	Modified Dickey-Fuller *t*	Dickey-Fuller *t*	Augmented Dickey-Fuller *t*	Unadjusted modified Dickey-Fuller *t*	Unadjusted Dickey-Fuller *t*
Sample value	-10.7564 ***	-0.3318	-0.5427	-10.8940 ***	-0.3686
p-values	0.000	0.37	0.297	0.000	0.356
Westerlund (2005) with constant and trend					
Statistics	Variance ratio				
Sample value	-2.62 ***				
p-values	0.0044				

Notes: *** , ** and * denote 1 %, 5% and 10 % significance level, respectively. Kao-ADF, Pedroni-PP, and Pedroni ADF indicate ADF based on Kao (1999) and PP-based and ADF-based tests Pedroni (1999; 2004). Variance ratio statistic stands for cointegration test of Westerlund (2005). Pedroni and Westerlund cointegration vectors include time trend. Kernel method was used to estimate the long-run variance of each panel's series.

Table 6
Regression models.

Variables	FE	FE-with DK	FMOLS	DOLS
lnGDP	-0.0737**	-0.0737**	-0.0818***	-0.129*
	(0.264)	(0.289)	(0.008)	(0.051)
lnREN	-0.052***	-0.052 ***	-0.0494***	-0.043*
	(0.004)	(0.015)	(0.002)	(0.026)
lnNREN	0.949***	0.949***	0.985***	1.043***
	(0.023)	(0.030)	(0.008)	(0.045)
lnTO	0.113***	0.113***	0.117***	0.094*
	(0.027)	(0.033)	(0.009)	(0.049)
lnAVA	0.343**	0.343*	0.034***	-0.032
	(0.013)	(0.019)	(0.004)	(0.044)
lnAVI	0.443***	0.443***	0.420***	1.401***
	(0.044)	(0.051)	(0.014)	(0.044)
lnAVS	0.670***	0.670***	0.669***	3.477***
	(0.118)	(0.137)	(0.037)	(0.282)

Notes: *** , ** and * denote 1 %, 5 % and 10 % significance level, respectively. Numbers in parentheses represent standard errors. All variables were transformed using natural logarithms. The heterogenous pooled estimation method was employed, incorporating a constant in level as the deterministic trend across all specifications. The long-run variance estimator, utilized for computing the coefficient covariance matrix, was determined using the Newey-West Automatic bandwidth. The FMOLS estimation method employed heterogeneous long-run coefficients during the initial stage of the residual calculation. A fixed number of lags and leads was also chosen for the DOLS estimation method.

Table 7
Quantile regression models (MMQR).

Variables	q = 0.25	q = 0.50	q = 0.75
lnGDP	-0.078*	-0.073**	-0.069*
	(0.044)	(0.030)	(0.038)
lnREN	-0.052**	-0.052***	-0.052***
	(0.021)	(0.015)	(0.018)
lnNREN	0.989***	0.948***	0.906***
	(0.049)	(0.034)	(0.042)
TO	0.154	0.111***	0.067
	(0.057)	(0.040)	(0.049)
lnAVA	0.043**	-0.038**	-0.033*
	(0.022)	(0.0155)	(0.019)
lnAVI	0.457***	0.443***	0.428***
	(0.087)	(0.060)	(0.075)
lnAVS	0.720***	0.669***	0616***
	(0.190)	(0.131)	(0.162)

Notes: *** , **, and * denote 1 %, 5 %, and 10 % significance level, respectively.

(2020), Waheed et al. (2018), and Agboola and Bekun (2019) but contrast with Belbute, Pereira (2017) and Asumadu-Sarkodie and Owusu (2017). Similarly, the findings for industry and services follow Rafiq et al. (2016) and Jebli et al. (2020) but are opposed by Dong et al. (2020). After that, Table 7 presents the quantile regression models (MMQR).

The quantile approach can reveal possible asymmetric associations between the variables of interest. As can be seen, higher economic growth seems to be consistently associated with lower CO_2 emissions across all quantiles, suggesting a negative relationship between economic growth and carbon emissions, but with a diminishing effect as we move towards higher quantiles. Renewable energy consumption exhibits negative coefficients across all quantiles, signifying that higher renewable energy consumption is consistently linked to lower CO_2 emissions, implying that greater reliance on renewable energy sources may lead to reduced air pollution irrespective of the level of consumption. On the contrary, nonrenewable energy consumption shows positive coefficients at all quantiles, implying that higher nonrenewable energy consumption is consistently associated with increased CO_2 emissions, diminishing the effect as we progress towards higher quantiles. Trade openness demonstrates varying coefficients across quantiles, suggesting that its impact on CO_2 emissions differs at different points in the distribution. However, at the 50th quantile, higher trade openness is linked with higher CO_2 emissions, indicating a potential positive association between trade openness and carbon emissions at median levels. The coefficient of agriculture-added value is positive for low quantiles but becomes negative beyond certain thresholds. This implies that agriculture can mitigate air pollution at higher levels of CO_2 emissions. Finally, industry and services all exhibit positive coefficients across all quantiles, indicating that higher value added in industry and services sectors, is associated with increased CO_2 emissions, highlighting the role of economic activities in driving carbon emissions regardless of their level. Lastly, the heterogenous panel causality test, which detects possible causality directions amid the considered variables, proposed by Juodis et al. (2021), is presented in Table 8.

The Juodis et al. (2021) Granger causality findings show a bidirectional relationship at a 5 % significance level between CO_2 emissions and economic growth. Similarly, the feedback hypothesis is confirmed between CO_2 and trade openness at a 1 % significance level. There is a significant unidirectional causality from renewable energy consumption to CO_2 emissions, while there is unidirectional causality from CO_2 emissions to nonrenewable energy consumption. Finally, a significant unidirectional causality is observed between AVA, AVI, AVS, and CO_2 emissions in the selected European countries, flowing from the AVA, AVS and AVIto CO_2 emissions.

5. Conclusions and policy implications

This study's primary objective was to investigate the intricate

Table 8
Panel Granger causality tests.

H₀	*HPJ Wald-Stat*	*BIC selection*
lnGDP does not Granger-cause lnCO2	3.024*	-3049.81* (1 lag)
lnCO2 does not Granger-cause lnGDP	8.238**	-3629.64* (1 lag)
lnREN does not Granger-cause lnCO2	3.1248*	-2980.36* (1 lag)
lnCO2 does not Granger-cause lnREN	1.8090	-1214.46* (1 lag)
lnNREN does not Granger-cause lnCO2	3.88**	-3115.72* (1 lag)
lnCO2 does not Granger-cause lnNREN	0.826	-3040.35* (1 lag)
lnTO does not Granger-cause lnCO2	12.276***	-3028.45* (1 lag)
lnCO2 does not Granger-cause lnTO	9.2094**	-2938.76* (1 lag)
lnAVA does not Granger-cause lnCO2	17.42***	-3022.89* (1 lag)
lnCO2 does not Granger-cause lnAVA	0.613	-2233.02* (1 lag)
lnAVI does not Granger-cause lnCO2	13.96***	-3037.39* (1 lag)
lnCO2 does not Granger-cause lnAVI	0.0018	-3383.25* (1 lag)
lnAVS does not Granger-cause lnCO2	12.92***	-3034.15* (1 lag)
lnCO2 does not Granger-cause lnAVS	1.737	-4031.57* (1 lag)

Notes: ***, ** and * denote 1 %, 5 % and 10 % significance level, respectively. The bootstrapping approach is implemented.

relationships between economic, energy-related variables and CO_2 emissions. Employing various regression models, we sought to understand the drivers behind air pollution. Our empirical analysis yields many significant findings regarding the indicators influencing air pollution. Notably, economic growth must mitigate environmental sustainability. Renewable energy consumption consistently and negatively impacts CO_2 emissions across all models, highlighting its crucial role in reducing carbon emissions. Conversely, nonrenewable energy consumption showcased a positive relationship with air pollution, underscoring the pressing need for transitioning towards more sustainable energy sources. Furthermore, our results reveal that sectors such as agriculture, industry, and services value-added display significant associations with CO_2 emissions, shedding light on areas that effectively necessitate targeted interventions to curb European emissions. Trade openness can also play a vital role in European air pollution levels.

The policy implications drawn from our study are multifaceted and profound. First, given the significant impact of renewable energy consumption on reducing CO_2 emissions, policymakers are advised to prioritize investments in renewable energy infrastructure and promote energy efficiency measures. More specifically, shifting from fossil fuels to renewable energy sources offers a double success for environmental health. Burning fossil fuels is the dominant release of significant CO_2 emissions. In other words, policymakers and stakeholders must combat climate change by incentivizing renewable energy infrastructure that will drastically reduce greenhouse gas emissions. Feed-in tariffs, tax credits, and renewable portfolio standards are possible financial and structural measures to foster sustainability. In addition, stricter energy efficiency standards and public education campaigns could create a powerful force for a cleaner future.

Additionally, empirical results suggest that economic growth could mitigate air pollution in Europe, implying the need for new policies promoting sustainable economic growth. Emphasizing investments in green technologies and infrastructure can facilitate this goal. The added value in agriculture, industry, and services poses a complex challenge for policymakers. Findings indicate that while value-added in these sectors increases, CO_2 emissions may also rise. Therefore, policies promoting precision agriculture, energy-efficient technologies in industries, and low-carbon service industries like green finance are crucial. By implementing these strategies, governments and stakeholders can achieve economic prosperity while maintaining environmental responsibility.

Despite the valuable policy implications of this study, future research must address several shortcomings. It should investigate the effectiveness of specific policy interventions in reducing CO_2 emissions and explore innovative strategies for sustainable emission reduction. Furthermore, examining the interactions between socioeconomic variables and environmental outcomes across diverse geographical contexts can provide essential insights for regional policy-making and climate change mitigation. Continuous research and informed policy-making are essential for a sustainable and resilient future for coming generation.

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CRediT authorship contribution statement

Dimitrios Papadas: Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Bikramaditya Ghosh:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Ioannis Kostakis:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis.

Data Availability

Data will be made available on request.

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.

Appendix

Table 1

Summary of the literature regarding their region, methodology, and key findings.

#	Authors	Countries/ regions	Period	Variables	Methods	Findings
1	Jebli and Youssef (2015)	Tunisia	1980–2009	CO2, REN, NREN, GDP, TR	ARDL Cointegration, Granger Causality	In long-run estimations, NREN and TR positively influence CO2. Conversely, REN exhibits a weak and negative impact on CO2.
2	Piaggio et al. (2015)	Uruguay	2004	CO2	Input–output analysis	Services' direct emissions are primarily from transport-related sectors. Pollution generated by the service subsystem significantly impacts the rest of the economy. Nearly all pollution attributed to the service subsystem originates from non-transport-related sectors.
3	Xu nd Lin (2016)	30 Chinese provinces	2000-2013	CO2, POP, GDP, Specific energy consumption, Urb, Ind, Energy consumption structure	Unit root, cointegration and concurvity tests	Nonlinear effect of population growth on CO2 in manufacturing industry: positive "U-shaped" pattern.Economic growth: inverted "U-shaped" effect, supporting the Environmental Kuznets Curve (EKC). Specific energy consumption: positive "U-shaped" pattern concerning CO2 emissions. Nonlinear impact of industrialization: inverted "U-shaped" pattern, indicating increased CO2 emissions in the early stages of rapid growth.
4	Rafiq et al. (2016)	53 countries	1980-2010	CO2, POP, GDP, AVA, AVS, AVI	cointegration test, Granger causality tests	Nonlinear estimations show that industrialization increases pollution levels; AVS, and AVA help reduce emissions. Linear panel estimates, affluence, NREN, and energy intensity are the major drivers behind pollutant emissions.
5	Liu et al. (2017a)	ASEAN-4 countries	1970-2013	CO2, REN, NREN, GDP,AVA	cointegration tests, OLS, FMOLS, DOLS, Panel causality test	REN exerts a negative influence, whereas NREN positively impacts CO2 emissions. Additionally, AVA to CO2 has a negative effect. The study reveals unidirectional causalities exist in a unidirectional manner from NREN to AVA, from GDP to AVA, and directly from AVA to REN, while causal relationships extend from AVA and GDP to CO2
6	Liu et al. (2017b)	BRICS	1992-2013	CO2, REN, NREN, GDP,AVA	cointegration and causality tests	GDP, REN negatively impact emissions, whereas NREN and AVA positively affect CO2.
7	Jebli and Youssef (2017)	five North Africa countries	1980-2011	CO2, REN, NREN, GDP,AVA	DOLS, FMOLS, Cointegration tests, Causality test	Bidirectional causality exists between CO2 and AVA, indicating mutual influences. Unidirectional causality is observed from AVA to GDP, from GDP to REN, and from REN back to AVA
8	Asumadu-sarkodie, and Owusu (2017)	Ghana	1971- 2011	CO2, AVI, POP, TR, GDP, Fossil fuel energy consumption, Livestock production index, Electricity production, Crop production index, biomass burned crop, Enteric Emissions, Methane Emissions, Nitrous Oxide Emissions	Partial Least Squares Regression, SIMPLS regression model,	A linear correlation exists between energy, agriculture, macroeconomic factors, human-induced indicators, and carbon dioxide emissions. Specifically, increasing the crop production index by 1% is associated with reducing CO2 by 0.71%. Moreover, a 1% increase in GDP leads to a decrease in CO2 by 0.46%, aligning with the environmental Kuznets curve hypothesis.
9	Waheed et al. (2018)	Pakistan	1990-2014	CO2, REN, AVA and the covered forest area	ARDL, VECM	In the long run, there are adverse and significant effects on CO2 from REN and forest coverage, suggesting that increasing REN and expanding forest areas can effectively reduce CO2. Conversely, AVA has a positive and significant impact on CO2.

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Table 1 (*continued*)

#	Authors	Countries/ regions	Period	Variables	Methods	Findings
10	Ramos et al. (2018)	Portugal	1996-2013	CO2,Agriculture;Extractive;Manufacturing;Electricity, gas, water; Construction; Wholesale and retail trade; Transport; Accommodation, catering; Financial and insurance; Real estate; Human health	OLS	Nearly every sector of activity demonstrates a notable and favourable trend, indicating their contribution to the rise in CO2
11	Qiao et al. (2019)	G20 countries	1990- 2014	CO2, REN, GDP,AVA	cointegration test, VECM Granger causality test	EKC indeed exists in all economies. AVA significantly increases CO2, REN reduces CO2 in all economies, while GDP only positively impacts CO2 for developing economies.
12	Agboola and Bekun (2019)	Nigeria	1981–2014	GDP, AVA, TO, FDI, CO2, and EC.	Bayer and Hanck cointegration technique, Granger causality test	Inverted U-shape relationship between environmental degradation and income level, AVA contribute to CO2, FDI attraction helps mitigate CO2
13	Balsalobre-Lorente et al. (2019)	Brazil, Russia, India, China and South Africa	1990-2014	GDP, Electricity consumption, CO2, Agricultural sector, TO,	DOLS, FMOLS, Cointegration and causality tests	A positive connection between electricity consumption, the agricultural sector, TO, and CO2. The impact of mobile use is harmful. Inverted U-Shape between GDP andCO2
14	Nwaka et al. (2020)	15 ECOWAS countries	1990-2015	CO, Liquid CO2, AVA, GNI, REN, AVI, TO	Random, Fixed Effects,FMOLS, Panel quantile regression, cointegration tests	REN is negatively correlated with total CO2, while TR also shows a negative correlation. AVA reduces CO2 from liquid sources but increases CO2, suggesting a transition from mechanized to traditional farming methods and the use of agricultural biomass for energy.
15	Hafeez et al. (2020)	OBORI economies	1980- 2017	CO2, AVA, Energy demand, Total Energy use, Forest area	cointegration Test, FMOLS, DOLS, Panel causality test	Agriculture and energy demand contribute to environmental degradation, while forests enhance environmental quality. There's a bidirectional causality inferred between environmental degradation, finance, agriculture, and energy demand.
16	Dong et al. (2020)	China	2000-2017	agriculture, industry, construction, transportation, retail and accommodation and other industries value-added, GDP, CO2	STIRPAT decomposition model	The share of agriculture, industry, and transportation value added to GDP correlates negatively with CO2. Conversely, the share of construction, retail, accommodation, and other industries value added to GDP correlates positively with CO2
17	Jebli et al. (2020)	102 countries	1990–2015	CO2, GDP, REN, AVI, AVS	Generalized Method of Moments system and Granger causality test	In low-income countries, GDP and AVI positively affect CO2 emissions. However, in lower-middle-income countries, GDP has a negative impact on CO2, while both AVI and AVS contribute positively to CO2. Conversely, GDP is positively associated with CO2 in upper-income countries. However, REN and AVS lead to reduced CO2 levels in these countries.
18	Aydoğan and Vardar (2020)	E7	1990-2014	CO2, REN, NREN, GDP,AVA	cointegration tests, OLS, FMOLS, DOLS, Panel causality test	Over time, a positive relationship exists between CO2 and GDP, NREN and AVA. Conversely, a negative correlation exists between CO2 and the square of GDP and REN
19	Murshed et al. (2020)	12 OPEC countries	1992-2015	CO2, Gross value added, EC, TO, Urb, AVS	dynamic SDM model	EC decreases CO2. TR increases CO2. Urb increases CO2. National income from the transportation sector decreases CO2 in the short run. National income from the construction sector increases CO2. National income from the tourism sector decreases CO2.

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Table 1 (*continued*)

#	Authors	Countries/ regions	Period	Variables	Methods	Findings
20	Singh (2021)	21 European countries	2000-2018	CO2, FDI, GDP, Gross Value Added (GVA) of agriculture, service, manufacturing, and resource extensive industries	3SLS CGVA, AGVA, SGVA models	The relationship between CO2 and each industrial sector exhibits bi-directional causality. There exists a bidirectional relationship between CO2 and GDP. The relationship between CO2 and FDI yields heterogeneous findings.
21	Khan et al. (2022)	22 developing and developed countries	1991- 2010	CO2, REN, AVA, GNI, AVI, TR	FMOLS, random effect (RE), fixed effect (FE), and quantile regression	AVA has a positive impact on overall CO2 but a negative impact, specifically on CO2 from liquid fuel usage. A negative correlation was observed between CO2 and GDP in developing countries and their energy consumption.
22	Khurshid et al. (2022)	Pakistan	1971- 2021	CO2, GDP, Energy use, TR, Globalization Index, Urb	ECM, NARDL,	Agriculture production, GDP, and Energy use, are significant contributors to CO2; however, TR decreases CO2, and the impact of globalization and economic globalization is insignificant to CO2
23	Balogh (2022)	152 Non-EU countries	2000-2018	CO2, GDP, Agricultural machinery, AVA, Agricultural raw materials exports.	Dumitrescu and Hurlin causality test, FMOLS, DOLS, Kao cointegration test.	AVA leads to increased CO2, while agricultural exports have a diminishing effect on greenhouse gas (GHG) emissions.
24	Chang and Fang (2022)	BRICS and N-11 economies	1995–2019	GDP,REN, TO, labor force, gross fixed capital formation.	Augmented Mean Group and Methods of Moments Quantile Regression (MMQR	The renewable energy-led growth hypothesis applies to BRICS countries across all quantiles in the AMG model, but it surprisingly does not hold for N-11 economies in either estimation.
25	Tagwi (2022)	South Africa	1972- 2021	CO2, REN, AVA, Mean annual temperature, Annual precipitation	ARDL bounds test, Error Correction, Granger Causality Tests	Climate change hampers agricultural economic growth, while CO2 rise with agricultural economic growth. The impact of REN was negligible in both short and long terms.
26	Aluwani (2023)	South Africa	1990 - 2021	CO2, REN, AVA, TO	Cointegration and causality tests	Expansion in the agricultural sector contributes to environmental degradation, while TR benefits this sector. Additionally, the pace of renewable energy supply growth has hindered the agricultural economy.
27	Adebayo et al. (2023)	Pakistan	1965- 2021	CO2, GDP, EC, Urb, AVA	Causality in continuous wavelet transform	Urb, AVA, EC, and CO2 positively influence GDP. There's a feedback relationship between GDP and the factors (CO2, Urb, EC and AVA)
28	Raihan (2023)	Vietnam	1984 - 2020	CO2, GDP, Energy use, AVA	ARDL bounds test, VECM, FMOLS, Toda-Yamamoto causality test	GDP and energy use drive up CO2, while improving AVA adds quality and reduces CO2.
29	Wang et al. (2023)	38 sub-Saharan African countries	2000-2019	CO2, REN, GDP, Urb, EI, agricultural land	FGLS, GMM	REN lowers CO2s, whereas agriculture increases them. The reduction in CO2 due to REN is more significant in low-income countries compared to high-income countries.
30	Kostakis et al. (2023)	OECD countries	2014-2019	Global sustainable competitiveness (Index), Coal use, Petroleum use, Natural gas use, Renewable energy use, HDI, GDP, TO, Urb	OLS, FGLS, Quantile regressions, GMM	fossil fuels decrease sustainability, renewable and nuclear energy contribute positively to sustainable socioeconomic development, alternative energy sources strongly influence socioeconomic sustainability in the lower and upper quantiles, the HDI and TO improve sustainability

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Table 1 (*continued*)

#	Authors	Countries/ regions	Period	Variables	Methods	Findings
31	Kostakis et al. (2023)	Middle East and North Africa-MENA	1994-2014	CO2, GDP, REN, NREN, TO, Population Density, Globalization Index.	Cointegraion tests, FGLS, FMOLS, DOLS, and Granger causality	Energy consumption has a notable negative impact on environmental quality. Globalization exacerbates environmental degradation, while trade openness and population density could potentially mitigate CO2
32	Ghosh et al. (2024)	Global	1961–2023	Total Renewable Water resources per capita (TRW), Total Internal Renewable Water resources per capita (TIRW), Total Water Withdrawal per capita (TWW), Global Food Consumption per capita (GFC), Global Crop Production (GCP), and Global Electricity Consumption (GEC).	Quantile Vector Auto-Regression (QVAR)	Positive shocks have a more pronounced effect on variables than negative shocks. Crop production primarily responds to shocks. Renewable water consistently emits more than it absorbs in all scenarios, whereas water withdrawal is significant during negative shocks and neutral periods.
33	HAMED et al., (2024)	Selected MENA countries	1990-2015	CO2, AVA, EC, Crop water productivity	Westerlund cointegration, CCE-MG regression, VECM Granger Causality test.	Short-term: AVA influences CO2 and water productivity affects CO2 unilaterally, without reciprocal effects. A mutual relationship exists between EC and CO2. Long-term: CO2 emissions, AVA, water productivity, and EC exhibit feedback causality.
34	Kostakis (2024)	Selected ASEAN economies	1996-2018	CO2, REN, capital account openness index,	Cointegration tests, FE, Quantile regression	REN enhances environmental quality, while financial openness contributes to environmental degradation. Quantile analysis demonstrates that GDP impact diminishes with rising CO2, whereas financial openness has a stronger effect in countries with higher air pollution levels.

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