Journal of Open Innovation: Technology, Market, and Complexity 10 (2024) 100360

Contents lists available at ScienceDirect

Journal of Open Innovation: Technology, Market, and Complexity

journal homepage: www.sciencedirect.com/journal/journal-of-open-innovation-technology-market-and-complexity

Links between technological innovation, financial efficiency and environmental quality using quantile regressions: The role of foreign direct investment, institutional quality and natural resources

Rafael Alvarado [a,*], Brayan Tillaguango [b], Elisa Toledo [c], Muntasir Murshed [d,e], Cem Işık [f,g,h,i]

[a] Carrera de Economía and Centro de Investigaciones Sociales y Económicas, Universidad Nacional de Loja, Loja 110150, Ecuador
[b] Esai Business School, Universidad Espíritu Santo, Samborondon 091650, Ecuador
[c] Departamento de Economía, Universidad Técnica Particular de Loja, Loja 110104, Ecuador
[d] Department of Economics, School of Business and Economics, North South University, Dhaka-1229, Bangladesh
[e] Department of Business Administration, Daffodil International University, Dhaka, Bangladesh
[f] Department of Economics, Faculty of Economics and Administrative Sciences, Anadolu University, Eskişehir, Turkiye
[g] Faculty of Tourism, Atatürk University, 25240, Erzurum, Turkiye
[h] Azerbaijan State University of Economics (UNEC), Clinic of Economics, Baku, Azerbaijan
[i] Western Caspian University, Economic Research Center (WCERC), Baku, Azerbaijan

ARTICLE INFO

Keywords:
Technology
Financial efficiency
Environmental quality
Cointegration
MMQR

ABSTRACT

Policymakers and academics are interested in identifying mechanisms that promote environmental sustainability due to their relationship with climate change. This research evaluates the channels that transmit the effect of technology and financial efficiency on environmental quality. The relationship is moderated by real production per capita, foreign direct investment, natural resource rents, and institutional quality in the context of the Environmental Kuznets Curve. The research covers the 1996–2021 period for a sample of 88 economies classified into three groups according to the World Bank Atlas Method. We use second-generation cointegration techniques with structural breaks and quantile regression models. The findings offer sufficient evidence to conclude that the impact of technology and financial efficiency on environmental quality is heterogeneous throughout the distribution. Our findings suggest that technology is more associated with maximizing production than mitigating or restoring environmental deterioration. A policy implication derived from our research is to encourage the generation of carbon-free technology and promote financial efficiency in upper-middle-income countries to achieve environmental sustainability.

1. Introduction

Modern economies face significant economic and environmental challenges derived from the costs of global warming and climate change. One of the most accepted environmental mitigation strategies in the academic and political debate is that economic development and technology will reduce environmental degradation significantly in the long run (Kwilinski et al., 2024). Technological innovation has brought numerous advances that have transformed daily activities in the social environment, improving efficiency, communication, and social well-being (Kim, 2021; Hoa et al., 2023b; Fernandez-Pinto et al., 2024). Technological innovation has revolutionized society in recent decades and influenced the environment's quality. For example, the massive use of computers in the labor market and the use of the Internet, mobile devices, and social networks have transformed the ways of communicating, doing work, and consuming information, directly impacting environmental sustainability. In this sense, technological advancement boosts the efficiency and productivity of the most specialized sectors, facilitating tasks that previously required more time and effort. In addition, technology has allowed the development of new industries and the creation of jobs related to innovation and digitalization, which increases production and consumption and ultimately increases environmental pollution. However, technological progress has also been one of the main sources of environmental degradation, posing severe

* Corresponding author.
E-mail addresses: jose.r.alvarado@unl.edu.ec (R. Alvarado), brayan.tillaguango@unl.edu.ec (B. Tillaguango), eetoledo@utpl.edu.ec (E. Toledo), muntasir.murshed@northsouth.edu (M. Murshed), cemisik@anadolu.edu.tr (C. Işık).

https://doi.org/10.1016/j.joitmc.2024.100360

Available online 9 August 2024

challenges to sustainability and preserving our planet for future generations (Shokrollahi et al., 2024). Part of technological innovation is associated with the consumption of polluting energy, particularly from non-renewable sources such as coal and oil, that increase greenhouse gas emissions (Da Silveira Cachola et al., 2023). In practice, several technological advances increase environmental damage, but technological solutions have also been developed to mitigate the degradation of nature. For example, the production and consumption of renewable energy such as solar, wind, and hydroelectric energy constitute an example of the environmental benefits of technological progress (Hoa et al., 2024; Ngoc and Xuan, 2024). In this sense, green technologies can reduce CO_2 emissions indirectly by improving the energy and industrial structure (Lin & Ma, 2022). The analysis and debate on the link between technology and CO_2 emissions remain open and requires further study to expand the understanding of the sources of pollution or environmental mitigation.

In parallel, the modernization of economies caused transactions to be carried out through the financial system, which has caused a decrease in the demand for cash. The evidence indicates that financial development constitutes an environmental mitigation mechanism (Patel and Mehta, 2023). However, financial efficiency can reduce companies' costs, freeing up companies' scarce resources for environmental protection (Faulkner et al., 2022). On the contrary, in countries with low financial efficiency, financing could be directed to finance speculative investments rather than to promote companies' environmental responsibility. In practice, financial efficiency promotes that savings be used only to finance investment and responsible consumption with nature.

This research moderates the relationship between technology, financial efficiency, and environmental quality by real per capita output, natural resource rents, foreign direct investment, and institutional quality. The inclusion of covariates is widely supported in previous literature and the analyzed context. Financial efficiency could facilitate the application of environmental policy measures by directing credits towards sectors with fewer CO_2 emissions. Likewise, the evidence of the link between FDI and CO_2 emissions is scattered, and the debate has identified heterogeneous impacts between countries with different levels of development or due to the use of different methodologies (Lee and Zhao., 2023). Several investigations support the idea that pollution is promoted by the FDI within the context of the pollution haven hypothesis. The basic idea is that investments move to poor countries with little environmental regulation, with greater interest in attracting foreign investments than protecting the environment (Muhammad and Khan, 2019). However, there needs to be more conclusive evidence on the pollution haven hypothesis, and the stylized facts show that FDI flows in different directions, not only from rich to poor countries. Another factor contributing to increasing CO_2 emissions as a proxy for environmental quality is the income from natural resources. At least two mechanisms explain the positive relationship between natural resource rent and CO_2 emissions. On the one hand, the natural resources rents increase the consumption capacity of governments and society, increasing aggregate demand and ultimately increasing CO_2 emissions. On the other hand, exploiting natural resources requires machinery that uses fossil energy, transportation for the material, fuel burning, and other aspects related to extractive activities. Finally, solid institutional quality implies effective governance and efficient public administration of economies. Karim et al. (2022) demonstrate that CO_2 emissions are reduced by controlling corruption and improving regulatory quality and the rule of law. This allows for properly implementing and enforcing environmental mitigation and restoration laws.

This research uses the novel second-generation cointegration technique with structural breaks by Westerlund and Edgerton (2008) and the recent Methods of Moments Quantile Regression (MMQR) technique formalized by Machado and Silva (2019). Our research contributes to the debate on the nexus between environmental sustainability and technology by analyzing the joint effect of economic progress, natural resource rents, financial efficiency, and institutional quality. In parallel, we group countries according to income level to facilitate environmental policy recommendations derived from the work. Our findings provide strong empirical evidence that in high-income countries (HICs), technology, financial efficiency, FDI, NR, and IQ increase CO2 emissions. Technology increases polluting gas emissions in upper-middle-income countries (MHIC) and lower-middle-income countries (MLIC). In MHICs, financial efficiency and institutional quality reduce emissions, but in MLICs, they increase them. These results indicate that the covariates have a heterogeneous impact on emissions throughout the distribution, highlighting the heterogeneity of the countries as a factor to be considered in formulating environmental mitigation policies.

The rest of this research has the following structure. The second section systematically reviews similar literature to identify the gap in the literature. The third section presents the data and the methodological strategy. The fourth section contains the results and a discussion of the findings with previous literature, explaining the similarities or differences between the findings. The last section presents the conclusions and environmental policy recommendations derived from the work.

2. Literature review

2.1. CO_2 emissions and economic growth nexus

From the pioneering works of Grossman and Krueger (1991) and Panayotou (1993), empirical evidence has shown that CO_2 emissions are mainly the result of anthropogenic activities aimed at improving the quality of life of the population (Esmaeili et al., 2023;). The analysis of the link between environmental quality as a function of economic development has been called the Environmental Kuznets Curve (EKC). If we evaluate the findings of the economic growth-CO_2 emissions nexus, we found two main lines of research concerning the methodological strategy used. In the first line, they mainly use time series to analyze the trajectory of CO_2 emissions in a single country or a small group of countries (Chen et al., 2024). The evidence using time series is biased mainly by the availability of data for a relatively short period, where it is only possible to observe some stages of a country's economic development in short periods (Hasan et al., 2023; Rasheed and Liu, 2024). Validating the EKC for a single country requires an extensive database that covers the different stages of development, which limits the robustness of the available empirical evidence. A limited number of investigations have data for a long series, mainly in developed countries (Yilanci et al., 2023; Jebabli et al., 2023; Raza and Tang., 2024). The second group includes research that studies the economic growth-CO_2 emissions nexus using panel data techniques (Wang et al., 2023; Ganda, 2024b; Naseem et al., 2024). Including countries with different levels of development facilitates empirical verification of the EKC when the sample of countries includes high, upper-middle, lower-middle, and low-income countries (Li et al., 2024). There is a belief that environmental pollution is a problem of economic and social development, but the evidence found has been essentially dispersed and needs to be more conclusive (Abban et al., 2022; Guo and Shahbaz, 2024). Instead, the findings differ from one country to another or between groups of countries. Furthermore, the results are heterogeneous according to the application of the methodological strategy (Ridwan et al., 2024). Furthermore, some studies confirm the existence of an inverted N-shaped environmental Kuznets curve that is statistically significant (Purwono et al., 2024; Wang and Xu, 2024). However, most empirical results support the idea that environmental quality is a function of real per capita output and other factors (Jia et al., 2024).

2.2. CO_2 emissions and technology nexus

The underlying mechanism that explains the relationship between technological innovation and CO_2 emissions can be summarized in two aspects. First, there is a hypothesis that the creation or adoption of new technologies will reduce CO_2 emissions because new products emit fewer polluting emissions than old products (Kwilinski et al., 2024b; Shen and Zhang, 2024). Second, the use of new technologies facilitates the application of regulatory policies, whether preventive or environmental remediation, improving the quality of the environment (Hu et al., 2023; Khan et al., 2024; Elfaki and Ahmed, 2024). Empirical evidence is growing and includes a wide variety of methodological strategies. For example, Saqib et al. (2023) found a negative influence of technology on CO_2 emissions using Cross-Sectional Autoregressive Distributed Lag Model (CS-ARDL), Fully Modified Ordinary Least Square (FMOLS), and Dynamic Ordinary Least Squares (DOLS). In the case of Africa, Obobisa et al. (2022) and Wang et al. (2023), through the CS-ARDL models, augmented mean group (AMG), common correlated effects mean group (CCEMG). The authors reveal that technological innovation promotes environmental sustainability by mitigating the increase in CO2 emissions. Furthermore, Somoye et al. (2024), using the quantile over quantile (QQ) technique, reveal that technological innovation increases in Nigeria negatively impact CO2 emissions at all quantiles. On the other hand, in 30 highly emitting countries, Shahbaz et al. (2024), using the MMQR method, point out that technologies play a fundamental role in reducing emissions, particularly in the low and middle quantiles. For developed countries, such as those in the OECD, Marra et al. (2024), using a PVAR model, identify that technological change has a total impact on reducing CO2 emissions. These results are similar to those of Zhu et al. (2024) in the case of the BRICS through the CS-ARDL method. On the other hand, Da Silveira Cachola et al. (2023) highlight the importance of including carbon capture technologies in industrial companies because they play a fundamental role in achieving a zero-carbon economy in 2050. In China, a panel data analysis found an inverted U relationship between the innovation of green technology and CO_2 emissions. Only when the level of green technological innovation reaches a certain level can it positively affect environmental quality (Chen et al., 2023). Similarly, in the first phase, it was found that the new technology positively affected CO_2 emissions. In contrast, the effect was negative in a later stage when the technology improved (Kwilinski et al., 2024). Hoa et al. (2023) indicate that technological innovation positively affects environmental pollution in Vietnam. Although technologies do not have a statistically significant effect, Alataş (2022) found that the increase in environmentally related patent applications leads to increase per capita CO_2 emissions from the transportation sector. Some studies have shown that transportation, household appliances, vehicles, specific manufacturing industries, the most sustainable agricultural methods, exploitation of natural resources, and others can reduce emissions if they adopt new technologies (Chatti and Khan, 2024; Guo and Shahbaz, 2024; Raihan et al., 2024).

2.3. CO_2 emissions and foreign direct investment nexus

The evidence of the link between environmental quality and foreign direct investment (FD) is not definitive, as several recent studies have noted (Ozturk et al., 2023; Uddin et al., 2024). According to Xi et al. (2020); Boubacar et al. (2024); Yu et al. (2024), FDI has a direct effect on an increase in the concentration of CO_2 emissions, particularly in developing countries (Essandoh et al., 2020). Other research also finds a negative impact of foreign investment on CO_2 emissions. For example, evidence indicates that FDI is a mechanism to introduce more advanced and cleaner technologies in developing countries (Boateng et al., 2024; Hanif et al., 2019). In West Africa, Limazie and Woni (2024) point out that the interaction between FDI inflows and governance quality has a negative effect on carbon emissions. However, for this group of countries, Abid et al. (2024) confirm the pollution haven hypothesis, since FDI reduces environmental quality in the long term. In Middle East and North Africa (MENA) countries, Shahbaz et al. (2019) found that foreign direct investment inflows positively impact environmental quality in the medium term due to the enactment of new strategies to attract clean foreign capital. In this sense, several developing countries face a dilemma between favoring FDI inflows into polluting projects or protecting environmental quality. Liu et al. (2024) conducted a study in two panels of countries. The first group consists of 16 European countries, and the second consists of 30 Asian and MENA countries. In the first group, the authors suggest that FDI flows are environmentally friendly, contributing to reducing CO2 emissions. In contrast, in the second group the results support the hypothesis of pollution havens, where FDI increases carbon emissions. Through a territorial and consumption analysis, Adjei-Mantey and Adams (2023) found that FDI significantly positively affects CO_2 emissions from agriculture and manufacturing. On the other hand, Jijian et al. (2021) found a positive, although not significant, relationship between foreign direct investment and CO_2 in BRICS countries. Recent research, such as that of Lee and Zhao (2023), finds that the link between FDI and environmental quality is heterogeneous. The empirical evidence is still inconclusive, and the debate remains open.

2.4. CO_2 emissions and natural resources nexus

The extraction of natural resources causes various forms of environmental pollution. One of the hypotheses is that activities associated with exploiting natural resources contaminate the environment through deforestation (Amin et al., 2024). However, natural resource activities generate CO_2 emissions from drilling, oil transit, and burning liquefied petroleum gas. Through an analysis of panel data in the BRICS countries, Baloch et al. (2019) find that natural resources have a non-significant impact on CO_2 emissions in Brazil, China, and India, while in Russia, it favors pollution reduction due to the composition effect due to the level of development of the said country. According to Balsalobre-Lorente et al. (2018), natural resources reduce per capita CO_2 emissions in EU-5 countries due to institutional quality, pro-environmental regulation, and the population's environmental awareness. In G-20 countries, Jia et al. (2024) find evidence that rents from natural gas, oil, and forest resources generate more financial resources and contribute significantly to controlling environmental risks, especially alarming CO2 emissions. An analysis by Rao et al. (2023) reveals that the interaction of natural resources and ICT positively impacts CO_2 reduction. This fact occurs mainly when technology is used more in extractive activities than environmental mitigation. On the other hand, Khan and Hassan (2024), in a panel of 141 developing economies using the MMQR method, illustrate that high technology, GDP, and natural resource rents increase CO2 emissions. Although technology is essential in reducing emissions in the BRICS, Zhu et al. (2024) point out that natural resources increase environmental pollution. Cai et al. (2023a); Li et al. (2024) points out that the overexploitation of natural resources increases CO_2 emissions because it increases the production of goods and services. Similarly, Jiang et al. (2022) point out that natural resources drive CO_2 emissions in countries with low regulation and aimed at attracting capital to increase production. Agboola et al. (2021) find a significant positive link between natural resource rent and long-term and short-term CO_2 emissions in Saudi Arabia. It is well known that Saudi Arabia not only extracts natural resources but also adds value to oil and gas, which increases emissions of polluting gases. Overall, the evidence suggests that the findings are associated with the level of development of the countries or regions (Huang and Ren, 2024). It is logical to think that rich countries that exploit natural resources have strict environmental regulations concerning poor countries that exploit natural resources. The inclusion of countries with different levels of development would improve the understanding of the environmental quality-CO_2 emissions nexus.

2.5. CO_2 emissions and financial efficiency nexus

A growing literature examines the causal link between environmental quality and financial variables. For example, Singh et al. (2023) examine the role of financial inclusion (among other variables) on environmental behavior in emerging and advanced economies. The authors find a positive effect of financial inclusion on polluting gas emissions. Gao et al. (2024), in a study for G-7 economies, they show evidence of a long-term relationship between financial inclusion and environmental degradation, in addition to a positive effect of financial inclusion on CO2 emissions. Teskin et al. (2022) use the frequency domain causality test and found that using green bonds is a tool for energy efficiency and environmental mitigation. Likewise, other research has used financial development as a factor that affects environmental sustainability (Ahmad et al., 2024; Dong et al., 2024). One explanation for the positive relationship between financial development and CO_2 emissions is that the first variable links real and financial markets through the financing of consumption and investment. Therefore, greater economic dynamism implies more transactions through the financial system, causing more significant environmental pollution. However, financial development could improve environmental sustainability if the financial system is oriented to finance green investment projects or environmentally friendly consumption (Xuan et al., 2024). For example, Ahmad and Satrovic (2023) find that financial inclusion significantly deteriorates the environment, whose results are consistent with the findings of Zhang et al. (2023) and Boussaidi and Hakimi (2024). Furthermore, in the world's top ten emitting economies, Shang et al. (2024) show through the MMQR approach that financial inclusion is positively related to ecological pollution. On the other hand, in Asian economies, Rasheed et al. (2024) point out that financial inclusion, both traditional and digital, acts as a moderator of the adverse effects of inequality on CO2 emissions. In this sense, the empirical literature that uses financial efficiency is limited and more evidence is required to improve the environmental implications to promote sustainable development (Al-Karkhi, 2024).

2.6. CO_2 emissions and institutional quality nexus

Recent literature has identified institutional quality as one of the most effective mechanisms to mitigate environmental degradation, particularly in the medium and long term (Warsame et al., 2022; Ahmad et al., 2022; Cui et al., 2024; Dam et al., 2024). The underlying mechanism behind the mutually beneficial relationship between environmental quality and institutional quality is that the regulatory framework of economies will encourage compliance with actions that lead to achieving environmental sustainability (Abbas et al., 2024). The actions of the population, policymakers, and company managers will be regulated by the set of institutions that develop regulations following the long-term interests of the economies. In this sense, the search for economic and social sustainability implies protecting the environment for current and future generations (Geng and Fan, 2023; Qayyum et al., 2024; Zhang et al., 2024a). The empirical literature has identified some patterns that guide the analysis of the mechanisms that relate the two variables. For example, according to Acheampong et al. (2021), institutional quality in African countries exerts a weak effect on CO_2 emissions. A possible explanation for this finding is that African economies may be more interested in attracting investment than protecting the environment (Achuo et al., 2024). Likewise, Boateng et al. (2024), in a panel of 182 countries classified by income, point out that institutional quality is associated with higher levels of emissions in all income groups, suggesting that current regulations do not adequately improve environmental pollution. On the other hand, an analysis in 65 developing economies indicates that bureaucratic quality and corruption control (indicators of institutional quality) have a positive role in sustainable development in Latin America and the Caribbean (Hunjra et al., 2023). A study by Arvin et al. (2022) found that institutional solid quality in low-income and middle-income countries tends to reduce CO_2 emissions. In this same direction, Obobisa et al. (2022) affirm that institutional quality can effectively reduce environmental pollution. Similarly, using a panel of 78 countries from 1995 to 2014, green complexity can suppress CO_2 emissions in countries with a stable government, better investment profile, strict laws, and better bureaucratic quality (Wang and Yang, 2022). In practice, pro-environmental regulation cannot prevent the carrying out of anthropogenic activities, but it can regulate so that production, trade, and consumption activities are environmentally sustainable (Ashraf and Javed, 2023; Li et al., 2023; He and Zheng, 2023). Institutional quality could contribute significantly in this direction; however, empirical evidence supporting the hypothesis still needs to be discovered.

2.6.1. Literature gap

Empirical research has yet to identify the combined impact of technological innovation, financial efficiency, institutional quality, and natural resources on environmental quality as a proxy for environmental sustainability. Furthermore, the use of techniques that capture dependence in cross sections, heterogeneity in slope, and impacts across the distribution is limited.

3. Data and methodological strategy

3.1. The data and hypotheses

This research employs annual statistical data from international organizations. Environmental quality measured by carbon dioxide emissions, real per capita output, technological innovation, foreign direct investment, and natural resource income are taken from the World Bank's World Development Indicators database (2024). Financial efficiency is taken from the Financial Development Index Database constructed by the International Monetary Fund (2024). Finally, institutional quality is taken from the International Country Risk Guide (2024). La variable dependiente son las emisiones de CO_2 como proxy de la calidad ambiental, y la variable independiente es el producto real per cápita y el producto al cuadrado. En consecuencia, esta investigación se basa en la hipótesis de la curva de Kuznets ambiental formalizada por Grossman and Krueger (1991), (1995) y Panayotou (1993). Sin embargo, el interés de la investigación es examinar el impacto de la tecnología y la eficiencia financiera en la calidad ambiental. Para asegurar queue los estimadores sean estables, agregamos cuatro covariables adicionales: inversión extranjera directa, la renta de recursos naturales, la eficiencia financiera, y la calidad institucional. La investigación tiene una cobertura geográfica para 88 economías a nivel mundial, las cuales fueron incluidas debido a la disponibilidad de información estadística para la serie comprendida entre 1996 y el 2021. La muestra total de países fue clasificada según el Método Atlas del Banco Mundial (2023) en cuatro grupos: Países de Ingreso Alto (PIA), Países de Ingreso Medio Alto (PIB), Países de Ingreso Medio Bajo (PIB) y Países de Ingreso Bajo (PIB). La Table 1 contiene la definición de la serie, la unidad de medida y la fuente de los datos. La Fig. 1 ilustra la cobertura geográfica de la investigación y la clasificación de los países. Las hipótesis planteadas en esta investigación son las siguientes:

H1: Real per capita output, foreign direct investment, and natural resources rents worsen environmental quality heterogeneously. H2: Technology, financial efficiency, and institutional quality heterogeneously improve environmental quality. H3. There is a cointegration relationship between real per capita products, foreign direct investment, and income from natural resources, technology, financial efficiency, institutional quality, and environmental quality.

The descriptive statistics of the series report relevant aspects of the series that improve the preliminary understanding of the characteristics of the information analyzed. Table 2 reports the descriptive statistics of the seven series that comprise the econometric models. The data form a balanced panel that includes 2288 observations. The probability of the JB statistic indicates that the data follow an approximately normal distribution, except for FDI and FE. Fig. 2 reports the partial correlation matrix between the series and illustrates the dispersion between the pairs of variables. The preliminary information in this figure reports the

Table 1
Description of variables.

Variable	*Initials*	*Definition*	*Measurement*	*Source*	*Link*
Environmental quality	CO_2	CO_2 is a measurement of the carbon dioxide emissions being those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.	Metric tons per capita.	World Bank (2023)	https://databank.worldbank.org/source/world-development-indicators
Real per capita output	EP	EP is measurement by real per capita output is gross domestic output divide by midyear population.	Constants prices.	World Bank (2024).	
Technological innovation	TEC	R&D encompasses basic research, applied research and experimental development. The series is measured in dollar prices at constant 2010 prices.	Ratio R&D expenditures and output	World Bank (2024).	
Foreign direct investment	FDI	Foreign direct investment are the net inflows of investment to acquire a lasting management interest (10 percent or more of voting stock) in an enterprise operating in an economy other than that of the investor.	Percentage of the output	World Bank (2024).	
Natural resources rents	NR	Total natural resources rents are the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents.	Percentage of the output	World Bank (2024).	
Financial efficiency	FE	Financial institutions efficiency index which compiles data on banking sector net interest margin, lending-deposits spread, non-interest income to total income, overhead costs to total assets, return on assets, and return on equity.	Index.	International Monetary Fund (2024).	https://acortar.link/nBfqUh
Institutional quality	IQ	IQ is an index that contain the next factors; Government Stability, Socioeconomic Conditions, Investment Profile, Internal Conflict, External Conflict, Corruption, Military in Politics, Religious Tensions, Law and Order, Ethnic Tensions, Democratic Accountability, Bureaucracy Quality.	Index.	International Country Risk Guide (2024).	https://www.prsgroup.com/explore-our-products/icrg/

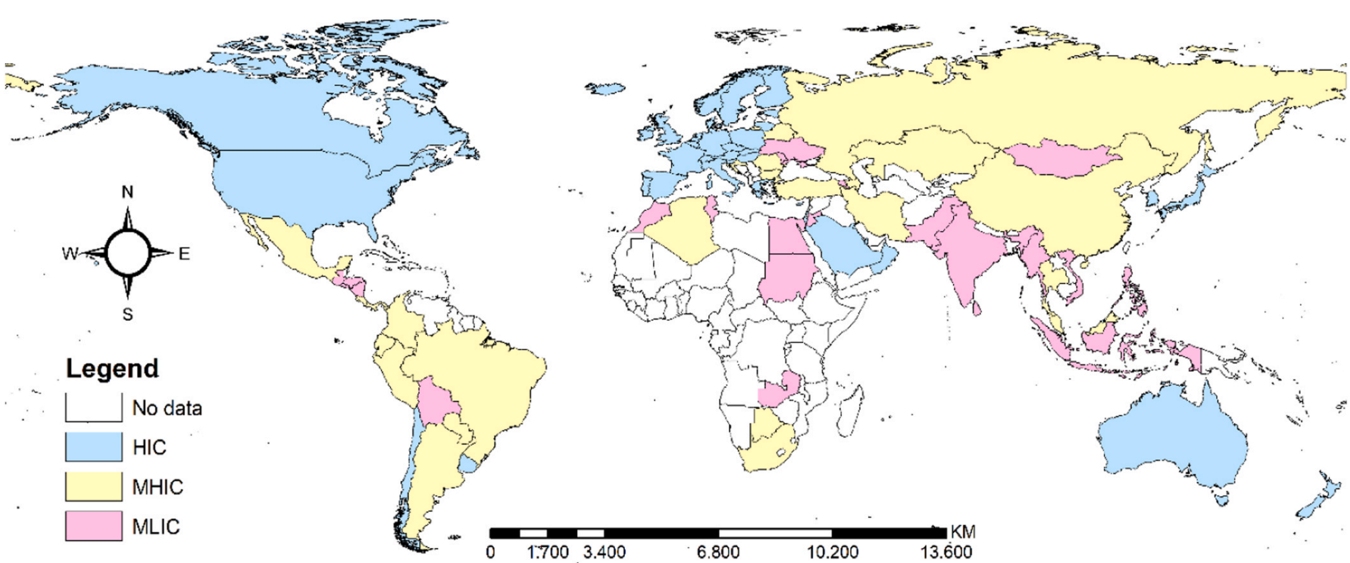

Fig. 1. Sample of countries analyzed according to level of development.

degree of association of CO_2 emissions with the covariates, the dispersion between the series, and their distribution.

Fig. 3 illustrates the evolution of CO_2 emissions for the period analyzed according to the country groups. A relevant aspect of Fig. 3 is that the share of pollution from developed countries (HIC) has decreased slightly due to the relocation of the manufacturing industry to countries with lower production costs (Hamaguchi, 2023; Cuesta et al., 2024). In parallel, CO_2 emissions from poor countries have grown as a counterpart

Table 2
Descriptive statistics.

	CO_2	EP	EP^2	TEC	FDI	NR	FE	IQ
Mean	1.42	9.20	86.30	20.51	19.97	21.15	−0.56	1.76
Minimun	−1.88	5.58	31.13	13.29	−26.65	8.41	−2.63	0.82
Q1 (0.25)	0.69	8.12	65.97	18.61	20.54	19.48	−0.65	1.65
Median	1.67	9.17	84.15	20.39	21.94	21.27	−0.52	1.78
Q3 (0.75)	2.13	10.46	109.33	22.68	23.39	23.35	−0.39	1.90
Maximun	3.86	11.63	135.19	27.06	30.04	26.96	−0.17	2.08
Std.Dev.	1.04	1.30	23.72	2.65	9.78	2.78	0.24	0.17
Skewness	−0.65	−0.14	0.05	0.04	−3.89	−0.61	−2.09	−0.74
Kurtosis	3.19	1.95	1.84	2.41	16.96	3.72	10.86	4.04
Jarque-Bera	1.31	0.85	0.02	1.23	0.29	2.26	1.37	1.47
Probability	(0.52)	(0.65)	(0.99)	(0.54)	(0.87)	(0.32)	(0.50)	(0.48)
Observation	2288	2288	2288	2288	2288	2288	2288	2288

Note: t statistics in parentheses* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

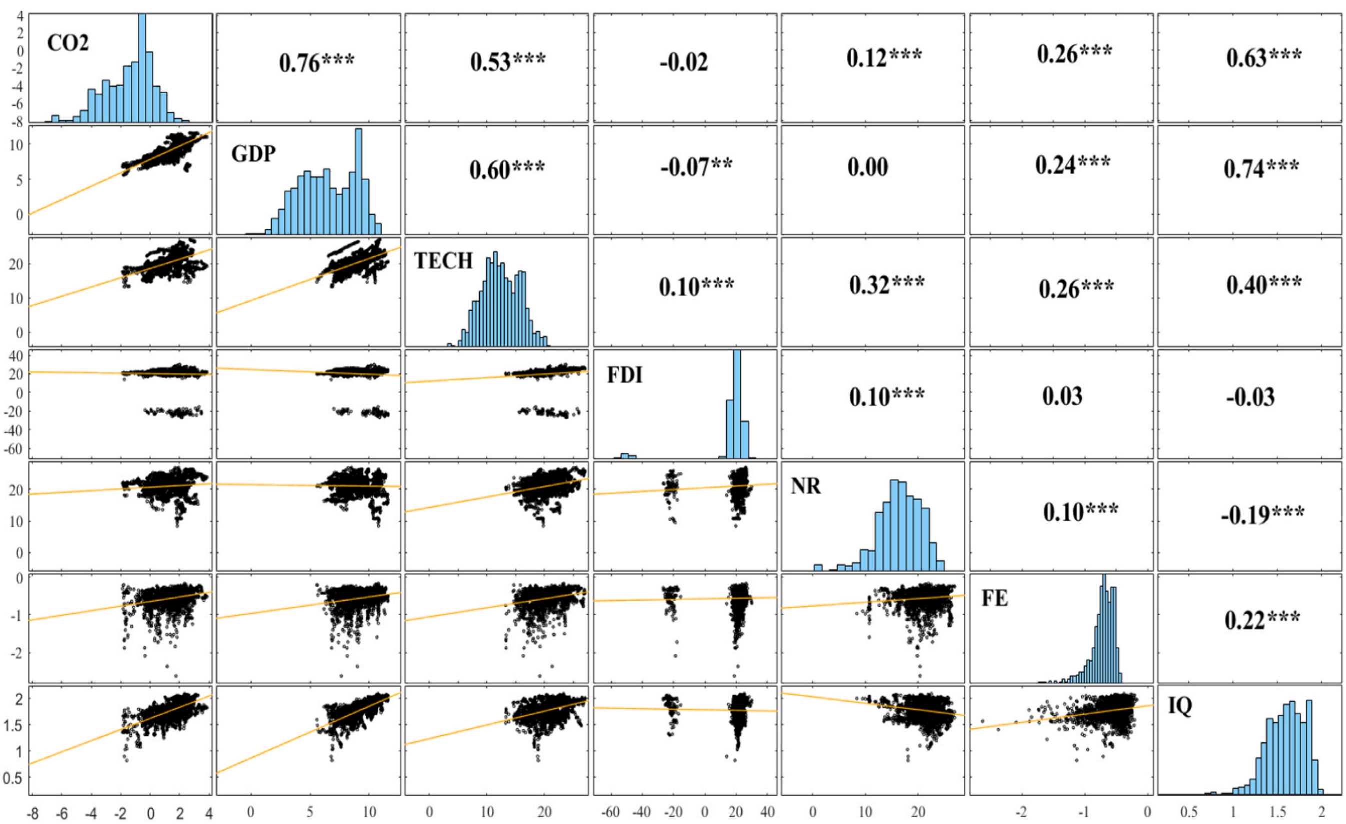

Fig. 2. Correlation matrix analysis.

to the previous premise. This idea has been widely analyzed in the context of the pollution refuge hypothesis (Naqvi et al., 2023). CO_2 emissions from MHICs have remained relatively stable during the period analyzed.

The estimates may present multicollinearity problems, causing bias in the estimators and imprecision in political inferences. Consequently, the covariates cannot present collinearity problems to guarantee that the estimators are unbiased and have minimal variance. Table 3 reports the results of the collinearity test between the series considered in the econometric model. The variance inflation factor (VIF) and tolerance test are used. Therefore, when the VIF is less than five, we conclude that there are no collinearity problems between the regressors. At the individual level, the VIF values do not exceed five, and the average is 1.81, indicating no have collinearity problems in the series.

3.2. *Methodological strategy*

3.2.1. *The basic model*

The methodological strategy is designed to achieve the research objective under a theoretical context of the Environmental Kuznets Curve (Grossman and Krueger, 1991, 1995; Panayotou, 1993). In order to verify the research hypotheses, we organize the methodological strategy in several stages. First, we propose a basic model where CO_2 emissions are a function of GDP and GDP2 as proposed by the EKC. Several investigations have examined the EKC for different regions and countries, finding evidence for and against said theory (Esmaeili et al., 2023; Aminu et al., 2023). The heterogeneity of the evidence is associated with the development levels of the countries and the diversity of methodologies used.

$$CO_{2it} = f\left(GDP_{it},\ GDP_{it}^2\right) \tag{1}$$

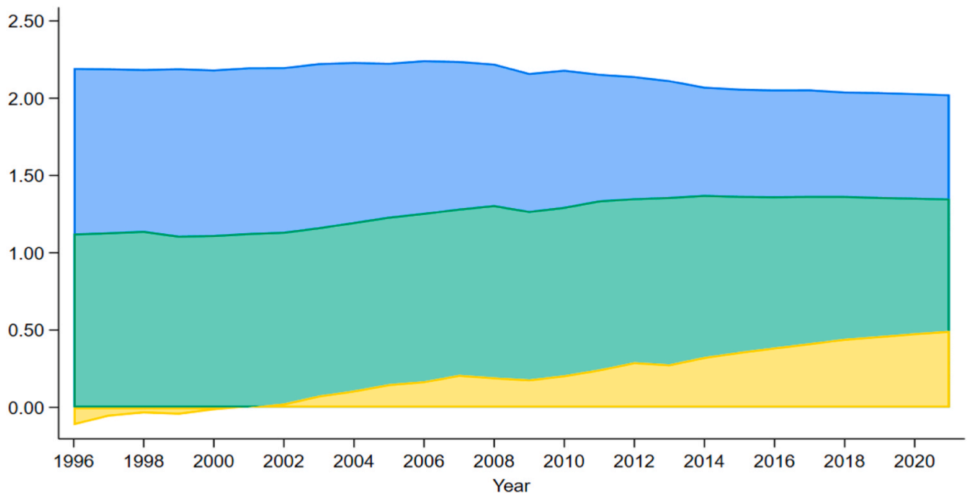

Fig. 3. Evolution of CO_2 emissions per capita by group of countries.

Table 3
Multicollinearity test.

Variable	*VIF*	*SQRT VIF*	*Tolerance*	*R-Squared*
Economic growth	2.93	1.71	0.34	0.66
Technology	2.02	1.42	0.49	0.51
Foreign direct investment	1.04	1.02	0.96	0.04
Natural resources	1.33	1.15	0.75	0.25
Financial efficiency	1.10	1.05	0.91	0.09
Institutional quality	2.41	1.55	0.42	0.58
Mean VIF	*1.81*			

Equation 1 collects the theoretical relationship based on the EKC. However, this research aims to examine the effect of technology and financial efficiency on CO_2 emissions. In order to achieve the research objective of Equation 2, we add technology, financial efficiency, and the rest of the control variables: FDI, NR, and IQ. The numerical variables are expressed in natural logarithms, while those expressed in indices or ratios are estimated directly. The functional form of the basic empirical model is expressed in Equation 2.

$$LnCO_{2it} = \varphi_0 + \varphi_1 LnGDP_{it} + \varphi_2 LnGDP_{it}^2 + \varphi_3 TECH_{it} + \varphi_4 FDI_{it} + \varphi_4 NR_{it} + \varphi_4 FE_{it} + \varphi_4 IQ_{it} + \varepsilon_{it} \tag{2}$$

The parameters φ_i are the coefficients that capture the impact of the covariates on environmental quality, while ε_{it} is the stochastic error term.

3.2.2. Cross-section dependence tests

The high interaction between countries requires applying a test that indicates whether the values of a country's variable are associated with the values of the said variable in the rest of the nations. The justification for incorporating CD tests lies in the interaction between countries in various forms, such as bilateral or multilateral trade relations, socio-cultural agreements, political agreements, and economic association agreements that are strengthened due to the geographical proximity between countries (Sikder et al., 2022). Ignoring CD implies that the estimators will be biased due to omitting relevant variables in the econometric model. In this research, we use the CD test proposed by Pesaran (2004) formalized in Equation (3):

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij} \right) \longrightarrow N(0,1) \tag{3}$$

In Equation 3, T indicates the number of periods, N the number of observations, and $\widehat{\rho}_{ij}$ captures the cross-section interaction among the countries. We assume that CD follows a standard normal distribution with mean 0 and constant variance equal to 1.

3.2.3. Slope homogeneity test (SH)

In parallel, another concern can cause biased and inefficient estimators in panel data: heterogeneity in the slope. Consequently, we applied the slope homogeneity test proposed by Pesaran and Yamagata (2008b). The null hypothesis of this test states that the slope coefficients are uniform in all units of the cross-section. Equations 4 and 5 formalize the SH test as follows:

$$\widetilde{\Delta}_{SH} = (N)^{\frac{1}{2}} (2K)^{-\frac{1}{2}} \left(\frac{1}{N} \widetilde{S} - k \right) \tag{4}$$

$$\widetilde{\Delta}_{SH} = (N)^{\frac{1}{2}} \left(\frac{2k(T-k-1)}{T+1} \right)^{-\frac{1}{2}} \left(\frac{1}{N} \widetilde{S} - k \right) \tag{5}$$

In Equations 4 and 5, the term $\widetilde{\Delta}_{SH}$ represents the delta statistic, and $\widetilde{\Delta}_{ASH}$ represents the adjusted delta statistic. In the environmental economics literature, empirical works frequently use the Pesaran and Yamagata (2008b) test to verify slope homogeneity and often conclude that slopes are heterogeneous. Figure 4 summarizes this research's methodological procedure to verify the three proposed hypotheses.

3.2.4. Method of moments quantile regression (MMQR)

The limitations of traditional regressions can be corrected using the quantile regression approach. This method provides a complete view of how the covariates affect the dependent variable in the different quantiles and not only in the average. In this research, we use the novel quantile estimators developed by Machado and Silva (2019). Quantile methodologies maintain non-additive fixed effects, including an inseparable disturbance term associated with the respective configurations in a panel data framework. Equation 6 formalizes the general quantile model as follows:

$$Q_\tau(LnCO_{2it}) = \beta_0 + LnGDP_{it}\phi_\tau(\mu_{it}) + LnGDP_{it}^2\phi_\tau(\mu_{it}) + TECH_{it}\phi_\tau(\mu_{it}) + \varphi_4 FDI_{it}(\mu_{it}) + \varphi_4 NR_{it}(\mu_{it}) + \varphi_4 FE_{it}(\mu_{it}) + \varphi_4 IQ_{it}(\mu_{it}) + \varepsilon_{it} \tag{6}$$

In the Equation 6, the term Q_τ is the conditional quantile of Q_τ such that $\tau = (0.1,\ 0.2, \ldots,\ 0.9)$, and $\mu_{it} = f(\theta_i, \varepsilon_{it})$ capture the heterogeneous effects of each country.

The identification of the heterogeneous impact that, formalized with quantile regressions, requires to be reinforced through a long-term analysis. The main argument for estimating the long-term relationship

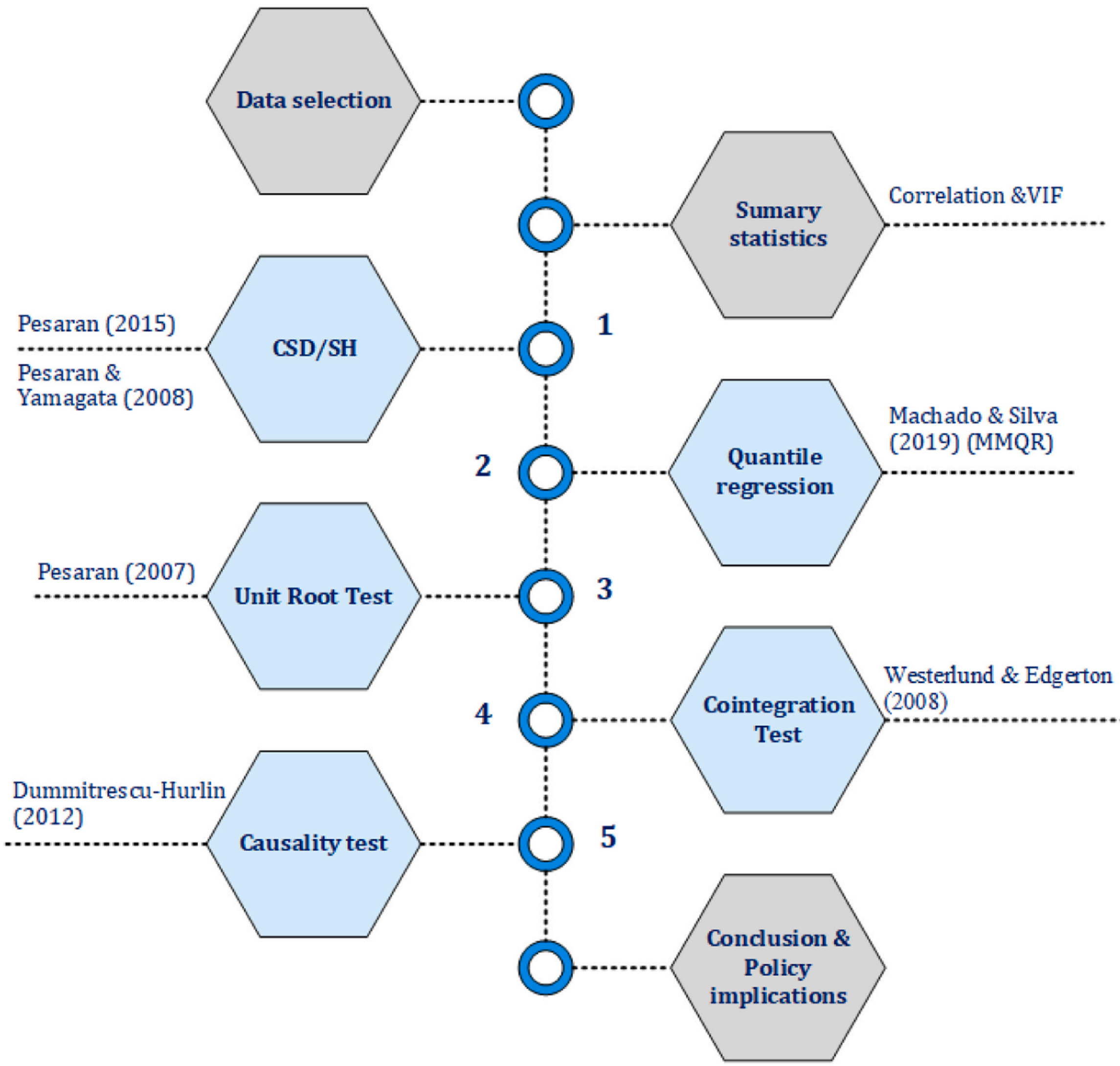

Fig. 4. Econometric process employed during the study.

between the series is the characteristics of the data. Specifically, when the series exhibits CSD and SH properties, including this data characteristic in the econometric estimates is necessary. Therefore, second-generation unit root tests are preferable to first-generation panel unit root tests. In this analysis, the CIPS second-generation unit root test, proposed by Pesaran (2007), is used. Equation 7 formalizes the CIPS test:

$$CIPS = \frac{\sum_{i=1}^{N} t_i(N,T)}{N} \tag{7}$$

3.2.5. Unit root test

In Equation 7, N is the number of transversal units present in the panel, which allows computing the averages of the individual t statistics of the Dickey & Fuller *ADF* statistic. The term $\sum_{t=1}^{N} t_1(N,T)$ is the sum of the individual statistics t of the *ADF* that ranges between 1 and N. Therefore, the CIPS test reports robust coefficients in the presence of CSD and HS.

3.2.6. Second-generation cointegration test

In the last stage of the econometric strategy, we formalize the methodological strategy aimed at verifying H3. Based on the CSD and HS of the data, we employ a second-generation cointegration test proposed by Westerlund and Edgerton (2008). One of the advantages of this test is that it considers possible structural breaks and the presence of CSD and HS. The basic structure of the cointegration model is defined as formalized by Equations 8 and 9:

$$y_{it} = \omega_1 + \varphi_1 t + \gamma_i D_{it} + x_{it}^{\prime}\alpha_i + (D_{it}x_{it})\rho_i^{\prime} + Z_{it} \tag{8}$$

$$x_{it} = x_{it-1} + \xi_{it} \tag{9}$$

3.2.7. Panel causality test

Within panel data analysis, once cointegration is determined, evaluating the direction of causality between the series is imperative. A particular consideration within panel data analysis is the need to specify heterogeneity across cross-sections (Mehmood et al., 2023). Given this specification, Dumitrescu and Hurlin (2012) panel causality test was chosen due to its ability to address cross-sectional dependence and the problem of heterogeneity. The test is based on Wald statistics, which assume no causality between two study variables. This test follows the regression presented in Equation 10:

$$y_{it} = \alpha_i + \sum_{j-1}^{J} \lambda_i^j y_{i(t-j)} + \sum_{j=1}^{J} \beta_i^j x_{i(t-j)} + \zeta_{it} \tag{10}$$

In Equation (10), the autoregressive parameters are denoted by λ_i^j, while the regression coefficient estimates are denoted by β_i^j. Furthermore, the parameters are expected to vary across the different cross sections. Finally, the null hypothesis of the HS test states that there is no causal link in any section, while the alternative hypothesis suggests that at least one causal relationship is present within the subset of the panel.

4. Results and discussion

4.1. Methods of Moments Quantile Regression (MMQR) results

Leng et al. (2024) and Guan et al. (2023) point out that the MMQR technique is the most recent one used in environmental litter and allows capturing heterogeneous effects throughout the distribution. The models of Machado and Silva (2019) use the conditional mean and bootstrapped standard errors corrected for potential bias derived from the CSD. Likewise, the classification of countries according to the level of development allows the findings and policy inferences to be disaggregated in a more specific way. Table 4 reports the results of the MMRQ using the method of moments formalized by Machado and Silva (2019). We report the decile-level estimators for the global sample, the HIC, MHIC, and MLIC. In the total sample, the findings indicate that an increase in real output per capita increases CO_2 emissions up to a certain threshold and then reduces them. This finding confirms the EKC for a sample of 88 countries worldwide, with temporal coverage from 1996 to 2021. In the total sample, the technology increases CO_2 emissions in all deciles. FDI reduces emissions in the first two deciles, while in the rest of the deciles, the relationship between FDI and CO_2 emissions are positive and statistically significant. Regarding NR, there is a heterogeneous relationship from quintile one to quintile 5; in the rest of the quantiles, the relationship is non-significant. FE has a non-significant effect on CO_2 emissions throughout the distribution. A disappointing result is that IQ increases CO_2 emissions. This result is consistent with other research findings and suggests that institutional quality protects production more than the environment. However, it is necessary to deepen the analysis according to the development levels of the countries.

In rich countries (HIC), production increases CO_2 emissions, as the EKC theoretical framework proposes. An unexpected result is that technology has a direct relationship with CO_2 emissions. This result could explain the multiple efforts of developed countries to maintain their level of development and quality of life by promoting industry return due to the high consumption of goods and services from fossil sources such as oil, coal, and gas. In this sense, our results differ from the findings of Zhang et al. (2024b), who point out that law and order and technological innovation reduce CO_2 emissions. The premise that technology can help mitigate environmental degradation is based on the fact that technology allows production to be more environmentally friendly. For example, new electric vehicles and equipment must have low levels of carbon emissions before they go on the market. In this same direction, in the MHICs and the MLICs, the technology increases emissions throughout the distribution, except for the first quantiles of the MLICs. Our results are partially similar to the works of Shen and Zhang (2024a) and Shokrollahi et al. (2024) regarding the effect of technology, although the methodological strategy differs significantly.

In HICs, FDI increases CO_2 emissions in all quantiles, and this effect is statistically significant. This result implies that policies to bring back the industry could significantly increase environmental pollution. After all, the rich attract large amounts of investment and resources, increasing consumption and demand for fossil fuels. In parallel, in the MHICs, the relationship between FDI and CO_2 emissions are not significant, indicating that the foreign capital that arrives in these countries does not generate increases in CO_2 emissions. A possible explanation for this result is that upper-middle-income countries attract capital in low-carbon activities. However, FDI may deteriorate the environment when environmental quality is measured with other indicators such as ecological footprint or forest cover. The relationship between FDI and CO_2 emissions is mainly negative in lower-middle-income countries. This finding reinforces the idea that investments in developing countries attract capital oriented to exploiting natural resources that are not emissions-intensive but can affect other dimensions of environmental quality.

In the global panel, natural resources decrease pollution throughout the distribution, although only in quantiles 2–5 is the effect statistically significant. In HICs, NR reduces CO_2 emissions in the low quantiles, but in the rest of the quantiles, the effect is not significant. This result could be explained by the strict environmental regulation in rich countries, where both the granting of exploitation licenses and subsequent regulation tend to be strict. In the MHIC, the NR significantly increases environmental pollution, while in the MLIC, the relationship between the two variables is negative and not significant in most of the quantiles. One explanation for these results is that, in developing countries, activities associated with natural resources are exploited mainly on a small and medium scale. In contrast, when the economy develops, there are more economic, financial, and technological resources to exploit natural resources on a large scale. The difference between rich and poor countries is that this aspect is environmental regulation. Baloch et al. (2019) suggest that natural resources cause an increase in polluting gas emissions. In the total sample, FE increases CO_2 emissions, except for the last quantiles. In HICs, FE increases emissions, while in MHICs, the effect of FE on CO_2 emissions are negative. The orientation of the financial system could be decisive in the application of stricter regulation both to promote investment financing and environmentally friendly consumption. In the MLICs, the relationship between FE and CO_2 emissions predominate the negative sign. Bai (2024) finds that financial development is central to CO_2 emissions.

Finally, the results of the MMQR model indicate that the institutional quality of HICs and MLICs is positive. There is the idea that the high IQ of rich countries attracts capital that increases emissions. In contrast, in lower-middle-income countries, institutional quality protects investments, increasing production and CO_2 emissions.

4.2. Cross-section dependence results

Table 5 reports the results of Pesaran's (2004) CSD test to verify the dependence between the cross sections. The null hypothesis of this test is that there is no cross-sectional dependence. The idea behind the CSD test is to verify if the interaction between the countries conditions the estimators. Consequently, it is required to test the CD in the full sample, in the HIC, MHIC, and MLIC. We found sufficient evidence to reject the null hypothesis of cross-sectional independence in all variables in the model at a 0.1 % significance level. Therefore, it is concluded that all series have transversal dependence. Concerning CO_2 emissions, countries have several agreements to mitigate pollution, such as the Paris Agreement (COP-21), which brings together global efforts to reduce environmental degradation (Adun et al., 2024). Concerning the product, it is logical that multilateral and bilateral trade and cooperation agreements will cause dependency due to said interaction. Likewise, in a highly interconnected economy regarding FDI, technology trade, and extraction of natural resources, among others, they cause countries to have mutual dependence, which is strengthened in the long term. Finally, the treaties to protect human rights, combat organized crime, and fight corruption, security agreements, and cooperation imply that countries depend in terms of their institutions. In practice, the CSD test has also been considered a test of external influence on a variable's values on a cross-sectional unit.

4.3. Slope homogeneity results

Table 6 reports the Pesaran and Yamagata (2008b) test results. The results indicate that the null hypothesis of homogeneity in the slope is rejected, either with the delta statistic or the delta-adjusted statistic. The findings of this test indirectly point out that the relationship cannot be expected to be linear or homogeneous throughout the distribution. In practice, the results indicate that the quantile regression approach to capture changes in slope is appropriate. In parallel, applying this

Table 4
Method of Moments Quantile Regression (MMQR) findings.

	Location	*Scale*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*
Total sample											
GDP	2.45***	−0.15	2.69***	2.62***	2.57***	2.51***	2.45***	2.39***	2.33***	2.28***	2.22***
	(11.61)	(−1.27)	(9.53)	(10.42)	(11.11)	(11.58)	(11.58)	(11.05)	(10.10)	(9.08)	(7.92)
GDP^2	−0.13***	0.01	−0.14***	−0.14***	−0.14***	−0.13***	−0.13***	−0.13***	−0.12***	−0.12***	−0.12***
	(−11.01)	(1.16)	(−9.01)	(−9.85)	(−10.51)	(−10.97)	(−10.98)	(−10.49)	(−9.59)	(−8.63)	(−7.53)
TECH	0.05***	0.01*	0.03**	0.04***	0.09***	0.04***	0.05***	0.05***	0.07***	0.06***	0.06***
	(5.58)	(2.27)	(2.69)	(3.46)	(4.19)	(4.95)	(5.60)	(5.94)	(6.03)	(5.94)	(5.72)
FDI	0.001***	−0.0002	0.002***	0.002***	0.002***	0.002***	0.001***	0.001***	0.001**	0.001**	0.001*
	(3.72)	(−0.97)	(3.42)	(3.64)	(3.79)	(3.83)	(3.71)	(3.42)	(3.00)	(2.60)	(2.16)
NR	0.01*	−0.02***	0.04***	0.03***	0.02***	0.02**	0.01	0.01	−0.001	−0.01	−0.01
	(1.97)	(−4.72)	(4.58)	(4.20)	(3.68)	(2.92)	(1.90)	(0.88)	(−0.14)	(−0.92)	(−1.64)
FE	0.02	−0.002	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	(0.85)	(−0.15)	(0.74)	(0.80)	(0.84)	(0.86)	(0.85)	(0.80)	(0.72)	(0.64)	(0.55)
IQ	0.37***	0.02	0.35***	0.36***	0.36***	0.37***	0.38***	0.38***	0.39***	0.39***	0.40***
	(5.63)	(0.44)	(3.93)	(4.49)	(4.97)	(5.40)	(5.64)	(5.60)	(5.33)	(4.98)	(4.54)
Constant	−11.88***	0.93	−13.30***	−12.92***	−12.59***	−12.24***	−11.86***	−11.51***	−11.15***	−10.83***	−10.46***
	(−12.35)	(1.68)	(−10.36)	(−11.26)	(−11.95)	(−12.39)	(−12.31)	(−11.68)	(−10.60)	(−9.48)	(−8.20)
Observations	2239	2239	2239	2239	2239	2239	2239	2239	2239	2239	2239
HIC											
GDP	1.41***	−0.31**	1.91***	1.77***	1.65***	1.51***	1.39***	1.26***	1.18***	1.08***	0.95***
	(6.75)	(−2.66)	(6.43)	(6.77)	(6.95)	(6.94)	(6.64)	(6.00)	(5.42)	(4.68)	(3.71)
GDP^2	−0.08***	0.02**	−0.11***	−0.10***	−0.10***	−0.09***	−0.08***	−0.08***	−0.07***	−0.07***	−0.06***
	(−7.80)	(2.81)	(−7.26)	(−7.69)	(−7.94)	(−7.98)	(−7.68)	(−7.01)	(−6.37)	(−5.55)	(−4.46)
TECH	0.04***	0.01	0.03*	0.04**	0.04***	0.04***	0.04***	0.05***	0.05***	0.05***	0.05***
	(4.14)	(0.93)	(2.33)	(2.84)	(3.32)	(3.84)	(4.19)	(4.36)	(4.36)	(4.25)	(4.01)
FDI	0.002***	0.0001	0.002***	0.002***	0.002***	0.002***	0.002***	0.001***	0.002***	0.002***	0.002***
	(6.18)	(0.54)	(4.01)	(4.67)	(5.28)	(5.88)	(6.23)	(6.29)	(6.17)	(5.89)	(5.42)
NR	0.01	−0.01*	0.03*	0.02*	0.02*	0.01	0.01	0.01	0.004	0.002	−0.002
	(1.50)	(−2.18)	(2.44)	(2.32)	(2.14)	(1.81)	(1.41)	(0.92)	(0.56)	(0.18)	(−0.25)
FE	0.07*	−0.02	0.11*	0.10*	0.09*	0.08*	0.07*	0.06	0.06	0.05	0.04
	(2.11)	(−1.05)	(2.14)	(2.22)	(2.25)	(2.21)	(2.07)	(1.82)	(1.60)	(1.34)	(1.01)
IQ	1.16***	0.05	1.07***	1.10***	1.12***	1.14***	1.16***	1.19***	1.20***	1.22***	1.24***
	(11.33)	(0.93)	(7.38)	(8.59)	(9.70)	(10.79)	(11.41)	(11.52)	(11.28)	(10.77)	(9.89)
Constant	−6.80***	1.46*	−9.13***	−8.46***	−7.89***	−7.25***	−6.69***	−6.11***	−5.71***	−5.25***	−4.64***
	(−6.37)	(2.43)	(−6.02)	(−6.35)	(−6.54)	(−6.54)	(−6.27)	(−5.69)	(−5.15)	(−4.46)	(−3.55)
Observations	1048	1048	1048	1048	1048	1048	1048	1048	1048	1048	1048
MHIC											
GDP	−1.60*	−1.14*	−0.01	−0.34	−0.76	−1.19	−1.65*	−2.09*	−2.45**	−2.86**	−3.48**
	(−2.05)	(−2.49)	(−0.01)	(−0.38)	(−0.92)	(−1.50)	(−2.08)	(−2.52)	(−2.77)	(−2.93)	(−3.06)
GDP^2	0.10*	0.06*	0.01	0.03	0.05	0.08	0.10*	0.13**	0.15**	0.17**	0.21**
	(2.26)	(2.51)	(0.18)	(0.56)	(1.11)	(1.71)	(2.29)	(2.72)	(2.96)	(3.11)	(3.21)
TECH	0.15***	0.01	0.13***	0.14***	0.14***	0.15***	0.15***	0.16***	0.16***	0.16***	0.17***
	(10.77)	(1.63)	(7.73)	(8.58)	(9.59)	(10.38)	(10.74)	(10.56)	(10.14)	(9.49)	(8.46)
FDI	0.004	−0.001	0.01*	0.01*	0.005	0.004	0.004	0.003	0.003	0.002	0.002
	(1.63)	(−0.94)	(1.96)	(1.98)	(1.95)	(1.83)	(1.60)	(1.32)	(1.08)	(0.83)	(0.50)
NR	0.04**	−0.01	0.06***	0.06***	0.05***	0.05**	0.04**	0.04*	0.03	0.03	0.02
	(2.87)	(−1.56)	(3.40)	(3.44)	(3.39)	(3.19)	(2.82)	(2.35)	(1.94)	(1.50)	(0.94)
FE	−0.10**	−0.01	−0.09*	−0.09*	−0.10**	−0.10**	−0.11**	−0.11**	−0.11**	−0.12**	−0.12*
	(−3.11)	(−0.60)	(−2.15)	(−2.40)	(−2.72)	(−2.98)	(−3.12)	(−3.09)	(−2.98)	(−2.81)	(−2.53)
IQ	0.06	−0.06	0.14	0.12	0.11	0.08	0.06	0.03	0.02	−0.001	−0.03
	(0.81)	(−1.28)	(1.52)	(1.45)	(1.30)	(1.08)	(0.77)	(0.46)	(0.22)	(−0.01)	(−0.29)
Constant	3.37	5.21**	−3.93	−2.45	−0.51	1.47	3.58	5.60	7.27	9.12*	11.99*
	(0.97)	(2.58)	(−0.93)	(−0.63)	(−0.14)	(0.42)	(1.02)	(1.52)	(1.85)	(2.11)	(2.38)
Observations	621	621	621	621	621	621	621	621	621	621	621
MLIC											
GDP	1.21	0.33	0.69	0.83	0.99	1.11	1.21	1.33	1.47*	1.60*	1.72*
	(1.61)	(0.61)	(0.50)	(0.71)	(1.03)	(1.32)	(1.61)	(1.94)	(2.15)	(2.15)	(2.03)
GDP^2	−0.04	−0.02	−0.0002	−0.01	−0.02	−0.03	−0.04	−0.05	−0.06	−0.07	−0.07
	(−0.77)	(−0.66)	(−0.00)	(−0.14)	(−0.35)	(−0.55)	(−0.77)	(−1.03)	(−1.26)	(−1.35)	(−1.34)
TECH	0.03	0.01	0.01	0.02	0.02	0.03	0.03	0.04*	0.04*	0.05*	0.05*
	(1.75)	(0.82)	(0.44)	(0.68)	(1.05)	(1.40)	(1.75)	(2.15)	(2.44)	(2.47)	(2.37)
FDI	−0.004*	−0.001	−0.003	−0.003	−0.004	−0.004	−0.004*	−0.005**	−0.01**	−0.01**	−0.01**
	(−2.33)	(−0.78)	(−0.78)	(−1.07)	(−1.52)	(−1.93)	(−2.32)	(−2.77)	(−3.05)	(−3.02)	(−2.84)
NR	−0.003	−0.02*	0.03	0.02	0.01	0.003	−0.003	−0.01	−0.02	−0.03*	−0.03*
	(−0.23)	(−2.00)	(1.15)	(0.94)	(0.58)	(0.20)	(−0.22)	(−0.82)	(−1.49)	(−1.97)	(−2.20)
FE	0.23**	0.05	0.12	0.16	0.19*	0.21*	0.22**	0.24***	0.27***	0.29***	0.31***
	(3.02)	(1.00)	(1.02)	(1.40)	(1.97)	(2.50)	(3.01)	(3.58)	(3.94)	(3.90)	(3.67)
IQ	0.59***	−0.06	0.68*	0.65**	0.62**	0.60***	0.58***	0.56***	0.54***	0.51***	0.49**
	(3.73)	(−0.52)	(2.37)	(2.67)	(3.09)	(3.44)	(3.72)	(3.92)	(3.77)	(3.29)	(2.78)
Constant	−8.07**	−0.69	−6.96	−7.26	−7.60*	−7.85*	−8.07**	−8.33**	−8.62***	−8.91**	−9.16**
	(−2.84)	(−0.34)	(−1.34)	(−1.64)	(−2.08)	(−2.47)	(−2.84)	(−3.20)	(−3.34)	(−3.15)	(−2.85)
Observations	570	570	570	570	570	570	570	570	570	570	570

Note: indicate the significance level at 0.1 %

Table 5
Prueba de dependencia en las secciones transversales.

Variable	*Total sample*	*HIC*	*MHIC*	*MLIC*
CO_2	15.56***	45.58***	28.67***	35.09***
	(0.00)	(0.00)	(0.00)	(0.00)
GDP	236.73***	94.36***	75.40***	71.37***
	(0.00)	(0.00)	(0.00)	(0.00)
GDP^2	236.23***	94.18***	75.33***	71.25***
	(0.00)	(0.00)	(0.00)	(0.00)
TECH	197.65***	121.53***	59.67***	20.39***
	(0.00)	(0.00)	(0.00)	(0.00)
FDI	19.59***	4.74***	17.40***	14.59***
	(0.00)	(0.00)	(0.00)	(0.00)
NR	155.22***	55.03***	53.25***	43.58***
	(0.00)	(0.00)	(0.00)	(0.00)
FE	27.19***	8.06***	15.38***	12.74***
	(0.00)	(0.00)	(0.00)	(0.00)
IQ	60.06***	38.08***	15.51***	9.31***
	(0.00)	(0.00)	(0.00)	(0.00)

Note: indicate the significance level at 0.1 %

Table 6
Results from the Pesaran and Yamagata (2008b) homogeneity test.

Tests	*GLOBAL*	*HIC*	*MHIC*	*MLIC*
Delta ($\tilde{\Delta}$)	33.25***	22.11***	15.02***	14.34***
	(0.00)	(0.00)	(0.00)	(0.00)
Adjusted-delta ($\tilde{\Delta}_{adj}$)	41.23***	27.35***	18.57***	17.73***
	(0.00)	(0.00)	(0.00)	(0.00)

Note: indicate the significance level at 0.1 %

cointegration test is helpful for the Westerlund and Edgerton (2008) test, which incorporates cross-sectional dependence and homogeneity in the slope in calculating the cointegration relationship. Other research that examines the factors that determine CO_2 have found similar conclusions (Cai et al., 2023b; Khan and Hassan, 2024).

4.4. Unit root tests results

Table 7 reports the results of Pesaran's (2007) second-generation unit root test, both in levels and in first difference for the global panel and the country groups. The series has an order of integration I(1). The differentiation of each series contributed to eliminating the trend effect, which reports robust results and solid political inferences. The CIPS test reports robust results in heterogeneity and cross-sectional dependence. The test was run using the trend specification to identify possible features not visible in the data-generating process.

4.5. Second-generation cointegration results

The existence of dependence in the cross sections and homogeneity in the slope requires second-generation cointegration techniques. Westerlund and Edgerton (2008) propose a cointegration test in the presence of structural breaks and consider slope dependence and heterogeneity. The findings of the Table 8 offer sufficient evidence to reject the null hypothesis of non-cointegration; therefore, we conclude that the series have a long-term relationship in the presence of structural breaks. This result means that, in the long term, the covariates impact polluting gas emissions. Structural breaks occur in economies due to sudden economic or technological shocks or a change in the regulatory or political framework (Yunzhao, 2022; Li et al., 2023; Sharif et al., 2023). The cointegration findings suggest that real per capita output, technology, foreign direct investment, natural resources, financial efficiency, and institutional quality are instruments to influence the trajectory of CO_2 emissions.

Table 7
Panel unit-root test (Pesaran, 2007).

	Variable	*Level*		*First difference*	
		Constant	*With trend*	*Constant*	*With trend*
Total sample	CO_2	−1.90	−2.44	−4.67***	−4.90***
	GDP	−2.14*	−2.18	−3.20***	−3.40***
	GDP^2	−2.06	−2.12	−3.19***	−3.38***
	TECH	−2.05	−2.31	−3.92***	−4.24***
	FDI	−3.43***	−3.82***	−5.43***	−5.67***
	NR	−1.92	−2.08	−4.25***	−4.37***
	FE	−3.43***	−3.65***	−5.60***	−5.73***
	IQ	−2.22**	−2.51	−4.10***	−4.36***
HIC	CO_2	−1.74	−2.29	−4.66***	−5.02***
	GDP	−1.94	−1.92	−3.59***	−3.63***
	GDP^2	−1.93	−2.02	−3.57***	−3.61***
	TECH	−1.99	−2.27	−3.88***	−3.94***
	FDI	−3.96***	−4.11***	−5.69***	−5.91***
	NR	−2.02	−2.31	−4.31***	−4.37***
	FE	−2.79***	−3.40***	−5.60***	−5.74***
	IQ	−2.26**	−2.61*	−4.06***	−4.22***
MHIC	CO_2	−2.16**	−2.37	−4.53***	−4.61***
	GDP	−1.57	−2.00	−3.31***	−3.68***
	GDP^2	−1.56	−2.06	−3.31***	−3.66***
	TECH	−1.72	−1.64	−4.15***	−4.38***
	FDI	−3.16***	−3.33***	−5.51***	−5.65***
	NR	−2.00	−2.63*	−4.81***	−4.92***
	FE	−3.62***	−3.04***	−5.69***	−5.71***
	IQ	−2.02	−2.55	−3.77***	−4.14***
MLIC	CO_2	−1.67	−1.69	−4.46***	−4.83***
	GDP	−1.78	−1.80	−3.24***	−3.58***
	GDP^2	−1.79	−1.82	−3.18***	−3.54***
	TECH	−1.71	−2.24	−4.26***	−4.41***
	FDI	−3.24***	−3.63***	−5.32***	−5.73***
	NR	−1.56	−1.81	−4.04***	−4.11***
	FE	−3.34***	−3.56***	−5.16***	−5.29***
	IQ	−2.30***	−2.63**	−4.46***	−4.76***

Note: indicate the significance level at 0.1 %

4.6. Robustness analysis

Table 9 reports the findings of the panel data causality test using Equation 10. The findings reveal certain heterogeneity in the causal relationships between series, coinciding with the results of Table 4 when we use quantile regressions. Specifically, we find evidence favoring the environmental Kuznets curve and that technology is central to achieving countries' environmental sustainability. Contrary to expectations, FDI does not have a causal relationship with CO2 emissions in the global and individual panels.

In practice, the findings only partially support H1 and H2, but we find evidence favoring H3.

5. Conclusions and policy implications

This research examined the causal link between CO_2 emissions with technology and financial efficiency from 1996 to 2021 in 88 countries worldwide. The relationship between the variables was moderated by real per capita product, foreign direct investment, natural resources, and institutional quality. Countries were grouped by their development level to improve estimators' forecasting and the quality of policy inferences. We apply panel data econometric techniques as a methodological strategy to capture similar productive structures between countries. Specifically, we apply the novel MMQR technique formalized by Machado and Silva (2019) and cointegration techniques in the presence of structural breaks by Westerlund and Edgerton (2008), including dependence on cross sections and structural breaks.

The MMQR-based findings support the following conclusions. The evidence favoring EKC is strong in HIC countries, showing that economic and social progress will motivate environmental mitigation and restoration. However, in upper-middle- and lower-middle-income countries, the theoretical relationship is unclear, and further analysis

Table 8
Results of Westerlund and Edgerton (2008) cointegration test.

		No Shift		*Level shift*		*Regime shift*	
		Statistic	p-value	Statistic	p-value	Statistic	p-value
Total sample	LM_t	−29.74***	0.00	−3.30***	0.00	−3.27**	0.01
	LM_Φ	−157.91***	0.00	−7.43***	0.00	−7.38***	0.00
HIC	LM_t	−24.92***	0.00	−2.66***	0.00	−2.66***	0.00
	LM_Φ	−117.53***	0.00	−5.92***	0.00	−5.93***	0.00
MHIC	LM_t	−15.67***	0.00	−1.42	0.08	−1.94*	0.03
	LM_Φ	−51.90***	0.00	−2.97***	0.00	−3.75***	0.00
MHIC	LM_t	−11.85***	0.00	−2.52**	0.01	−3.36***	0.00
	LM_Φ	−35.59***	0.00	−4.94***	0.00	−6.18***	0.00

Note: indicate the significance level at 0.1 %

Table 9
Dumitrescu & Hurlin (2012) causality test results.

Null Hypothesis	*Panel w bar*	*Critical Values*			*Panel w bar*	*Critical Values*		
	Test Stat.	1 %	5 %	10 %	Test Stat.	1 %	5 %	10 %
All countries					*HIC*			
GDP → CO_2	2.99*	4.07	3.02	2.51	2.18*	4.16	2.75	2.18
CO_2 →GDP	4.78***	4.18	3.03	2.45	5.29***	4.09	3.01	2.41
GDP^2 → CO_2	2.85*	4.13	2.86	2.34	2.15	4.19	2.74	2.17
CO_2 →$EGDP^2$	4.70***	4.30	3.15	2.61	5.29***	4.02	2.79	2.24
TEC → CO_2	3.93**	4.44	3.13	2.59	4.08**	4.23	2.81	2.26
CO_2 →TEC	5.02***	4.30	3.16	2.61	6.19***	3.72	2.76	2.17
IED → CO_2	2.05	4.68	3.45	2.93	1.25	4.60	2.99	2.25
CO_2 → IED	2.09	4.62	2.89	2.08	1.76	4.78	2.48	2.19
NR → CO_2	2.59*	4.35	3.03	2.50	2.33*	3.87	2.71	2.12
CO_2 → NR	4.47***	4.29	3.18	2.63	4.83***	3.85	2.86	2.30
FE → CO_2	4.99***	4.46	3.17	2.68	4.28**	4.57	2.77	2.20
CO_2 → FE	3.56**	4.87	3.42	2.79	4.28***	3.42	2.47	1.99
IQ → CO_2	6.08***	4.11	3.27	2.72	4.54***	3.95	2.90	2.36
CO_2 → IQ	4.31**	4.48	3.36	2.78	4.88***	3.99	2.91	2.41
MHIC					*MLIC*			
EC → CO_2	3.38**	3.88	2.67	2.18	4.11***	4.00	2.69	2.12
CO_2 →EC	4.39***	4.27	2.62	2.14	4.23***	4.05	2.59	1.94
EC^2 → CO_2	3.26**	3.69	2.61	2.02	4.13***	3.85	2.54	2.04
CO_2 →EC^2	4.17***	3.97	2.60	2.16	4.14***	3.69	2.79	2.00
TEC → CO_2	4.30**	4.34	2.78	2.27	2.25*	3.90	2.61	2.11
CO_2 →TEC	3.66**	3.74	2.83	2.27	4.27***	4.23	2.85	2.09
IED → CO_2	3.68*	6.27	4.02	2.43	3.68**	4.06	2.63	2.05
CO_2 → IED	1.75	5.11	3.26	2.30	2.01	3.39	2.68	2.24
NR → CO_2	4.06**	4.44	2.86	2.34	1.46	3.86	2.55	1.98
CO_2 → NR	4.90***	4.50	3.02	2.34	3.35**	4.33	2.71	2.18
FE → CO_2	2.35	4.00	2.90	2.38	6.34***	4.15	2.70	2.14
CO_2 → FE	5.02***	3.95	2.67	1.99	3.28**	4.18	2.96	2.26
IQ → CO_2	9.80***	4.93	3.24	2.63	4.97***	3.83	2.73	2.10
CO_2 → IQ	2.69*	4.02	3.10	2.25	1.82	4.17	2.57	2.04

Notes: Estimated based on a maximum lag order of 1 whereas indicate the significance level at 0.1 %

is required to make definitive inferences. The idea that economic progress will reduce pollution is dubious in both groups of countries. Likewise, we find that technology has a positive relationship in rich countries, in upper-middle-income countries, and in the last quantiles of lower-middle-income countries. This result leads us to conclude that technology in its current form aims to promote production rather than mitigate or restore environmental degradation. The contribution of technology in reducing CO_2 emissions is not questionable; instead, it is a question of primacy and that it is insufficient to mitigate environmental damage. The dilemma between maximizing production and environmental conservation has a pillar that has tipped the balance in favor of the search to increase production over environmental protection. Policies to promote technological innovation, such as applied technology subsidy programs, should promote new products that tend towards zero carbon emissions. In this way, the achievement of development goals will continue to be promoted, but with environmental sustainability.

Furthermore, we conclude that FDI increases CO_2 emissions in rich countries and the middle quantiles of MHICs and that, in lower-middle-income countries, capital flows reduce emissions. The findings suggest that, in lower-middle-income countries, FDI environmental pollution is not reflected in polluting gas emissions but may be reflected in other indicators such as ecological footprint or deforestation. We find that the impact of natural resources on emissions is heterogeneous and inconclusive. However, in some quantiles, the relationship between the two variables is positive, indicating that the activities associated with exploiting raw materials generate pollution. Concerning financial efficiency, we conclude that in rich and upper-middle-income countries, more financial efficiency implies more emissions. In contrast, financial efficiency is a mechanism for reducing emissions in lower-middle-income countries. We conclude that institutional quality worsens environmental quality in high-income and lower-middle-income countries, indicating that institutions are more oriented toward protecting production than promoting the conservation of environmental quality.

Finally, the findings of Westerlund and Edgerton's (2008) cointegration test support the conclusion that the series have a long-run relationship. Therefore, in the long term, covariates are valid mechanisms to influence environmental quality by promoting low-carbon technology and, in general, stricter regulation so that production, capital flows, and institutions take the importance of achieving sustainable development in harmony with the environment more seriously. One of the limitations of the research is the need for more data for low-income countries. Some research has shown that highly polluting industries move where there are lax environmental regulations, significantly increasing total emissions. However, the findings and conclusions are robust to high-income, upper-middle-income, and lower-middle-income countries. Future research should deepen the link between financial efficiency and institutional quality as environmental mitigation mechanisms, particularly in developing countries where data availability limits the evidence to improve pro-environmental policies.

Funding

This study was not received any funding from any institution/ organization or person.

Ethical statement

Not applicable because this study did not involve the use of animal or human subjects.

Ethical statement

All participants provided written informed consent prior to engagement in the study. Ethical Statement/Approval is not applicable because the research paper does not include animal and humans as subjects.

CRediT authorship contribution statement

Brayan Tillaguango: Investigation, Data curation, Conceptualization. **Rafael Alvarado:** Investigation, Conceptualization. **Muntasir Murshed:** Writing – original draft, Supervision. **Elisa Toledo:** Methodology, Formal analysis. **Cem Isik:** Writing – original draft, Methodology.

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

Abban, O.J., Hongxing, Y., Nuta, A.C., Dankyi, A.B., Ofori, C., Cobbinah, J., 2022. Renewable energy, economic growth, and CO2 emissions contained Co-movement in African oil-producing countries: a wavelet-based analysis. Energy Strategy Rev. *44*, 100977.

Abbas, Q., HongXing, Y., Ramzan, M., Fatima, S., 2024. BRICS and the climate challenge: navigating the role of factor productivity and institutional quality in CO2 emissions. Environ. Sci. Pollut. Res. *31* (3), 4348–4364.

Abid, L., Kacem, S., Saadaoui, H., 2024. Addressing the environmental kuznets curve in the west african countries: exploring the roles of FDI, Corruption, and Renewable Energy. J. Knowl. Econ. 1–25.

Acheampong, A.O., Dzator, J., Savage, D.A., 2021. Renewable energy, CO2 emissions and economic growth in sub-Saharan Africa: does institutional quality matter? J. Policy Model. *43* (5), 1070–1093.

Achuo, E.D., Miamo, C.W., Kouhomou, C.Z., 2024. Resource rents and environmental pollution in developing countries: does the quality of institutions matter? Rev. Dev. Econ. *28* (1), 360–387.

Adjei-Mantey, K., Adams, S., 2023. Renewable energy, foreign direct investment and carbon dioxide emissions: do sectoral value additions and policy uncertainty matter? Energy Nexus *10*, 100193.

Adun, H., Ampah, J.D., Bamisile, O., & Hu, Y. (2024). The synergistic role of carbon dioxide removal and emission reductions in achieving the Paris Agreement goal. *Sustainable Production and Consumption*. In Press.

Agboola, M.O., Bekun, F.V., Joshua, U., 2021. Pathway to environmental sustainability: nexus between economic growth, energy consumption, CO2 emission, oil rent and total natural resources rent in Saudi Arabia. Resour. Policy *74*, 102380.

Ahmad, M., Satrovic, E., 2023. Relating fiscal decentralization and financial inclusion to environmental sustainability: criticality of natural resources. J. Environ. Manag. 325, 116633.

Ahmad, M., Ahmed, Z., Yang, X., Hussain, N., Sinha, A., 2022. Financial development and environmental degradation: do human capital and institutional quality make a difference? Gondwana Res. 105, 299–310.

Ahmad, M., Balbaa, M.E., Zikriyoev, A., Nasriddinov, F., Kuldasheva, Z., 2024. Energy efficiency, technological innovation, and financial development-based EKC premise: fresh asymmetric insights from developing Asian regions. Environ. Chall. *15*, 100947.

Alataş, S., 2022. Do environmental technologies help to reduce transport sector CO2 emissions? Evidence from the EU15 countries. Res. Transp. Econ. *91*, 101047.

Al-Karkhi, M.I., 2024. Statistical analysis and open innovation in economic growth of scottish business SMEs for sustainable development. J. Open Innov.: Technol., Mark., Complex. 10 (2), 100275.

Amin, A., Peng, S., Işık, C., Ullah, A., Akbar, M., 2024. The influence of energy transition, and natural resources on carbon emissions in China: an augmented ARDL application. Environ., Dev. Sustain. 1–19.

Aminu, N., Clifton, N., Mahe, S., 2023. From pollution to prosperity: investigating the Environmental Kuznets curve and pollution-haven hypothesis in sub-Saharan Africa's industrial sector. J. Environ. Manag. 342, 118147.

Arvin, M.B., Pradhan, R.P., Nair, M.S., Dabir-Alai, P., 2022. Exploring the temporal links between foreign aid, institutional quality, and CO2 emissions for poorer countries. Energy Build. *270*, 112287.

Ashraf, J., Javed, A., 2023. Food security and environmental degradation: do institutional quality and human capital make a difference? J. Environ. Manag. 331, 117330.

Baloch, M.A., Mahmood, N., Zhang, J.W., 2019. Effect of natural resources, renewable energy and economic development on CO2 emissions in BRICS countries. Sci. Total Environ. *678*, 632–638.

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., Farhani, S., 2018. How economic growth, renewable electricity and natural resources contribute to CO2 emissions? Energy Policy *113*, 356–367.

Boateng, E., Annor, C.B., Amponsah, M., Ayibor, R.E., 2024. Does FDI mitigate CO2 emissions intensity? Not when institutional quality is weak. J. Environ. Manag. *354*, 120386.

Boubacar, S., Sarpong, F.A., Nyantakyi, G., 2024. Shades of sustainability: decoding the impact of foreign direct investment on CO2 emissions in Africa's growth trajectory. Environ., Dev. Sustain. 1–34.

Boussaidi, R., & Hakimi, A. (2024, January). Financial inclusion, economic growth, and environmental quality in the MENA region: What role does institution quality play? In *Natural Resources Forum*. Oxford, UK: Blackwell Publishing Ltd.

Cai, X., Li, K., Wang, W., Lu, Y., Wang, R., 2023a. The role of resource rent in shaping CO2 emissions in BRICS countries: a panel data approach. Resour. Policy 85, 103857.

Cai, Y., Zhou, P., Zhang, Y., Shen, Y., 2023b. Natural resources extraction and sustainable environment: COP26 perspective for China. Resour. Policy *82*, 103530.

Chatti, W., Khan, Z., 2024. Towards smart sustainable cities: does technological innovation mitigate G7 CO2 emissions? Fresh evidence from CS-ARDL. Sci. Total Environ. *913*, 169723.

Chen, C., Qin, Y., Gao, Y., 2023a. Does new urbanization affect CO2 emissions in China: a spatial econometric analysis. Sustain. Cities Soc., 104687

Chen, Y., Subhan, M., Ahmad, G., Adil, M., Zamir, M.N., 2024. Unveiling the linkages among digital technology, economic growth, and carbon emissions: a resource management perspective. Resour. Policy *91*, 104868.

Cui, X., Wang, W., Işık, C., Uddin, I., Yan, J., Gu, X., Ahmad, M., 2024. Do geopolitical risk and economic policy uncertainty cause CO2 emissions in BRICS? The role of institutional quality and energy productivity. Stoch. Environ. Res. Risk Assess. *38* (5), 1685–1699.

Da Silveira Cachola, C., Ciotta, M., dos Santos, A.A., Peyerl, D., 2023. Deployng of the carbon capture technologies for co2 emission mitigation in the industrial sectors. Carbon Capture Sci. Technol., 100102

Dam, M.M., Durmaz, A., Bekun, F.V., Tiwari, A.K., 2024. The role of green growth and institutional quality on environmental sustainability: a comparison of CO2 emissions, ecological footprint and inverted load capacity factor for OECD countries. J. Environ. Manag. *365*, 121551.

Dong, K., Wang, S., Hu, H., Guan, N., Shi, X., Song, Y., 2024. Financial development, carbon dioxide emissions, and sustainable development. Sustain. Dev. *32* (1), 348–366.

Elfaki, K.E., Ahmed, E.M., 2024. Digital technology adoption and globalization innovation implications on Asian Pacific green sustainable economic growth. J. Open Innov.: Technol., Mark., Complex. 10 (1), 100221.

Esmaeili, P., Lorente, D.B., Anwar, A., 2023. Revisiting the environmental Kuznets curve and pollution haven hypothesis in N-11 economies: fresh evidence from panel quantile regression. Environ. Res. 228, 115844.

Essandoh, O.K., Islam, M., Kakinaka, M., 2020. Linking international trade and foreign direct investment to CO2 emissions: any differences between developed and developing countries? Sci. Total Environ. *712*, 136437.

Faulkner, C.A., Castellini Jr, J.E., Lou, Y., Zuo, W., Lorenzetti, D.M., Sohn, M.D., 2022. Tradeoffs among indoor air quality, financial costs, and CO2 emissions for HVAC operation strategies to mitigate indoor virus in US office buildings. Build. Environ. 221, 109282.

Fernandez-Pinto, H., Duarte, C.A.M., Villamizar, S.P., Suarez, J.E.S., 2024. Horizontal innovation: the core of open innovation in the construction of the dynamic capacities in the Colombian industry. J. Open Innov.: Technol., Mark., Complex. 10 (1), 100229.

Ganda, F., 2024b. The influence of democracy, corruption, economic growth and ICT on carbon emissions in Sub-Saharan African countries: does FDI matter? J. Open Innov.: Technol., Mark., Complex. 10 (3), 100324.
Gao, S., Zhu, Y., Umar, M., Kchouri, B., Safi, A., 2024. Financial inclusion empowering sustainable technologies: insights into the E-7 economies from COP28 perspectives. Technol. Forecast. Soc. Change *201*, 123177.
Geng, Y., Fan, A., 2023. How trade diversification affects resources sustainability in China: exploring the role of institutional quality and environmental policies uncertainty. Resour. Policy 86, 104072.
Grossman, G.M., Krueger, A.B., 1991. Environmental Impacts of a North American Free Trade Agreement (No. W3914). National Bureau of Economic Research.
Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Q. J. Econ. 110 (2), 353–377.
Guan, Z., Hossain, M.R., Sheikh, M.R., Khan, Z., Gu, X., 2023. Unveiling the interconnectedness between energy-related GHGs and pro-environmental energy technology: lessons from G-7 economies with MMQR approach. Energy 281, 128234.
Guo, X., Shahbaz, M., 2024. The existence of environmental Kuznets curve: critical look and future implications for environmental management. J. Environ. Manag. *351*, 119648.
Hamaguchi, Y., 2023. Environmental tax evasion as a determinant of the Porter and pollution haven hypotheses in a corrupt political system. Econ. Anal. Policy 79, 610–633.
Hanif, I., Raza, S.M.F., Gago-de-Santos, P., Abbas, Q., 2019. Fossil fuels, foreign direct investment, and economic growth have triggered CO2 emissions in emerging Asian economies: some empirical evidence. Energy *171*, 493–501.
Hasan, M.B., Wieloch, J., Ali, M.S., Zikovic, S., Uddin, G.S., 2023. A new answer to the old question of the environmental Kuznets Curve (EKC). Does it work for BRICS countries? Resour. Policy 87, 104332.
He, Y., Zheng, H., 2023. How does environmental regulation affect industrial structure upgrading? Evidence from prefecture-level cities in China. J. Environ. Manag. 331, 117267.
Hoa, P.X., Xuan, V.N., Thu, N.T.P., 2023b. Nexus of innovation, renewable consumption, FDI, growth and CO2 emissions: the case of Vietnam. J. Open Innov.: Technol., Mark., Complex. 9 (3), 100100.
Hoa, P.X., Xuan, V.N., Thu, N.T.P., 2024. Determinants of renewable energy consumption in the fifth technology revolutions: evidence from ASEAN countries. J. Open Innov.: Technol., Mark., Complex. 10 (1), 100190.
Hu, J., Chen, H., Dinis, F., Xiang, G., 2023. Nexus among green finance, technological innovation, green fiscal policy and CO2 emissions: a conditional process analysis. Ecol. Indic. *154*, 110706.
Huang, Z., Ren, X., 2024. Impact of natural resources, resilient economic growth, and energy consumption on CO2 emissions. Resour. Policy *90*, 104714.
Hunjra, A.I., Azam, M., Bruna, M.G., Bouri, E., 2023. A cross-regional investigation of institutional quality and sustainable development. J. Int. Finan. Markets Inst. Money *84*, 101758.
Jebabli, I., Lahiani, A., Mefteh-Wali, S., 2023. Quantile connectedness between CO2 emissions and economic growth in G7 countries. Resour. Policy *81*, 103348.
Jia, Z., Alharthi, M., Haijun, T., Mehmood, S., Hanif, I., 2024. Relationship between natural resources, economic growth, and carbon emissions: the role of fintech, information technology and corruption to achieve the targets of COP-27. Resour. Policy *90*, 104751.
Jiang, Q., Rahman, Z.U., Zhang, X., Guo, Z., Xie, Q., 2022. An assessment of the impact of natural resources, energy, institutional quality, and financial development on CO2 emissions: evidence from the B&R nations. Resour. Policy *76*, 102716.
Jijian, Z., Twum, A.K., Agyemang, A.O., Edziah, B.K., Ayamba, E.C., 2021. Empirical study on the impact of international trade and foreign direct investment on carbon emission for belt and road countries. Energy Rep. *7*, 7591–7600.
Karim, S., Appiah, M., Naeem, M.A., Lucey, B.M., Li, M., 2022. Modelling the role of institutional quality on carbon emissions in Sub-Saharan African countries. Renew. Energy *198*, 213–221.
Khan, Y., Hassan, T., 2024. Promoting sustainable development: evaluating the influence of natural resources, high-tech export and corruption on CO2 emissions in developing economies. Resour. Policy *88*, 104511.
Kim, Y., 2021. Technological innovation, the Kyoto protocol, and open innovation. J. Open Innov.: Technol., Mark., Complex. 7 (3), 198.
Kwilinski, A., Lyulyov, O., Pimonenko, T., 2024b. Reducing transport sector CO2 emissions patterns: environmental technologies and renewable energy. J. Open Innov.: Technol., Mark., Complex. 10 (1), 100217.
Lee, C.C., Zhao, Y.N., 2023. Heterogeneity analysis of factors influencing CO2 emissions: the role of human capital, urbanization, and FDI. Renew. Sustain. Energy Rev. 185, 113644.
Leng, C., Wei, S.Y., Al-Abyadh, M.H.A., Halteh, K., Bauetdinov, M., Le, L.T., Alzoubi, H. M., 2024. An empirical assessment of the effect of natural resources and financial technologies on sustainable development in resource abundant developing countries: evidence using MMQR estimation. Resour. Policy 89, 104555.
Li, R., Wang, Q., Guo, J., 2024. Revisiting the environmental Kuznets curve (EKC) hypothesis of carbon emissions: exploring the impact of geopolitical risks, natural resource rents, corrupt governance, and energy intensity. J. Environ. Manag. *351*, 119663.
Limazie, M.S., Woni, S., 2024. Foreign direct investment and carbon emissions in ECOWAS: does good governance matter? J. Econ. Dev. *26* (2), 139–153.
Liu, P., Ur Rahman, Z., Jóźwik, B., Doğan, M., 2024. Determining the environmental effect of Chinese FDI on the Belt and Road countries CO2 emissions: an EKC-based assessment in the context of pollution haven and halo hypotheses. Environ. Sci. Eur. *36* (1), 1–12.
Machado, J.A., Silva, J.S., 2019. Quantiles via moments. J. Econ. 213 (1), 145–173.
Marra, A., Colantonio, E., Cucculelli, M., Nissi, E., 2024. The 'complex'transition: energy intensity and CO2 emissions amidst technological and structural shifts. Evidence from OECD countries. Energy Econ., 107702
Mehmood, B., Khan, S.A., Raza, M., 2023. Econometric evidence of catalytic effect of seaport activity in OECD Countries: getting it right. Marit. Transp. Res. 4, 100090.
Muhammad, B., Khan, S., 2019. Effect of bilateral FDI, energy consumption, CO2 emission and capital on economic growth of Asia countries. Energy Rep. 5, 1305–1315.
Naqvi, S.A.A., Hussain, M., Hussain, B., Shah, S.A.R., Nazir, J., Usman, M., 2023. Environmental sustainability and biomass energy consumption through the lens of pollution Haven hypothesis and renewable energy-environmental Kuznets curve. Renew. Energy 212, 621–631.
Naseem, S., Hu, X., Sarfraz, M., Mohsin, M., 2024. Strategic assessment of energy resources, economic growth, and CO2 emissions in G-20 countries for a sustainable future. Energy Strategy Rev. *52*, 101301.
Ngoc, N.B., Xuan, V.N., 2024. Nexus between carbon dioxide emissions, population, migration, foreign direct investment, and gross domestic product: New evidence in the context of Vietnam. J. Open Innov.: Technol., Mark., Complex. 10 (2), 100281.
Obobisa, E.S., Chen, H., Mensah, I.A., 2022. The impact of green technological innovation and institutional quality on CO2 emissions in African countries. Technol. Forecast. Soc. Change *180*, 121670.
Ozturk, I., Farooq, S., Majeed, M.T., Skare, M., 2023. An empirical investigation of financial development and ecological footprint in South Asia: bridging the EKC and pollution haven hypotheses. Geosci. Front., 101588
Panayotou, T. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. Working paper.
Patel, N., Mehta, D., 2023. The asymmetry effect of industrialization, financial development and globalization on CO2 Emissions in India. Int. J. Thermofluids, 100397.
Pesaran, M.H., 2007. A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econ. 22 (2), 265–312.
Pesaran, M.H., Yamagata, T., 2008b. Testing slope homogeneity in large panels. J. Econ. 142 (1), 50–93.
Purwono, R., Sugiharti, L., Esquivias, M.A., Fadliyanti, L., Rahmawati, Y., Wijimulawiani, B.S., 2024. The impact of tourism, urbanization, globalization, and renewable energy on carbon emissions: testing the inverted N-shape environmental Kuznets curve. Soc. Sci. Humanit. Open *10*, 100917.
Qayyum, M., Zhang, Y., Ali, M., Kirikkaleli, D., 2024. Towards environmental sustainability: the role of information and communication technology and institutional quality on ecological footprint in MERCOSUR nations. Environ. Technol. Innov., 103523
Raihan, A., Hasan, M.A., Voumik, L.C., Pattak, D.C., Akter, S., Ridwan, M., 2024. Sustainability in Vietnam: examining economic growth, energy, innovation, agriculture, and forests' impact on CO2 emissions. World Develop. Sustain., 100164
Rao, A., Talan, A., Abbas, S., Dev, D., Taghizadeh-Hesary, F., 2023. The role of natural resources in the management of environmental sustainability: Machine learning approach. Resour. Policy *82*, 103548.
Rasheed, M., Liu, J., 2024. Unraveling the environmental Kuznets curve: interplay between CO 2 emissions, economic development, and energy consumption. Environ. Sci. Pollut. Res. *31* (9), 13372–13391.
Rasheed, S., Adeneye, Y., Farooq, R., 2024. Income inequality and carbon emissions in Asia: Does financial inclusion matter? Sustainable Development. In press.
Raza, M.Y., Tang, S., 2024. Nuclear energy, economic growth and CO2 emissions in Pakistan: Evidence from extended STRIPAT model. Nucl. Eng. Technol. 56 (7), 2480–2488.
Ridwan, M., Urbee, A.J., Voumik, L.C., Das, M.K., Rashid, M., Esquivias, M.A., 2024. Investigating the environmental Kuznets curve hypothesis with urbanization, industrialization, and service sector for six South Asian Countries: fresh evidence from Driscoll Kraay standard error. Res. Glob. *8*, 100223.
Saqib, N., Radulescu, M., Usman, M., Balsalobre-Lorente, D., Cilan, T., 2023. Environmental technology, economic complexity, renewable electricity, environmental taxes and CO2 emissions: implications for low-carbon future in G-10 bloc. Heliyon *9*, 6.
Shahbaz, M., Balsalobre-Lorente, D., Sinha, A., 2019. Foreign direct Investment–CO2 emissions nexus in Middle East and North African countries: Importance of biomass energy consumption. J. Clean. Prod. *217*, 603–614.
Shahbaz, M., Patel, N., Du, A.M., Ahmad, S., 2024. From black to green: Quantifying the impact of economic growth, resource management, and green technologies on CO2 emissions. J. Environ. Manag. *360*, 121091.
Shang, T., Samour, A., Abbas, J., Ali, M., Tursoy, T., 2024. Impact of financial inclusion, economic growth, natural resource rents, and natural energy use on carbon emissions: the MMQR approach. Environ., Dev. Sustain. 1–31.
Sharif, A., Kocak, S., Khan, H.H.A., Uzuner, G., Tiwari, S., 2023. Demystifying the links between green technology innovation, economic growth, and environmental tax in ASEAN-6 countries: the dynamic role of green energy and green investment. Gondwana Res. 115, 98–106.
Shen, A., Zhang, J., 2024. Technologies for CO2 emission reduction and low-carbon development in primary aluminum industry in China: a review. Renew. Sustain. Energy Rev. 189, 113965.
Shokrollahi, M., Teymouri, N., Navarri, P., 2024. Identification and evaluation of most promising CO2 utilization technologies: Multi criteria decision analysis and techno-economic assessment. J. Clean. Prod. 434, 139620.
Sikder, M., Wang, C., Yao, X., Huai, X., Wu, L., KwameYeboah, F., Dou, X., 2022. The integrated impact of GDP growth, industrialization, energy use, and urbanization on CO2 emissions in developing countries: evidence from the panel ARDL approach. Sci. Total Environ. *837*, 155795.

Singh, A.K., Raza, S.A., Nakonieczny, J., Shahzad, U., 2023. Role of financial inclusion, green innovation, and energy efficiency for environmental performance? Evidence from developed and emerging economies in the lens of sustainable development. Struct. Change Econ. Dyn. 64, 213–224.
Somoye, O.A., Seraj, M., Ozdeser, H., Mar'I, M., 2024. Modelling the connection between energy intensity, renewable energy, globalization, technological innovation and CO2 emissions: a quantile–on–Quantile technique. Geol. J. 59 (4), 1322–1336.
Uddin, M.M.M., Sharif, T., Islam, A.R.M., Abedin, M.Z., 2024. Moderating impact of FDI on the growth-environment nexus in the pre-COVID-19 eras. Res. Int. Bus. Financ. 67, 102114.
Wang, E.Z., Yang, M., 2022. Green complexity and CO2 emission: does institutional quality matter? Energy Econ. *110*, 106022.
Wang, Q., Yang, T., Li, R., 2023a. Does income inequality reshape the environmental Kuznets curve (EKC) hypothesis? A nonlinear panel data analysis. Environ. Res. 216, 114575.
Wang, Y., Xu, Y., 2024. Green natural capital, the environmental Kuznets curve and development financing in the Global South. Iscience *27* (5).
Warsame, A.A., Sheik-Ali, I.A., Mohamed, J., Sarkodie, S.A., 2022. Renewables and institutional quality mitigate environmental degradation in Somalia. Renew. Energy 194, 1184–1191.
Westerlund, J., Edgerton, D.L., 2008. A simple test for cointegration in dependent panels with structural breaks. Oxf. Bull. Econ. Stat. 70 (5), 665–704.
Xuan, S., Ge, W., Yang, P., Zhang, Y., 2024. Exploring digital finance, financial regulations and carbon emission nexus: new insight from resources efficiency, industrial structure and green innovation in China. Resour. Policy *88*, 104452.
Yilanci, V., Gorus, M.S., Andreoni, V., 2023. Reinvestigation of the validity of the EKC hypothesis extended with energy: a time-varying analysis for the United Kingdom. J. Clean. Prod. 428, 139284.
Yu, X., Kuruppuarachchi, D., Kumarasinghe, S., 2024. Financial development, FDI, and CO2 emissions: does carbon pricing matter? Appl. Econ. *56* (25), 2959–2974.
Yunzhao, L., 2022. Modelling the role of eco innovation, renewable energy, and environmental taxes in carbon emissions reduction in E− 7 economies: evidence from advance panel estimations. Renew. Energy 190, 309–318.
Zhang, H., Chen, T., Yu, Y., 2023a. From finance to sustainability: understanding the financial development-environment nexus with the environmental Kuznets curve in East-Asia and Pacific economies. Borsa Istanb. Rev. 23 (6), 1448–1457.
Zhang, S., Xie, W., Sun, S., Wu, F., Xue, Y., 2024a. Nexus of green energy innovation, governance quality, and CO2 emissions in natural resource sector: the role of sustainable human development. Resour. Policy *88*, 104493.
Zhang, W., Xu, Y., Jiang, L., Streets, D.G., Wang, C., 2024b. Direct and spillover effects of new-type urbanization on CO2 emissions from central heating sector and EKC analyses: evidence from 144 cities in China. Resour., Conserv. Recycl. *192*, 106913.
Zhu, R., Xu, Q., Xiqiang, X., Sibt-e-Ali, M., Waqas, M., Ullah, I., Anwar, A., 2024. Role of resources rent, research and development, and information and communication technologies on CO2 emissions in BRICS economies. Resour. Policy *93*, 105072.