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Do asymmetric green technology innovation and institutional quality shocks matter for CO_2 emissions in OECD countries? New evidence from an ARDL–PMG approach

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A B S T R A C T

Harmful climatic effects caused by increasing levels of carbon emissions are nowadays considered a serious problem for countries all over the world. Some nations are not yet making best use of their resources to promote long-term growth, while others are making great efforts to maintain a clean environment. Governments and policymakers worldwide however are considering climate challenges and global warming as critical risks. This research enriches previous literature on reducing CO_2 emissions by exploring effects on carbon dioxide emissions from asymmetric green technology innovation and institutional quality within OECD nations. The short- and long-term impact of upward and downward fluctuations of GTI and IQ on CO_2 emissions are assessed across a panel of 35 OECD nations for the period 1995-2020. The findings show: (i) that the EKC hypothesis is supported for long term effect but not short term in the countries studied; (ii) the existence of asymmetric long-term effects for GTI and dimensions of IQ; and (iii) that controlling corruption seems to have the most important effect on environmental degradation compared to other IQ measures. The study contributes to current understandings by revealing the nuanced and complex relations linking technological and institutional factors and environmental outcomes in developed economies. Based on the results, OECD countries must stimulate and support green technological innovation by defining appropriate governance reforms to foster sustainable development and meet sustainable development goals.

1. Introduction

Climate change has emerged as one of humanity's most pressing concerns (Zhang et al., 2023; Abrahms et al., 2023; Akter, 2024). The unprecedented increase in CO_2 (carbon dioxide) emissions forms a key variable driving the global warming phenomenon (Rehman et al., 2023), threatening environmental stability (Nunes, 2023; Rehman et al., 2021) and economic prosperity across the planet (Saint Akadiri et al., 2020; Gyimah et al., 2023). Organization for Economic Co-operation and Development (OECD) nations, which tend to have significant industrial capacities and high energy consumption, are responsible for many global emissions (Barkat et al., 2024). This reality necessitates a deeper appreciation of the various influences on these emissions, enabling the development of effective mitigation strategies to address this issue. Many previous studies provide deep discussion of causal factors in mitigating emissions (Wu et al., 2021; Ragmoun, 2023a; Zhao, and Yang, 2021; Kartal et al., 2024), and green technological innovation (GTI) (Mehmood et al., 2024; Zeng et al., 2024; Obobisa et al., 2022; Shan et al., 2021) and institutional quality (IQ) (Fatima et al., 2022; Mehmood et al., 2021; Jiang et al., 2022; Ragmoun, 2024) have been identified as pivotal forces with the potential to significantly impact efforts to decrease the carbon emitted. The GTI concept represents a broad array of technological advances that promote a sustainable approach to the environment (Shan et al., 2021; Lv et al., 2021). This includes developing and deploying renewable energy resources, processes which use energy efficiently, and techniques for decreasing waste,

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among other initiatives (Sharif et al., 2022; Habiba et al., 2022; Lin and Ma, 2022). These innovations are essential for transitioning towards the low-carbon economy as well as for climate change impact mitigation (Dong et al., 2022). Institutional quality (IQ) may also improve environment quality through stimulating environmental protection policies and regulations and decreasing carbon dioxide emissions (Teng et al., 2021). IQ refers to the effectiveness and integrity of governance structures, and includes enforcing regulations, protecting property rights, and institutional capacity to design and implement effective policy (Haldar & Sethi, 2021; Ragmoun, 2023b). Some studies support the idea that effective institutions can develop a country's ability to combat pollution and increase environmental quality (Ibrahiem & Hanafy, 2020). IQ is generally considered effective in reducing crime and corruption, but studies regarding its environmental consequences and impact are limited (Obobisa et al., 2022). Therefore, this research aims to explore the effect of GTI and IQ on the CO_2 emitted by OECD countries, considering asymmetry.

OECD countries are selected as the focus of the study, for many reasons. First, these countries are regarded as leaders in economic and technological progress and play an instrumental role in orchestrating responses to pressing environmental concerns. The intricate relationship between financial development, technological innovation, institutional quality, and environmental quality in these nations provides opportunities for scholarly inquiry, providing valuable insights that can guide policy formulation and foster international collaboration (Du Jianguo et al., 2022). Second, the insufficient support for GTI is considered as one of the main regulatory dilemmas in OECD countries (Wang et al., 2023). Third, the relationships linking GTI, IQ, and CO_2 emissions are characterized by complexity and potential non-linearity, which suggests that there may be different effects at different levels or stages of innovation and institutional development. It is essential to explore this relationship thoroughly to understand how positive and negative changes in GTI and IQ correlate with fluctuations in CO_2 emissions. This nuanced understanding is crucial for informing policymakers and stakeholders, enabling them to tailor their environmental strategies more effectively to the specific needs and circumstances of their countries. Previous research has laid the groundwork for understanding GTI and IQ's effects upon CO_2 emissions across various contexts. Research by Obobisa et al. (2022) provides valuable insights into how developing regions, such as African countries, respond to advances in green technology and improvements in institutional frameworks. Their findings shed light on the importance of these factors. Despite the valuable contributions of their study however, there remains a lack of research regarding asymmetric impacts from GTI and IQ on CO_2 emissions, and particularly in the context of OECD countries, where economic structures, levels of technological advancement, and environmental policies differ substantially from those in developing regions. Considering the literature reviewed for the current research, this effect in the context of the OECD is under-studied, and there is very limited empirical research dealing with this combined impact from GTI and IQ upon CO_2 emissions. The findings of this research can help towards development of the required policies to guide OECD countries to recognize causal factors that mitigate CO_2 emissions.

In summary, the study investigates nuances in CO_2 emission responses to GTI and IQ within OECD countries, considering the asymmetry of these relationships. It seeks to enrich current knowledge through applying non-linear autoregressive distributed lag (NARDL) in dissecting long- and short-term impacts of GTI and IQ on emitted CO_2. By examining 35-country OECD panel between 1995 and 2020, the research will comprehensively analyze the complicated dynamics occurring between these critical variables. By providing empirical evidence of these asymmetric effects, this study seeks to assist policymakers in designing more nuanced and effective strategies for CO_2 emission reductions in OECD countries. The results are expected to have practical implications for environmental regulation, innovation policy, and the broader goal of sustainable development. This paper will first review the extant literature to establish the current state of knowledge regarding the interplay between GTI, IQ, and CO_2 emissions. There is then an explanation of the NARDL methodology, which is particularly well-suited to the research question as it can distinguish between positive and negative change effects from GTI and IQ. Further, this methodology offers a more detailed understanding of different interrelationships with CO_2 emissions by capturing the asymmetric effects of GTI and IQ.

2. Literature review

The interplay between asymmetric green technology innovation, institutional quality shocks, and CO_2 emissions in OECD nations is significant. Recent studies employing the ARDL-PMG approach reveal that positive and negative shocks in green technology and institutional quality can substantially impact emission levels.

2.1 Innovative green technologies and CO_2 emissions

Innovative green technologies are considered a novel form of technological innovation which reduces energy intensity as well as pollutant emissions to increase the quality of the environment and stimulate the green economy (Wang et al., 2021). GTI is also relevant to adopting specific technologies to generate eco-friendly products which reduce energy consumption and pollution. This process applies to clean energy generation by using alternative fuels (Sohag et al., 2021) and aids in advancing the country's use of renewable energy (Wang et al., 2020) and achieving long-term sustainable development. Furthermore, investing in GTI can promote sustainable economic activity and production by providing a potential solution for CO_2 emissions (Obobisa et al., 2022). Rong et al. (2023) use empirical tests in LSDVC and dynamic spatial SAR models to demonstrate that GTI directly inhibits agricultural CO_2 emission intensity (ACEI) and exhibits significant positive spatial spillover impacts upon ACEI reductions for both short and long term. Cui et al. (2024) find that GTI negatively impacts CO_2 emissions. They conclude that carbon trading prices and government subsidies substantially influence GTI and impact companies' strategies in carbon emissions trading markets to reduce CO_2 emissions. Zeng et al. (2024) employ the spatial Durbin model to analyze panel data from 30 provinces during the period 2008–2020 and conclude that green technological progress significantly inhibits local CO_2 emissions, primarily through industrial structure, energy structure, and energy efficiency, with notable regional disparities in its effectiveness across China. Following the same line of thinking, Thi et al. (2024) adopt simultaneous equation modelling (SEM) with three-stage least squares (3SLS) in exploring impacts from innovation upon CO_2 emissions. They conclude that innovation negatively influences carbon emissions, while carbon emissions positively influence innovation, indicating a complex relation linking green technology innovation with CO_2 emissions. The authors posit a two-way relationship linking innovation and carbon emissions, in which various factors influence emissions and innovation toward sustainable development goals. Through adopting panel data analysis from 16 Shanghai districts, Zhu et al. (2024) explore the nonlinear relationships linking GTI and CO_2 emissions across different environmental contexts and seek to identify other factors influencing carbon emissions reduction. They confirm a nonlinear relationship linking technological innovation and emitted carbon and emphasize the importance of patent applications, citations, and grants in this context. As seen from the above, increasing research evidence points to a negative effect of GTI upon CO_2 emissions in the long and short term. So, it is hypothesized that:

H_1: *GTI negatively impacts CO_2 emission rates in OECD countries.*

2.2 Institutional quality and emitted CO_2

The relationship between institutional quality and CO_2 emissions is complex and multifaceted, and researchers have increasingly considered this relationship in published work this research area. An effective institutional framework with anti-corruption enhancement can improve environmental conditions (Ibrahiem & Hanafy, 2020; Zhan et al., 2023) by promoting measures for environmental protection and reducing CO_2 emissions while improving the quality of the environment (Teng et al., 2022). IQ is recognized to have had a considerable positive effect in reducing corruption, especially in developing countries (Kumar et al., 2021). Nevertheless, little research has investigated its environmental impact and consequences (Egbetokun et al., 2020). Ebaidalla's (2023) research provides a comprehensive examination of how indirect taxes impact CO_2 emissions, with a special focus on institutional quality within this dynamic. Utilizing the Government Revenue Dataset (2021) and advanced panel data approaches, the author suggests that indirect taxes can negatively and significantly influence CO_2 emissions in a global sample. A nuanced exploration further differentiates between developing and developed countries, suggesting that the effectiveness of indirect taxes on emitted CO_2 can be reduced at higher levels of tax saturation in advanced economies. Additionally, Dahmani (2023) underscores institutional quality's amplifying influence on the efficacy of indirect taxes for reducing emissions, providing a valuable contribution to the discourse on environmental tax policy and its intersection with institutional factors. Xaisongkham and Liu (2022) offer an innovative perspective on the link between institutional quality, employment distribution across sectors, and environmental degradation in developing nations. Employing balanced panel data methodology and harnessing a 2-step SYS-GMM estimator technique, these authors reinforce the environmental Kuznets curve (EKC) hypothesis while shedding light on the differential impacts agricultural, industrial and service-sector employment on CO_2 emissions. This study considers simultaneous short and long-run impacts, finding a pivotal impact of effective institutions for combating environmental degradation. Similarly, Ahmad et al. (2023) study associations linking employment, openness of trade, institutional quality and emitted CO_2 through a panel ARDL approach, covering the top ten CO_2-emitting countries over nearly two decades. This study stands out for its critical assessment of the assumption that institutional quality is universally beneficial for environmental outcomes. The findings suggest that while strong institutional quality can stimulate trade and economic growth, CO_2 emissions can also increase, thus calling for a nuanced understanding of these interconnections. Khan et al. (2023) investigate effects of urbanization and institutional quality on quality of the environment within Belt and Road Initiative nations. Their approach, utilizing the two-step generalized method of moments, reveals a highly complex urbanization-environmental quality nexus, where urbanization initially contributes to higher CO_2 emissions but may eventually lead to reductions after surpassing a certain threshold. In addition, the authors find a transformative role for government effectiveness in steering urbanization toward environmental sustainability. Ullah et al. (2023) offer a regional view by examining areas where institutional factors like corruption control play a significant role in shaping the nexus linking economic growth and CO_2 emissions. Using the ARDL estimation technique, this study offers new insight into the moderating influence of corruption upon environmental quality. The preceding discussion forms the basis for the second hypothesis:

H_2: *IQ delimits CO_2 emissions.*

2.1.3 Institutional quality, green technology innovation, and CO_2 emissions

Evidence strongly supports the view that high-quality institutions are crucial for fostering an environment that encourages development and adoption of green technology (Zhang et al., 2023). As discussed below, the fostering of green technological advances has the potential to drive substantial reductions in CO_2 emissions, and the efficacy of such innovations is often contingent upon the vigor and integrity of the institutions responsible for their oversight and regulation (Gu et al., 2023). The synergy between these elements exerts a profound influence on the natural environment, shaping policy agendas and steering the trajectory of technological progress for sustainability. In previous studies, it is suggested that the association between technological innovation and the quality of the environment exhibits considerable variation across different countries, which confirms the extensive influence of other factors, including economic development levels, rigor of environmental regulations, and the integration of renewable energy systems (Jaffe et al., 2003; Tao et al., 2023). Such heterogeneity necessitates an in-depth exploration of the specific conditions under which green technological innovation can create a meaningful positive influence on preservation of environmental quality, which is the main objective of this study. Sethi et al.'s (2023) study focuses on the connections linking green finance, green technology innovation, and institutional quality within the developing economy context. The research presents a compelling case for green finance and technology innovation as important factors in CO_2 emissions reduction while highlighting the critical influence of institutional quality in this process. Furthermore, the study examines the moderating effects of these variables, offering a nuanced view of their interactions and the policy measures necessary to stimulate investment and innovation related to green energy. Zaman and Yu (2023) shift the geographical focus to the G7 countries, analyzing the effects of developing infrastructure, technology innovation, and institutional quality on the quality of the environment. Using a cross-sectional autoregressive distributed lags (CS-ARDL) model, the research provides robust evidence of the dual character of technological advances and economics as related to outcomes for the environment. It becomes evident that while factors such as foreign direct investment and institutional quality can enhance environmental quality, other aspects of infrastructure development may exacerbate CO_2 emissions. These contradictions underscore the complexity of the environmental sustainability challenge within the context of economically advanced nations. Existing accounts identify a level of interdependence between GTI, IQ, and CO_2 emissions in different contexts and circumstances. However, they fail to provide a clear picture of the tendencies within this interrelationship, which constitutes a serious weakness across most previous work. In view of this, the present research adopted an asymmetric approach in order to identify and investigate this impact over a short and long period in the OECD context, as characterized by a high level of technological innovation and a very restricted number of research works in this field:

H_3: *An asymmetric effect of IQ and GTI on CO_2 emissions exists*

3. Empirical Methodology

This research investigates the effect of green technology innovation and institutional quality on carbon dioxide emissions for 35 OECD nations for the period 1995-2020. The basic equation applied is as follows (Eq. (1)):

$$Ln(CO2)_{i,t} = \alpha_i + \beta_1 Ln(GDP)_{i,t} + \beta_{21} Ln(GDP)^2{}_{i,t} + \beta_3 Ln(EI)_{i,t} + \beta_4 Ln(URB)_{i,t} + \beta_5 IQ_{i,t} + \beta_6 TI_{i,t} + \varepsilon_{i,t} \quad (1)$$

where carbon dioxide emissions (CO_2) depend on GDP per capita (GDP), GDP per capita square (powered), Energy Intensity (EI), Urbanization rate (URB), Quality of Institutions (IQ), and Green Technological Innovation (GTI). α_i indicates the fixed country effect and $\varepsilon_{i,t}$ denotes an error term with the assumption of independent and normal distribution. In this study, the six dimensions of governance as presented by the Worldwide Governance Indicators (WGI) dataset are used. **Table 1** details definitions for the different variables used, as well as their sources:

Table 1
Variables applied for analysis

Variables	Abbreviations	Description	Units	Data source
Environmental degradation	**CO2**	Production-based emissions of carbon dioxide (in MMtonnes)	MMtonnes	EIA
Urbanization level	**URB**	Urban population (% total population)	%	World Bank data
Economic activity	**GDP**	GDP per capita	Constant 2015 US$	World Bank data
Energy intensity	**EI**	Measured as energy consumption per GDP	in Btu/2015$ GDP	EIA
Technological innovation related to environment	**TI**	Number of technological patents related to environment	Number	OECD
Quality of institutions:	**QI**			
Corruption	**CORR**	Control of corruption	Scored between -2.5	World Bank data:
Voice and Accountability	**VOICE**	Perceptions of: how far the nation's citizenry can participate in choosing governments; freedom of expression, freedom to associate; and freedom of the media.	Score from a range of -2.5 (low participation) to +2.5 (high participation)	World Bank data: Worldwide Governance Indicators
Political Stability and Ab-	**STAB**	Perceptions of the probability of government desta-	Score from a range	World Bank data:
Government Effectiveness	**GE**	Perceptions regarding public services quality civil service quality and extent of political independence, and quality in formulating and implementing policy. the credibility of the government's commitment to such policies.	Score from a range of -2.5 (weak Government Effectiveness) to +2.5 (strong Government Effec-	World Bank data: Worldwide Governance Indicators
Regulatory Quality	**RQ**	Perceptions of the ability of the government to for-	Score for a range of	World Bank data:
Rule of Law	**RL**	Perceived degree of confidence of agents in and degree to which they follow societal rules, , especially including contract enforcement quality, property rights, courts and police, in addition to likelihood	Score for a range of -2.5 (weak Rule of law) to +2.5 (strong Rule Quality)	World Bank data: Worldwide Governance Indicators

In line with empirical work, two models are estimated using modelling based on ARDL methodology, estimated by the PMG method proposed by Pesaran and Smith (1995) and Pesaran et al. (1999). This methodology is based on an ARDL (distributed lag autoregressive) model of the following order (p,q…….q), which is estimated using the PMG technique. The main equation can be expressed as follows,

$$Ln(CO2)_{it} = \sum_{j=1}^{p_i} \Psi_{1ij} Ln(CO2)_{it-j} + \sum_{j=0}^{q} \delta_{1ij} X'_{it-j} + \alpha_{1i} + \varepsilon_{1it} \quad (2)$$

in which i=1, 2, …, N , T=1, 2, …, T and N is the number of cross-section units; T denotes number of years and X_{it} is a vector of regressors for cross-section unit i. α_{1i} represents individual fixed effects, while Ψ_{1ij}, j = 1, . . . , p and δ_{1ij}, j = 1, 2 . . ., q represent scalar variables. The PMG estimator utilizes ARDL panel modelling, presented as an error-corrected model as follows,

$$\Delta Ln(CO2)_{it} = \eta_i + \gamma_{1i} Ln(CO2)_{i,t-1} + \beta_{1i}' X_{i,t} + \sum_{j=1}^{p-1} \Psi^*_{1ij} \Delta Ln(CO2)_{it-j} + \sum_{j=0}^{q-1} \delta^*_{1ij} \Delta X'_{it-j} + \alpha_{1i} + \varepsilon_{1it} \quad (3)$$

with β_{1i}' representing the vector of long-term effects of the various variables upon CO_2 emissions, while Ψ^*_{1ij} and δ^*_{1ij} represent the coefficients of the short-term dynamics and ε_{1it} refers to error terms. According to Shin et al. (2014), non-linear modeling includes cumulative positive and negative variations in explanatory variables, formulated here as follows,

$$\Delta Ln(CO2)_{it} = \eta_i + \gamma_{1i} Ln(CO2)_{i,t-1} + \beta_{1i}^{+\prime} X^{+}_{i,t} + \beta_{1i}^{-\prime} X^{-}_{i,t} + \sum_{j=1}^{p-1} \Psi^*_{1ij} \Delta Ln(CO2)_{it-j} + \sum_{j=0}^{q-1} \delta^{*+}_{1ij} \Delta X'^{+}_{it-j} + \sum_{j=0}^{q-1} \delta^{-*}_{1ij} \Delta X'^{-}_{it-j} + \alpha_{1i} + \varepsilon_{1it} \quad (4)$$

Here, $X^{+}_{i,t}$ refers to a positive partial sum that detects upward fluctuations of X, $X^{-}_{i,t}$ is a negative partial sum that detects downward fluctuations of X, and $\beta_{1i}^{+\prime}$ and $\beta_{1i}^{-\prime}$ evaluate long-term asymmetric impact from CO_2 on positive and negative fluctuations on X, respectively. The coefficients $\delta^{*}{}_{1i}^{+\prime}$ $\delta^{*}{}_{1i}^{-\prime}$ evaluate the short-term asymmetric impact of CO_2 on positive and negative fluctuations on X, respectively. In this study, the presence of asymmetric impacts of IQ and TIE on CO_2 emissions is evaluated. Thus, the following variable is introduced:

$$QI^{+}_{i,t} = \sum_{j=1}^{t} \Delta QI^{+}_{i,j} = \sum_{j=1}^{t} \max(\Delta QI^{+}_{i,j}, 0) \quad (5)$$

$$TI^{+}_{i,t} = \sum_{j=1}^{t} \Delta TI^{+}_{i,j} = \sum_{j=1}^{t} \max(\Delta TI^{+}_{i,j}, 0) \quad (6)$$

$$QI^{-}_{i,t} = \sum_{j=1}^{t} \Delta QI^{-}_{i,j} = \sum_{j=1}^{t} \min(\Delta QI^{-}_{i,j}, 0) \quad (7)$$

$$TI^{-}_{i,t} = \sum_{j=1}^{t} \Delta TI^{-}_{i,j} = \sum_{j=1}^{t} \min(\Delta TI^{-}_{i,j}, 0) \quad (8)$$

where:

QI^+ and QI^- denote positive and negative components within the quality of the institution, respectively; and
TI^+ and TI^- denote positive and negative components of technological innovation relevant to the environment.

4. Empirical Results

4.1 Descriptive Statistics

Table 2 presents the results for the descriptive statistics. Based upon these results, the STAB variable seems to be the most volatile, with the highest coefficient of variation (0.94). Proportionally, URB seems to be the least volatile variable, with a very low coefficient of variation (0.034). The "Skewness" asymmetry coefficient shows that all variables have a level close to zero except for the STAB and VOICE variables. The results show that certain variables display a kurtosis value lower than 3, pointing to platykurtic values, with a lower density of distribution near to the mean. Variables which have values over 3 are leptokurtic, with greater density near the mean.

Table 2
The summary of descriptive statistics

	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Coefficient of variation
LN_CO2	4.5587	4.1657	8.7021	1.4681	1.5741	0.2548	2.7508	0.3453
LN_URB	4.3036	4.3320	4.5854	3.9244	0.1498	-0.5729	2.6853	0.0348
LN_EI	8.3801	8.3470	9.4161	7.3533	0.3540	0.3087	2.8810	0.0422
LN_GDP	10.1093	10.3618	11.6300	8.2717	0.7738	-0.3348	2.1544	0.0765
LN_PATENT	2.2806	2.3125	3.5124	-0.0834	0.4331	-0.6336	5.3554	0.1899
CORR	1.1817	1.3260	2.4591	-0.9329	0.8306	-0.3765	1.9901	0.7029
GOV	1.2055	1.3580	2.3464	-0.4879	0.6389	-0.4761	2.1531	0.5300
LAW	1.1729	1.3194	2.1248	-0.9250	0.6936	-0.8733	3.0250	0.5913
REG	1.2147	1.2618	2.0866	-0.1682	0.4981	-0.5569	2.5196	0.4101
STAB	0.7310	0.9025	1.7587	-2.3760	0.6909	-1.7981	6.7081	0.9451
VOICE	1.1197	1.1783	1.8010	-0.8511	0.4660	-1.6536	5.9457	0.4162

4.2 Panel unit root test results

The use of the PANEL-ARDL methodology means that every variable is not required to be I(1). This approach is suitable in cases where variables are a mix of I(0) and I(1). It must be ensured that none of the variables are I(2). The tests applied in the current work are Levin, Lin and Chu's (2002) LLC test, and Im et al.'s (1997) test (IPS). The results reported in Table 3 show that VOICE, GDP, TI, GOV and LAW are all stationary at level I(0). On the other hand, CO2, URB, EI, CORR, REG and STAB, all appear to be stationary in first difference (I (1)). Since no variable is I(2), it is possible to proceed to estimate the PANEL-ARDL model

Table 3
Panel unit root test

	At level				At first difference			
	With constant		With constant and trend		With constant		With constant and trend	
	LLC	*IPS*	*LLC*	*IPS*	*LLC*	*IPS*	*LLC*	*IPS*
LN_CO2	-2.73 (0.00)	0.71 (0.76)	-2.93 (0.00)	-1.35 (0.087)	-23.76 (0.00)	-23.64 (0.00)	-18.83 (0.00)	-19.73 (0.00)
LN_URB	-4.19 (0.00)	0.57 (0.71)	-1.01 (0.13)	-0.59 (0.27)	-2.63 (0.00)	-2.99 (0.00)	-24.69 (0.00)	-12.11 (0.00)
LN_EI	-0.50 (0.30)	6.55 (1.00)	-4.72 (0.00)	-3.64 (0.00)	-18.50 (0.00)	-20.15 (0.00)	-14.22 (0.00)	-17.42 (0.00)
LN_GDP	-8.25 (0.00)	-2.36 (0.00)	-3.23 (0.00)	-1.92 (0.02)	-	-	-	-
	-5.03 (0.00)	-6.63 (0.00)	-2.66 (0.00)	-5.97 (0.00)	-	-	-	-
CORR	-0.57 (0.28)	-0.76 (0.22)	-1.29 (0.09)	-1.62 (0.052)	-19.97 (0.00)	-18.83 (00.00)	-14.21 (0.00)	-14.19 (0.00)
GOV	-2.214 (0.00)	-2.11 (0.017)	-2.91 (0.00)	-4.59 (0.00)	-	-	-	-
LAW	-3.62 (0.00)	-3.74 (0.00)	-1.91 (0.027)	-2.56 (0.00)	-	-	-	-
REG	-0.60 (0.27)	-1.71 (0.04)	-0.079 (0.21)	-4.21 (0.00)	-14.28 (0.00)	-17.58 (0.00)	-19.82 (0.00)	-13.75 (0.00)
STAB	-1.20 (0.11)	-1.31 (0.09)	-1.64 (0.05)	-3.49 (0.00)	-18.94 (0.00)	-18.83 (0.00)	-14.81 (0.00)	-15.08 (0.00)
VOICE	-3.35 (0.00)	-4.85 (0.00)	-3.61 (0.00)	-4.79 (0.00)	-	-	-	-

Values in () are probabilities

4.3 Nonlinear Panel ARDL Results

Table 4 shows that PMG is preferable to MG. The Hausman test accepts the null hypothesis of homogeneity restriction upon long-term regressions, indicating that PMG has greater effectiveness compared to the MG estimator. The results of the non-linear model show long-term validation of EKC. Indeed, GDP and GDP_SQ show statistically significant positive effects. However, the EKC hypothesis does not appear to be valid for the short term. The rate of urbanization exhibits positive and statistically significant effects. Rapid industrialization will lead to greater levels of urbanization, urban employment, and industrialization in OECD countries by increasing their CO_2 emissions. However, the long-term effect remains insignificant. The impact of environmental technological innovation on carbon dioxide emissions appears be negative, with statistical significance. The long-term effect of negative fluctuations appears to be greater (in absolute terms) than positive fluctuations. The Wald asymmetry test indicates that there is an asymmetric effect from the TI variable on CO_2 emissions (p-value lower than 5%). The short-term asymmetry effect is valid only at a level of significance of 10%. Regarding the six institutional quality dimensions, the findings show the existence of an asymmetric effect for all measures except for the LAW variable. In contrast, the Wald for asymmetry test shows no short-term asymmetry effect for the six IQ measures. Another important result suggests that negative fluctuations in corruption control seem to have the most important effect on CO_2 emissions (-0.09). The same applies in the short term, where positive fluctuations seem to have the greatest negative effects in absolute terms (-0.02).

Table 4
Long-run Non-linear impact of TI and QI on CO_2 emissions for 35 OECD countries

	TI	CORR	GOV	STAB	LAW	REG	VOICE
Ln_URB	0.722 (0.610)	-4.402*** (0.454)	-0.430** (0.207)	0.360** (0.164)	0.0833 (0.228)	-0.895*** (0.182)	-0.772*** (0.211)
Ln_GDP	-0.119 (2.352)	3.382*** (0.561)	3.187*** (0.546)	4.824*** (0.830)	1.746*** (0.478)	1.980*** (0.499)	0.772* (0.454)
Ln_GDP_SQ	0.00384 (0.111)	-0.0942*** (0.0277)	-0.0887*** (0.0277)	-0.199*** (0.0436)	-0.0198 (0.0235)	-0.0381 (0.0247)	-0.103*** (0.0233)
Ln_EI	0.672*** (0.0897)	0.749*** (0.0366)	1.423*** (0.0529)	0.965*** (0.0588)	1.359*** (0.0422)	1.180*** (0.0383)	1.208*** (0.0439)
TI+	-0.0164*** (0.00151)						
TI-	-0.0449*** (0.0102)						
QI+		-0.0527*** (0.0140)	0.00603 (0.0234)	-0.0857*** (0.0182)	-0.00036*** (0.000115)	-0.0238* (0.0137)	-0.0136*** (0.00267)
QI-		-0.0917*** (0.0285)	-0.0379** (0.0164)	-0.00438 (0.0186)	-0.0822*** (0.0271)	-0.0971*** (0.0159)	0.0126*** (0.00200)
Testing for Asymmetric Nonlinear Long-run	15.53(0.00)	8.94(0.00)	4.50(0.03)	23.31(0.00)	2.46(0.11)	96.56(0.00)	93.13(0.00)

***, ** and * denote that results are statistically significant respectively at 1%, 5% and 10%, or *p-value<0.10; **p-value<0.05; and ***p-value<0.01. Testing for Asymmetric Nonlinear Short-run: p-value in parentheses H0 indicate rejection of the null hypothesis, and asymmetry is present, Ha indicates non-rejection of the Null hypothesis, or absence of confirmation of asymmetry. *Source: Authors' computations*

Table 5
Short-run Non-linear effect of TI and QI on CO2 emissions in 35 OECD countries

	TI	CORR	GOV	STAB	LAW	REG	VOICE
Constant	-0.270** (0.119)	-1.508*** (0.306)	-8.919*** (1.415)	-9.138*** (1.482)	-11.97*** (1.318)	-5.361*** (0.909)	-0.0292 (0.202)
ECM(t-1)	-0.0950** (0.0438)	-0.265*** (0.0515)	-0.317*** (0.0499)	-0.296*** (0.0471)	-0.474*** (0.0537)	-0.347*** (0.0593)	-0.329*** (0.0467)
D.Ln_URB	3.213 (11.30)	1.905 (9.000)	-1.120 (3.166)	-4.285 (6.480)	4.489 (5.960)	-9.726 (7.408)	-5.047 (3.909)
D.Ln_GDP	7.957 (14.17)	22.86* (12.32)	6.484 (10.26)	-7.665 (14.50)	16.50 (11.56)	2.685 (10.22)	1.219 (6.973)
D.Ln_GDP_SQ	-0.353 (0.688)	-1.034* (0.579)	-0.256 (0.483)	0.443 (0.678)	-0.758 (0.542)	-0.0864 (0.488)	0.0110 (0.330)
D.Ln_EI	0.796*** (0.100)	0.721*** (0.0860)	0.505*** (0.0959)	0.616*** (0.102)	0.372*** (0.0903)	0.544*** (0.0872)	0.538*** (0.0790)
TI+	-0.00325* (0.00191)						
TI-	0.0299* (0.0161)						
QI+		-0.0200* (0.0103)	-0.00995 (0.0211)	0.0336 (0.0458)	-0.00792 (0.0476)	-0.00709 (0.0330)	0.0108** (0.0491)
QI-		-0.0340 (0.0644)	-0.0525 (0.0344)	0.00112 (0.0146)	-0.0370 (0.0519)	-0.00327 (0.0397)	-0.00526 (0.0509)
Wald statistic Testing for Asymmetric Nonlinear Short-run	2.80(0.09)	1.42(0.23)	0.36(0.54)	0.04(0.83)	0.00(0.96)	0.01(0.91)	3.33(0.06)
PMG versus MG	0.25	0.52	0.53	0.18	0.14	0.63	0.88
Observations	804	804	804	804	804	804	804

***, ** and * denote that results are statistically significant respectively at 1%, 5% and 10%, or *p-value<0.10; **p-value<0.05; and ***p-value<0.01. Testing for Asymmetric Nonlinear Short-run: p-value in parentheses H0 indicate rejection of the null hypothesis, and asymmetry is present, Ha indicates non-rejection of the Null hypothesis, or absence of confirmation of asymmetry. *Source: Authors' computations*

5. Discussion

This extensive study offers robust findings to support long-term validation of the environmental Kuznets curve hypothesis, which postulates that as an economy develops, environmental degradation initially rises, continuing until a certain point of per capita income, after which it begins to decrease. In line with Udeagha et al. (2023), the findings indicate that while per capita GDP shows a significant positive effect upon CO_2 emissions, suggesting increased pollution with early economic development, the squared term of per capita GDP (GDP_SQ) demonstrates a negative effect. This inflection point indicates that beyond a certain level of economic prosperity, nations tend to adopt cleaner technology along with stricter environmental regulations, thus reducing emissions. However, it is critical to note the contrasting short-term results that fail to confirm the EKC hypothesis. The findings focus also on the relationship of urbanization, industrialization with environmental degradation. Urbanization is found to correlate positively with CO_2 emissions, suggesting that industrial expansion and increased urban employment may lead to higher pollution levels, as observed in OECD nations. This accords with Hanif et al.'s (2022) findings. However, the long-term implications of urbanization on CO_2 emissions appear to be less significant. Based on the results, GTI emerges as a pivotal factor for environmental sustainability, being negatively and significantly associated with CO_2 emissions, implying that advances in green technology might offer a powerful counterbalance to environmental impacts of industrial growth. This finding correlates with the insights provided by Udeagha et al. (2023). The research further confirms an asymmetric effect of GTI, which means that the environmental impact of negative technological shocks is more pronounced than the positive impact of technological improvements. The Wald asymmetry test sustains this asymmetry, by emphasizing the critical importance of maintaining and enhancing green technological innovation to mitigate environmental damage.

The multidimensionality of institutional quality is also reflected in this study through the definition of asymmetric impacts across its various dimensions, except for the law (LAW) dimension. The analysis suggests that enhancements or declines in the quality of institutions: including factors such as corruption control, accountability, and government effectiveness; exert different levels of influence on CO_2 emissions. While short-term asymmetries are not evident, according to the Wald test, long-term influence from these institutional factors upon environmental quality is more important. This point is in line with Ali et al. (2019) and Zhang et al. (2022). It can be concluded here that institutional quality acts as a foundational pillar in combating environmental pollution by reinforcing strong governance and regulatory frameworks. The most interesting result from this research is the significant and fluctuating impact of corruption control on CO_2 emissions. The data reveals that a decrease in corruption correlates with a notable reduction in emissions, with negative fluctuations in corruption control exhibiting a coefficient of (-0.09) in the short term. The importance of this relationship remains across short- and long-term models. Positive changes in the long term in corruption control also show a substantial negative effect on emissions, albeit to a lesser degree (-0.02). This empirical evidence underscores the importance of effective governance and anti-corruption measures as essential components of a strategy aimed at environmental sustainability, as widely supported by Ragmoun (2023). In synthesizing these research findings, it is clear that the intricate dynamics between economic growth, urbanization, green technological innovation, and institutional quality are significant in shaping environmental outcomes. While the EKC hypothesis and theories of green growth find support in long-term impacts from economic development and technological innovation, additional research is warranted to fully understand the immediate impacts and the nuanced role of urbanization. Furthermore, the prominent influence of institutional quality, particularly in the realm of corruption control, points to the indispensable need for comprehensive institutional reforms to foster a sustainable environmental trajectory.

6. Conclusion, implications, and future research

In summary, the study's findings have reaffirmed the environmental Kuznets curve hypothesis for an OECD sample, highlighting a long-term, inverse U-shaped association linking economic development and environmental degradation, while underscoring the absence of such a relationship in the short term. A critical insight derived from non-linear autoregressive distributed techniques comes from the asymmetric effects of innovations in green technology on CO_2 emissions, with long-term effects being particularly pronounced. Specifically, the control of corruption emerges as a pivotal component of IQ in mitigating environmental degradation, suggesting that governance quality significantly influences the efficacy of green technologies in reducing CO_2emissions. This underscores a requirement for policy frameworks that concurrently foster GTI and strengthen institutional integrity, particularly in the realm of anti-corruption measures, to enhance environmental outcomes. The study's limitations include its temporal scope and the potential variability of GTI and IQ across different OECD countries, which might influence the generalizability of the results. Future research should explore the causal mechanisms underlying associations between GTI, IQ, and CO_2 emissions, and expand its scope to non-OECD countries for a broader understanding of these dynamics on a global scale.

Abbreviations

Green technology innovation: GTI
Institutional quality: IQ
Organization for Economic Co-operation and Development: OECD

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