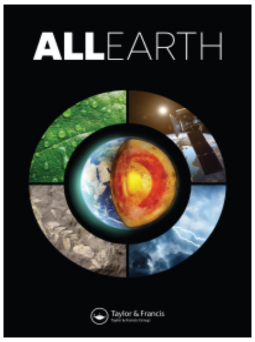

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RESEARCH ARTICLE

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Do green technological innovation, financial development, economic policy uncertainty, and institutional quality matter for environmental sustainability?

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ABSTRACT
Environmental sustainability is a pressing global concern that demands urgent attention from policymakers and researchers. The objective of our research is to investigate the influence of economic policy uncertainty (determined by the world uncertainty index) and financial development on carbon emissions, followed by green technological innovation, institutional quality, economic growth, foreign direct investment, energy consumption, and trade in Organization of Economic Co-operation and Development, for the period 2003–2019, to analyse the data, the second-generation econometric techniques are used. We applied the two-stage sequential techniques of the linear panel data model and generalised method of moments approach to tackle the endogeneity problem and report robust findings. The findings of the study revealed that economic policy uncertainty, financial development, economic growth, energy consumption, and trade decrease environmental quality by increasing CO_2 emissions, while green technological innovation and institutional quality increase environmental degradation by reducing CO_2 emissions. Our evidence-based study provides significant outcomes for green technological innovation and institutional quality conditioning's role in reducing carbon emissions in OECD economies.

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Economic policy uncertainty; financial development; green technology innovation; institutional quality; CO_2 emissions

1. Introduction

The global economy is confronted with two major challenges: climate change (carbon emissions) and world uncertainty. Apart from the COVID-19 pandemic outbreak, one of the major global issues today is the life-threatening impacts of climate change and global warming. CO_2 emissions (CO_2_Ems) are major contributing factors to increasing global warming and climate change, contributing to around three-quarters of total emissions (Danish et al. 2018). CO_2_Ems have received a lot of concentration in studies to evaluate pollution levels in the environment over the last few decades (Tiba & Omri, 2017). To avert the worst effects of climate change, the world must urgently decrease greenhouse gases (GHG), a significant source of climate change and global warming. CO_2 emissions must be reduced, making sustainable development challenging. The impacts of global climate change and environmental degradation are already observable in the increase in severe weather conditions, rising temperatures, intensified storms, melting glaciers, changing rainfall patterns, and rising ocean temperatures. Such changes significantly impact ecosystem processes and forest sustainability, decimated wildlife, and reduce the output of agriculture and human well-being (Pirgaip & Dinçergök, 2020). However, how this role is apportioned across countries, institutions, and individuals has long been controversial in international negotiations. Researchers conducted extensive studies on the elements that influence CO_2_Ems. As a result, various prior studies have called for the implementation of relevant policies and appropriate measures to maintain global environmental sustainability (I. Khan et al., 2021; Ma et al., 2021; Meo et al., 2020; Tan et al., 2021).

The fundamental goal of this research is to adhere to this framework by examining the mediating influence of GTI and IQT in the relationship between EPU, FDV, and CO_2_Ems in 35-OECD economies. Additionally, the author stated the study's key points, i.e. (a) Why OECD economies? (b) The nexus between EPU-CO_2_Ems and the relation between FDV-CO_2_Ems (c) The contemporary literature's research gap. (d) There is a moderation nexus between EPU*GTI and FDV*GTI on CO2_Ems and linkages between EPU*IQT and FDV*IQT on CO_2_Ems. These aspects are discussed and analysed in further depth below. There are several

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reasons why our research concentrates mainly on OECD nations. Therefore, it is crucial to comprehend the indicators affecting CO_2_Ems in OECD economies (Figure A1). However, previous studies have neglected the uncertainties in policies (economic policy and environmental policy), innovations, and institutional factors, which close the link to carbon emissions.

The selection of the Organization of Economic Co-operation and Development (OECD) as a case study is justified by several reasons related to carbon emissions, trade, political stability, economic growth, and renewable energy. Our study focuses on 35-OECD[1] economies; therefore, it is crucial to identify the dynamic factors of CO_2_Ems. The OECD nations share a common vision towards green growth strategies to enhance environmental quality to mitigate carbon emissions towards green society through green channels, green technology, green investment, and green financial development, and to reduce global temperature by less than2°C, after the signature of 196 countries in the Paris Climate Agreement (PCA) in November 2016. As per the EDGAR (Emission Database for global atmospheric research), since 1970, the OECD and developing nations have produced about 85% of global CO_2_Ems. OECD's carbon emissions were extremely high in 2007. According to the OECD (2019), the OECD economies are the major CO_2 emitters of 35% of total global emissions in 2019. Secondly, the OECD countries are major players in international trade. In 2019, the total merchandise trade of OECD countries was USD 48.3 trillion, which accounts for more than 60% of global merchandise trade. Therefore, analysing the relationship between economic policy uncertainty, financial development, and trade in the OECD countries can shed light on the potential trade-offs between economic growth and environmental sustainability. Thirdly, the OECD countries are generally characterised by political stability and institutional quality. The World Bank's Worldwide Governance Indicators (WGI) show that the OECD countries perform well in terms of political stability, voice and accountability, the rule of law, and control of corruption. This political stability and institutional quality can create an enabling environment for green technological innovation, which can contribute to reducing carbon emissions. Lastly, the OECD countries are at different stages of renewable energy development and energy consumption. By analysing the relationship between these factors and carbon emissions, we can identify the most effective policies for promoting the transition to a low-carbon economy.

However, after the global financial crisis (GFC) 2008–2009, emissions declined due to slow industrialisation, human and economic activities, and strengthened environmental policies. Due to lockdown policies, CO_2_Ems in OECD economies decreased during the COVID-19 epidemic, particularly in 2020–2021. However, carbon emissions have been observed and projected to rise again after the COVID-19 lockdown relaxation, especially in advanced countries where human activities and GHG emissions are set to increase again due to recent rises in emissions, such as cement production, deforestation, burning of fossil fuels, and coal and energy usage. However, the OECD nations are presently related to the research topic of the relationship between the economy and the environment because their energy usage level has slowly dropped over the previous few years. According to (OECD, 2021), the total OECD environmental quality improved by reducing CO_2 emissions from 8.69% to 7.64% between 2017 and 2020 (Figure 1). Canada, Australia, the United States, and Luxembourg emitted the most CO_2 per capita on average in the OECD in 2019, with 15.19%, 15.01%, 14.44%, and 14.62%, respectively. During the COVID-19 outbreak, OECD economies reduced CO_2 Ems. According to the most recent database, Australia reduced CO_2 emissions from 15.19% to 14.63% but remained the top-releasing CO_2 emitter economy in the OECD. Canada, the United States, and Luxembourg reduced CO_2_Ems by 13.77%, 12.98%, and 11.80%, respectively. While Columbia, Mexico, Sweden, and Portugal have the lowest average CO_2 emissions (Tones/per capita) in the OECD, with 1.42% and 3.00%, respectively (Figure 2). However, the world will need to do a lot more to save itself

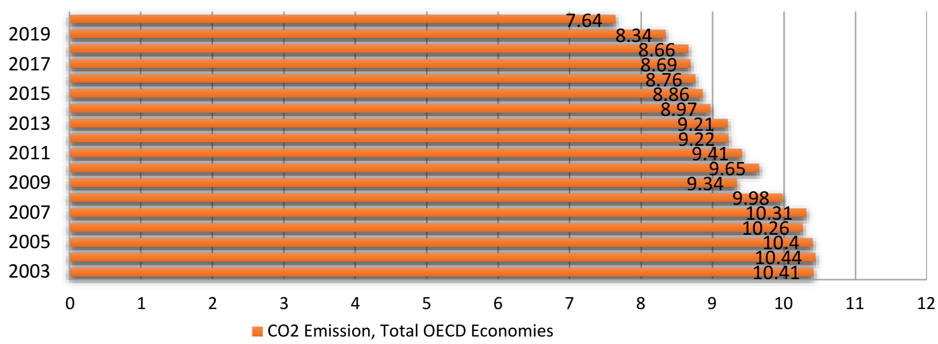

Figure 1. Share of the total OECD economies in their total CO_2_Ems.**Source**: Authors' calculations based on OECD database (2020)

from the existential threat of climate change and slowdown the further damages of global warming by reducing GHGs and human activity production emissions.

Second, our study aims to examine the relation of CO_2_Ems, and the level of EPU in OECD economies. Our study investigates the world uncertainty index[2] (WUI) as an indicator for EPU (Figure 3). Previous researchers used the EPU index (Baker et al., 2016), which covered just uncertainties related to economic policies such as (Fiscal, Monterey, and Trade), while it doesn't cover political events uncertainties. Another limitation of the EPU index is reliability and accuracy because the EPU index is not derived from a single foundation for different countries. WUI is better than EPU, which covers a country's economic and political events. (Ahir et al., 2019), developed WUI-index for 143 economies,[3] to overcome these limitations, it is calculated on the basis of country reports from the Economic Intelligence Unit (EIU). We employed WUI as a measurement indicator for EPU, and we followed the most recent studies, such as (Adams et al., 2020; Anser, Syed, et al., 2021), which evaluated the influence of EPU-WUI on CO_2_Emis. Anser, Apergis, et al. (2021) and Q. Wang et al. (2020), explored the positive nexus EPU-WUI on CO_2_Ems. (Adams et al., 2020) the WUI was used to examine the EPU, CO_2_Ems, and energy usage have a long-run relationship. Researchers, academics, and policymakers have shown an intense interest in global uncertainties that have been increasing, particularly after the global financial crisis (GFC) 2007–2009. These uncertainties are associated with economic policies (Monterey, fiscal, and trade) policies, which may originate from a recession, government uncertainty policies about (economic and environmental activities) or the collapse of large financial or non-financial institutions, which an impact on the economic environment in wherein business organisation operates (Abbasi & Adedoyin, 2021; Adams et al., 2020; Shabir et al., 2021). The literature has revealed that EPU-WUI waves impact environmental quality through different channels. (i) EPU stimulates manufacturers to use environmentally adverse production processes,

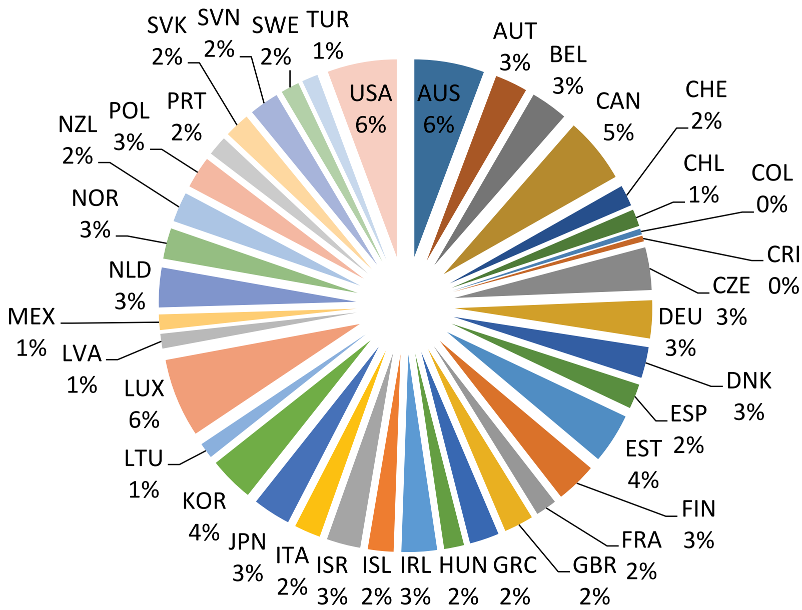

Figure 2. Regional shares of OECD economies, CO_2_Ems.**Source**: Authors' calculations based on the OECD database (2020)

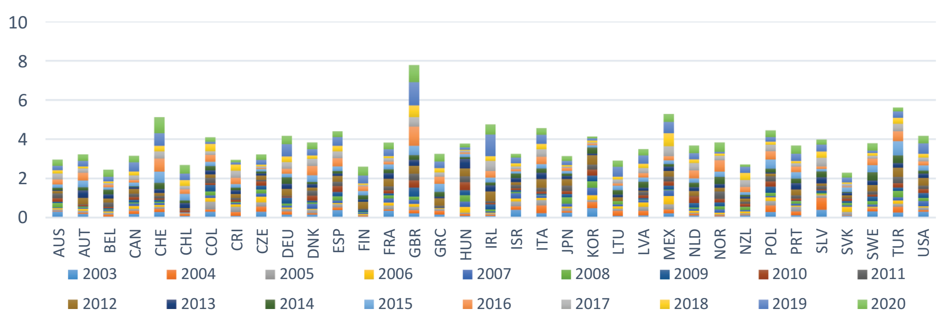

Figure 3. World uncertainty index (WUI) in the OECD economies.**Source**: Authors' own elaborations

leading to increased CO_2 emissions. (ii) Increases in the EPU sometimes result in reductions in innovation, R&D, and sustainable energy consumption, which may increase CO_2_Ems. (iii) The increasing EPU and its negative consequences for real economic activity may serve to deflect the attention of the government away from ecological concerns. This could undermine the government's and businesses' attempts to reduce CO_2 emission distorting local environmental policy to some extent. We argue that a rise in aggregate uncertainty is attributable to a rise in EPU (i.e. uncertainty about environmental policies) in OECD economies. As a result, the nexus between EPU-CO_2_Ems should be investigated to develop strategies and policies to address environmental degradation.

There are relatively few studies that have looked into the relationship between EPU and CO_2_ Ems. in the OECD economies and also at the global level perspective, for instance, (Q. Wang et al., 2020; Syed & Bouri, 2022), US level-sector data; (Abbasi & Adedoyin, 2021; Amin & Dogan, 2021; Lei et al., 2021), EPU-CO_2_Ems nexus for China; (Adedoyin & Zakari, 2020) for the UK; (Pirgaip & Dinçergök, 2020), and (Adams et al., 2020) relationship for G7 nations; (Adams et al., 2020), 10-resource reach economies, (Atsu & Adams, 2021) for BRICS economies; (Anser, Apergis, et al., 2021), top ten CO_2_Ems countries; (Shabir et al., 2021), 24-developed and developing economies; (Zakari et al., 2021), 22-OECD economies. There are limited studies on the nexus of EPU-CO_2_Emis. So, therefore, the present research attempt, to the best of our knowledge, addresses this gap by investigating and exploring EPU as a proxy for WUI and analysing the effect of EPU-WUI on CO_2_Ems in OECD countries.

Third, various researchers have recently attempted to investigate the relationship between environmental quality and other factors. This has always been a hot topic among ecologists who study the association between FDV and environmental quality. However, these studies ignore the role of EPU, FDV, and CO_2_Ems nexus. FDV stimulates financial operations, which stimulates economic activity, leading to greater demand for energy, and the relationship between the FDV and energy demand affects energy- and finance-related policy (Sadorsky, 2011). (Grossman & Krueger, 1995) CO_2_Ems are intimately associated with economic activity and fossil fuel use. However, according (Zhang, 2011), emissions in a country are dependent on their income level and FDV. According to (Antonakakis et al., 2017) CO_2_Ems rise in line with growth in income (GDP) and energy usage, respectively. Financial resources can boost economic growth but have a negative effect on the sustainable environment(Saud et al., 2020).

In several ways, financial development can positively impact the environment. First, stock market development can assist listed firms in improving their financing channels, minimising their financing costs, decreasing operational risk, making new investments, and enhancing energy consumption and CO_2 emissions (Paramati et al., 2021). Second, the accessibility of such technologies at a reasonable cost encourages consumers to adopt more efficient energy sources while also increasing expenditures in environmentally sustainable projects (Tamazian & Rao, 2010). Thirdly, financial development has the potential to exacerbate environmental degradation by increasing FDI inflows. Eventually, a developed financial situation of a country may make it considerably easier for clients to buy durable consumer items, resulting in increased CO_2 _Ems (Ali et al., 2020). Numerous studies demonstrate clearly that the development of the financial industry leads to increased CO_2_Ems (Ali et al., 2020; Nasreen & Anwar, 2020).

The Financial Development Index (FDV) is composed of financial market and financial institutional sub-indices; we used the Index of FDV developed by the 'International Monetary Fund (IMF)' (see Table 1). Current studies have emphasised the importance of adopting FDV on CO_2_Ems proxies, as recommended by the IMF database (Bayar & Maxim, 2020). We think that this is the first study to use the FDV index for 35-

Table 1. Variables description, data source, and indicators abbreviations.

Variables	Abbreviation	Descriptions	Source
Dependent variables			
CO_2, Carbon Emission	CO_2_Ems	Million tones per person	OECD database, (2020)
Independent Indicators			
World Uncertainty Index (WUI)	EPU	Economic Intelligence Unit (EIU) reports.	(Ahir et al., 2019), http//www.worlduncertinityindex.com
Financial Development	FDV	Financial markets and financial institutions (depth, access, and efficiency), Index, developed by IMF	IMF - Database
Moderating Variables			
Green Technology Innovation	GTI	The total number of patent applications (non-resident and resident) in thousands	OECD database, (2020)-WDI
Institutional Quality	IQT	Institutional quality index	World Governance Indicator, WGI
Control dimensions			
Economic Growth	ECG	GDP per capita growth % annual	WDI
Foreign Direct Investment	FDI	FDI net inflows, % of GDP	WDI
Energy Consumption	ENC	Consumption of energy, equal to per capita kg oil	WDI
Trade	TRD	The volume of total trade, % GDP	WDI

Source: The author's elaborations.

OECD economies, which includes a wide range of measuring variables.

The available literature explored the moderation effects that may decrease CO_2 emissions; Researchers only challenged whether or not EPU and FDV are dependable with CO_2_Ems decrease to generate these conditions. As a result, there is a methodological gap that occurs, so the research investigated the relations of GTI, IQT and CO_2_Ems, and GTI*EPU, GTI*FDV, and IQT*EPU, IQT*FDV on CO_2 _Ems. Our study is similar to (I. Khan et al., 2021; Chaudhry et al., 2021). IQT assists in analysing a country's environmental status; if state governments properly execute environmental laws and regulations, the condition of the environment will automatically increase (Ahmed et al., 2021; Jianguo et al., 2022). Our analysis also studies the moderating effects of green technological innovation. Studies have revealed that GTI decreases environmental pollution.

There is evidence to support that GTI has a significant impact to increase environmental quality by decreasing CO_2 emissions (Cheng et al., 2021; Q. Wang et al., 2020; Shan et al., 2021). They emphasised the importance of patents in advancing current technology that results in CO_2 emission reductions. According to the empirical studies, our research anticipates that GTI and IQT will play moderating effects, such as (GTI*EPU, GTI*FDV on CO_2_Ems, and IQT*EPU, IQT*FDV on CO_2_Ems) and indicates the negative nexus via EPU and FDV on CO_2_Ems, which will enhance environmental quality and mitigates CO_2 emissions in OECD economies.

The study aims to contribute to the existing literature by addressing the following research questions:

(i) Does green technology lead to a more environmentally sustainable future?
(ii) How does economic policy uncertainty affect environmental sustainability efforts?
(iii) Can financial development be leveraged to support environmental sustainability initiatives?
(iv) What role does institutional quality play in promoting environmental sustainability?

Our research contributes to the existing body of knowledge in four ways. (i) The reason for this research is to look into the interaction between EPU, FDV, and CO_2_Ems, using comprehensive panel data from 35 OECD economies for the first time; the authors have not found any existing research on this nexus in the context of 35-OECD nations, compared to earlier studies, which either focused on a sole economy or a small numeral of preferred OECD economies, which could prejudice conclusions. (ii) The empirical research explored the relationships between EPU, FDV, and CO_2 _Ems in the 35-OECD context will help clarify the moderation impact of green technology innovation. Institutional quality factors behind the CO_2_Ems are of utmost significance to realise low-carbon economies. Our research expands the scope of our investigation to include the entire region, i.e. 35-OECD economies, which received relatively little attention. (iii) Previous research has produced inconsistent findings regarding explanatory and conditioning indicators of CO_2_Ems. We will develop a complete framework for policymakers, institutions, and other stakeholders to address these concerns to establish green growth societies, green technologies, environmental policies, procedures, and legislation to reduce CO_2 emissions. Therefore, the findings of this research will contribute to developing and analysing environmental policies that improve environmental quality while also reducing carbon emissions at the lowest possible cost under current regulations. (iv) The current research investigates the effects of EPU, FDV, GTI, and IQT on CO_2_Ems. Also, it uses other different control indicators, such as Energy usage, Economic growth, FDI, and trade, as a control dimension, for the 35-OECD economies, during the period 2003–2019. We employed a cross-sectional dependency analysis; cross-section Panel unit root techniques include cross-sectional augmented IPS-CIPS and Dicky-Fuller-CADF methodologies. We use co-integration (Westerlund, 2007) and causal methods Dumitrescus and Hurlin that counter CD and other possible issues in the panel data. Our research also applies the two-stage Sequential techniques of the linear panel data model (SELPDM) to deal with the issue of endogeneity, which is prominent in panel analysis are used to investigate the nexus between explanatory indicators and CO_2 _Ems; we also utilised the Two-Step (SYS-GMM) approach to examine the findings' robustness. The results demonstrate that EPU, FDV, ECG, ENC, and TRD boost CO_2_Ems, while GTI and IQT increase environmental quality by decreasing CO_2_Ems.

The study provides insights into the relationship between economic policy uncertainty, financial development, green technological innovation, institutional quality, and carbon emissions, but it does not directly address the practical implications for policy design and implementation. Policymakers should consider the specific context and goals of their countries when designing environmental policies. In terms of existing knowledge, there are still several gaps in our understanding of the complex interactions between environmental sustainability, financial development, and economic policy uncertainty. For example, more research is needed to explore the role of social and cultural factors in shaping attitudes and behaviours related to environmental protection. Additionally, the impact of climate change on various sectors of the economy, such as agriculture, forestry, and tourism, requires further investigation. Moreover, future research could investigate the potential heterogeneity of the relationship between environmental sustainability and financial development across different countries or regions. For instance, the impact of financial development and economic policy uncertainty on environmental sustainability may vary depending on the level of economic development, income inequality, and institutional quality of different countries. Finally, there is a need to develop more effective policy frameworks that balance environmental, economic, and social objectives and promote sustainable development.

This study's significance for the OECD lies in providing policymakers with robust empirical evidence that can guide the formulation and implementation of environmental policies aimed at promoting sustainable economic growth and reducing carbon emissions.

The rest of the article is arranged as follows: Section 2 outlines the literature review. Section 3 focuses on the methodology, including the data and analytical approach. Section 4 discusses the empirical results, followed by Section 5, concluding policy implications and recommendations.

2. Literature review

As mentioned briefly in the introduction part, the purpose of this article is to provide clarity on how economic policy uncertainty, financial development, technological innovation, institutions quality, and CO_2 emissions are interrelated. The literature review is split into four sections: EPU and CO_2_Ems, financial development and CO_2_Ems, green technological innovation and CO_2_Ems, and institutional quality and CO_2_Ems.

2.1. Economic policy uncertainty and CO_2 emissions, (EPU-CO_2_Ems)

After the 2007–2009 global financial crisis (GFC), the subject of policy-related economic uncertainty has been recognised as a dominant issue. The COVID-19 pandemic, the most recent source of economic policy uncertainty, have also raised global concerns, such as health, environmental, financial stability, financial development, economic complexity, investment, and renewable energy usage are all factors to consider (Ahmed, Can, et al., 2022; Baker et al., 2020; Z. Liu et al., 2020). EPU is described in the literature as the government's regulatory uncertainties, taxation, environmental, monetary, trade, and fiscal policies, which ultimately impact economic growth and the environment (Bhowmik, Syed, et al., 2022). In this context, we use WUI-world uncertainty index as a measurement for EPU developed by (Ahir et al., 2019). The results of EPU, measured by WUI, for instance, recent studies (Anser, Apergis, et al., 2021), EPU, measured by WUI, explore the relationship between EPU-CO_2 nexus; findings show that in the short run, WUI mitigates CO_2 _Ems, while in the long run, WUI escalates CO_2_Ems. According to (Adams et al., 2020), the study reveals that WUI escalates CO_2_Ems. Similarly, (Q. Wang et al., 2020) also investigate that EPU-WUI enhances the CO_2_Ems in the U.S.A.

Several investigations have been conducted to investigate the relationships geopolitical risk, EPU and CO_2 Ems in different regions (Anser, Apergis, et al., 2021; S. M. Hashmi et al., 2022; Syed et al., 2022). Syed et al. (2022) investigated the role of geopolitical risk and EPU for CO_2_Ems in BRICST economies for domestic and cross-country economic uncertainty spillovers. (Adedoyin & Zakari, 2020) find that EPU mitigates CO_2_Ems in the short run, whereas it boosts them in the long run in the UK. (Abbasi & Adedoyin, 2021) and (Y. Liu & Zhang, 2021) study examines the impact of EPU on CO_2_Ems in regional analysis in China; EPU has an insignificant impact on CO_2_Ems, due to firms' sustainability policies in China. (Amin & Dogan, 2021) investigate in the China context, the association of EPU and energy environment nexus, and the results show that increasing EPU induces an increase in CO_2_Ems's volume in China. (Yu et al., 2021), observe the connection between EPU and CO_2_Ems in the China region, and the result revealed that EPU has a positive and significant on CO_2_Ems. The causality relations have been defined between different economies within the G7, report that EPU escalates CO_2_Ems (Pirgaip & Dinçergök, 2020). According to the study (Ulucak & Khan, 2020), EPU enhances energy consumption, boosting CO_2_Ems in the US. Shabir et al., (2021) investigate the 24 developed and developing economies' relationship between EPU and environmental quality, that economic policy uncertainty escalates CO_2_Ems, and mitigates environmental quality. According to (Atsu & Adams, 2021) and (Zhang et al., 2021), the study reveals that EPU contributes to CO_2_Ems, and creates an unhealthy environment in BRICS economies. Zakari et al., (2021) the result showed that energy consumption and EPU have positive impact on CO_2_Ems in the long run for 22-OECD economies.

Given the above explanation, even though some dimensions of EPU remain unknown, there has been minimal study on the effective outcome of the EPU-CO2 Ems nexus. The current study has not yet been investigated WUI as a proxy for EPU on CO_2_Ems in OECD economies. To fill this gap, the current research is devoted to analysing the effect of EPU as a measure of WUI on CO_2_Ems.

2.2. Financial development and CO_2 emission, (FDV, and CO_2_Ems)

The relationship between FDV and a sustainable environment is one of the rising concerns in the recent field of research (Ahmed et al., 2021). To achieve economic growth, developed financial sectors are essential (Ali et al., 2023). It is found that countries with well-equipped and well-developed financial markets have cleaner environments than economies with less effective financial systems (Bu & Ali, 2022). According to Zhang et al. (2021), financial development assists in expending renewable energy, having eco-friendly impacts and is likely to decline emission as compared to traditional energy sources. In contrast, some studies argued that financial development increases CO_2_Ems because when financial institutions are solid and well-organised, the process of acquiring loans becomes more accessible and quicker; therefore, consumers purchase things that produce more CO_2_Ems, such as investing in new projects, provide to loans to residents, buying to luxury items such as automobiles, generator, air conditioners (Sadorsky, 2011). In the literature, our outcomes revealed by several studies have examined the positive relations of FDV on CO_2_Ems in previous literature (Ali et al., 2020; Jianguo et al., 2022). The findings identified the causes for the financial sector's positive impact on CO_2_Ems. First, stock market development can encourage listed firms in expanding their financing channels, decrease their financing costs, reduce operational risk, make new investments, and boost energy consumption and CO_2_Ems. Second, FDV can cause environmental pollution by increasing FDI inflows.

Some studies reported the negative nexuses between FDV on CO_2_Ems, for instance, (Batool et al., 2020), highlighted that underdeveloped countries' ecological regulators would benefit from financial development. So, a well-functioning financial system reduces pollution. Some of the authors discuss the asymmetric effect of FDV on CO_2 emissions (Gök, 2020; Neog & Yadava, 2020). Overall, the financial development environmental nexus research reveals inconsistent findings; further analysis of this relationship appears worthy.

2.3. Green technological innovation and CO_2 emission, (GTI-CO2_Ems)

Green technology innovation is recognised as one of the most effective tools in the growth environment model for reducing CO_2_Ems, preserving energy, and boosting economic growth (Bhowmik, Rahut, et al., 2022; L. D. Xin et al., 2022). It is considered that increased financial development results in increased energy consumption, particularly of fossil fuels, and hence has an adverse impact on the environment. (Ahmad & Zheng, 2021; You et al., 2022) According to the authors, bring environmental innovation into the economic growth-CO2 Ems nexus; innovation is a primarily effective tool that moves the economy to a more sustainable environmental source of energy. (Solarin & Bello, 2020), indicate that energy technology innovation decreases CO_2 emissions significantly and encourages sustainability of the environment (D. Xin et al., 2022; Jianguo et al., 2023). Recognising the importance of environmental-related technological innovation can effectively mitigate CO_2 emissions (D. Xin et al., 2021), as a result, technological innovation is enabling the development of environmentally friendly product cycles, units and processes, improvement in energy efficiency and technology of production, and government organisations and businesses are increasingly putting a significant amount of money into research and development, and domestic innovation, developing clean energy, that economic growth can inflict favourable environment outcomes to reduce pollutions and are crucial for decreasing CO_2 emissions levels, (Aghabalayev & Ahmad, 2022; Khattak & Ahmad, 2022). Additionally, sustainable innovation is the crucial feature in mitigating ecological deterioration caused by increased economic activities (L. D. Xin et al., 2022). Li. F, Zhang. J & Li. X. (2022) illustrates that technological development in high-income, high-tech, and high-carbon emitting countries has a mitigating influence on surrounding countries' CO_2 emissions.

Our study uses a patent proxy for measured green technological innovation; our outcomes revealed that GTI is favourable to reducing CO_2_Ems and improving the sustainable environment. Most previous studies, focusing on R&D generation's impact instead of patent, suggested that GTI minimises environmental pollution. Our study is consistent with the literature (Cheng et al., 2021; Kirikkaleli, Sofuoğlu, et al., 2023).

From the perspective of cross-country analyses, relatively few researchers observed studies regarding GTI, CO_2 emissions at the OECD level. We explored the effect of GTI on CO_2_Ems in OECD nations, such as (Jianguo et al., 2022) for the period 1990–2014, 34-OECD; (Ahmad et al., 2021) 26-OECD economies, (1990–2014); (Ganda, 2019) selected OECD countries (2000–2014); (Álvarez-Herránz et al., 2017) 28-OECD-nations, (1990–2014); (Ahmad et al., 2021) from 1990 to 2014, 26-OECD; (Ahmad et al., 2020) 24-OECD (1993–2014); (Ahmad, 2021) 36-OECD economies (1981Q1-2014Q4), (Paramati et al., 2021) 25-OECD; (Zhang et al., 2021), selected-OECD economies (1990–2017), (Cheng et al., 2021) for 35-OECD economies, from 1996 to 2015; The majority of prior research indicated that technology improvements contribute to minimise environmental pollution (Ahmed. M, Ahmad. Z et al., 2022; Kirikkaleli, Abbasi, et al., 2023; Kirikkaleli, Sofuoğlu, et al., 2023). According to the latest study (Khattak & Ahmad, 2022; You et al., 2022), governmental entities have a significant impact on implementing innovative and modern technologies. (Ali et al., 2022) strong institutional qualities can efficiently implement government policies for environmental regulations. (Kirikkaleli, Sowah, et al., 2023; Liguo et al., 2022) explained that improving energy efficiency through technology advancement is helpful to offset carbon emissions.

In our study, we investigate the effect of GTI as a moderator term, the existing literature has been investigated economic policy uncertainty, financial development, and technological innovation. Still, few empirical studies have examined the GTI moderating term on CO_2 _Ems. The significant conditioning impact of GTI is observed on the nexus of financial inclusion-CO_2_Ems (Ahmad et al., 2022). According to (Zhao et al., 2021), the outcome reveals the interactive effect of GTI on CO_2 _Ems, the indirect impact of CO_2 emission mitigates by improving technological innovation. (Ahmed. M, Ahmad. Z et al., 2022) analyses show that GTI reduces environmental impact by decreasing CO_2_Ems, A moderately negative correlation is observed between GTI over CO_2 for G-7 economies. According to the findings of (Anwar et al., 2021), technological innovation, institutional quality enhancement, and increased use of renewable energy were determined to be effective ways to reduce carbon dioxide emissions. (Romer, 1990) investigate the heterogeneity relations of technological development on CO_2_Ems.

2.4. Institutional quality and CO_2 emissions; (IQT-CO_2_Ems)

The existing research does not address the impact of IQT on the increase of CO_2_Ems. (Abid, 2017), explored the effects of various IQT dimensions on environmental quality are substantial, yet better governance is critical for reducing CO_2 emissions, and IQT affects CO_2 emissions in both directions. Even when a country has a low level of income, the quality of its institutions decreases environmental degradation (Husnain et al., 2022). This indicates that the environment will improve as future income increases, as IQT can mitigate the environmental costs associated with a rapid economic boom. So, as a result, a higher IQT environment can also provide comprehensive methods for improving economic development and enhancing environmental quality (Wan et al., 2022). The institution is that environmental regulations will also increase in parallel when economic growth increases. The IQT is responsible for enforcing the environmental policy. (Wawrzyniak & Doryń, 2020) declare that a sound governance system encourages eco-friendly practices and improves the quality of the environment. Environmental quality will improve if institutions of governments are powerful and adequate to impose ecological laws and policies. As a result, IQT is critical for environmental quality.

Some findings confirmed that institutional quality is important in decreasing CO_2 emission (Abid, 2017; Bakhsh et al., 2021; Tamazian & Rao, 2010; Y. Wang et al., 2019). However, some empirical research found a significant positive nexus between IQT and CO_2_Ems (Batool et al., 2020; Le & Ozturk, 2020).

Our research relies on existing literature to re-examine the events that led to financial development and EPU like-minded decreases CO_2_Ems. We have identified two critical requirements: technology innovation and institutional quality. We anticipate a favourable relationship between FDV, EPU, and carbon emissions due to GTI and IQ*T* improvements. We consider the previous points and emphasise the effects of IQT on FDV and EPU and its interaction term with CO_2_Ems. Our study may expect IQT to affect FDV and EPU on CO2_Ems relation significantly. Followed recommendations (Ahmed et al., 2021; Jianguo et al., 2022), contribute to the existing literature to investigate the institutional mediating role of increasing the environmental quality to mitigate CO_2_Ems.

The study aims to explain a gap in the existing literature by identifying the mediating term (i.e. the mechanism or process through which the relationship between two variables occurs) in the following relationships:

Green technological innovation and economic policy uncertainty on the environmental dimensions of CO2 emissions, and Green technological innovation and financial development on the environmental dimensions of CO2 emissions. Institution quality and economic policy uncertainty on the environmental dimensions of CO2 emissions, and institution quality and financial development on the environmental dimensions of CO2 emissions.

The goal of the study is to provide a better understanding of how these factors are interconnected and how they contribute to the level of CO_2 emissions in a given context.

3. Model description, data collection, and estimation

3.1. Data collection and analysis

This research aims to investigate the relation between EPU, FDV on CO2_Ems, with the conditioning role of GTI and IQT in 35-OECD economies over the period 2003–2019. Table 1 shows the definitions of all the indicators applied in this study.

3.2. Empirical estimation techniques

The empirical study structure is based on CO_2_Ems as a dependent indicator. Economic policy uncertainty and financial development index are independent variables, while green technology innovation and institutional quality is a moderator indicator, with control dimensions, such as economic growth, trade, energy usage, and foreign direct investment.

In Eq.1 and Eq.2, the research function and econometric model are described:

$$CO_2\_Ems_{i,t} = \quad (EPU, FDV, GIT, IQT\ FDI, ECG, ENC, TRD) \qquad \text{Eq.1}$$

We applied the following linear form of the static and dynamic panel regression model in this study, which connects CO_2_Ems to EPU, FDV, GIT, IQT, and with control indicators:

$$\begin{aligned} CO_2\_Ems_{i,t} = \alpha_i + \lambda_t + \beta_1 EPU_{it} + \beta_2 FDV_{it} + \beta_3 \mathrm{GIT}_{it} \\ + \beta_4 \mathrm{IQT}_{it} + \beta_5 FDI_{it} + \beta_6 ECG_{it} + \beta_7 ENC_{it} \\ + \beta_8 TRD_{it} + \varepsilon_{it} \end{aligned} \qquad \text{Eq.2}$$

Where in Eq.1 and Eq. 2,CO_2_Ems, $EPU, FDV, GIT, IQT, FDI, ECG, ENC, and\ TRD$ represent carbon emissions, economic policy uncertainty, financial development, green technology innovation, institutional quality, foreign direct investment, economic growth, energy consumption, and trade. Further α_i the country-specific effect $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7$ represents the coefficients of cross-pending explanatory indicators and ε_{it} reports the error term.

The estimation equation for moderating effects* is given as we follow the Eq.3 and Eq.4:

Moderation effects; $EPU * GIT, FDV * GIT$ on CO_2_Ems and $EPU * IQT, FDV * IQT$ on CO_2_Ems

$$\begin{aligned} CO_2\_Ems_{i,t} = \quad (EPU, FDV, GIT, IQT, EPU * GIT, FDV * GIT, \\ FDI, ECG, ENC + TRD) \end{aligned} \qquad \text{Eq.3}$$

$$\begin{aligned} CO_2\_Ems_{i,t} = \alpha_i + \lambda_t + \beta_1 EPU_{it} + \beta_2 FDV_{it} + \beta_3 EPU_{it} \\ * GIT_{it} \\ + \beta_4 FDV_{it} * GIT_{it} + \beta_5 EPU_{it} * IQT_{it} \\ + \beta_5 FDV_{it} * IQT_{it} + \sum_{j=1}^{k} \delta_j Z_{jit} + \varepsilon_{it} \end{aligned} \qquad \text{Eq.4}$$

The estimation Eq.5 shows SYS-GMM, and SELPDM estimations.

$$\begin{aligned} CO_2\_Ems_{i,t} = \alpha_o + \alpha_1 CO_2\_Ems_{i,t-1} + \beta_1 EPU_{it} + \beta_2 FDV_{it} \\ + \beta_3 EPU_{it} * GIT_{it} + \beta_4 FDV_{it} * GIT_{it} + \beta_4 EPU_{it} \\ * IQT_{it} + \beta_5 FDV_{it} * IQT_{it} + \sum_{j=1}^{k} \delta_j Z_{jit} + \varepsilon_{it} \end{aligned} \qquad \text{Eq.5}$$

3.2.1. Cross-Sectional dependency-CD test

This research used the most modern econometric technique required to determine cross-sectional dependency across indicators, as conventional econometric techniques are incapable of addressing this issue. A CD can arise in panel data analysis because of interactions across countries in the same economic-social network, geographical effects, and other unobserved features. The recent empirical literature (Ahmad, 2021; Zafar et al., 2019); examined economies are connected through many channels, such as border sharing, import-export, financial and economical, religions, and geographical. Panel data are frequently not checked for cross-sectional dependency between series. We applied the (Pesaran et al., 2004) cross-sectional dependence (CD) test, and the Lagrang multiplier (LM-test) introduce to examine cross-sectional dependency in time series panel data for the OECD economies from 2003 to 2019, which is necessary before doing a unit root test. Table 2 shows the findings of the CD-Test. We used the following equation for CD-Test and LM-Test

$$CO_2\_Ems_{it} = \alpha_i + \beta_i x_{it} + \varepsilon_{it} \qquad \text{Eq.6}$$

Wherein Eq.6, i =*cross-section indicator*, $t = time$, $CO_2\_Ems_{it}$= *Carbon emission*, $\beta_i =$ *slope of the coefficient, and* $\varepsilon_{it} =$ *error term.*

H0: = 0 and H1: 0 are the null and alternative hypotheses for cross-sectional dependency, respectively, as determined by the following LM test in Eq.7:

Table 2. Descriptive statistics, correlation matrix, and test for Multicollinearity.

	CO_2	EPU	FDV	GTI	IQT	ECG	ENC	FDI	TRD	VIF	Tolerance
Mean	2.967	4.125	12.368	2432.10	2.986	6.425	2095.05	68.413	102.36		
Std.dev	0.763	0.524	42.257	6547.25	20.350	16.527	1169.98	52.674	72.54		
Min	0.835	0.025	−11.310	−2.983	−2.098	−9.658	−3.652	2.049	0.082		
Max	3.426	5.301	4.528	31267.9	46.729	8.560	7965.51	346.259	510.20		
CO_2	1.000									3.346	0.299
EPU	0.354*	1.000								2.109	0.475
FDV	0.207*	0.478**	1.000							1.689	0.593
GTI	−0.574**	−0.525**	0.689*	1.000						3.649	0.275
IQT	−0.387	0.629	0.723**	0.336*	1.000					1.628	0.615
ECG	0.468***	−0.625	0.198**	0.408**	0.716***	1.000				1.453	0.689
ENC	0.608*	0.483*	0.249	0.652**	0.528**	0.143**	1.000			1.354	0.739
FDI	0.726*	0.296	0.509**	0.483*	0.429***	0.634**	0.312*	1.000		2.657	0.377
TRD	0.476*	−0.564	0.4693*	0.474*	0.775**	0.714**	0.278*	0.437*	1.000	1.489	0.672

Note: ***, **, and * are significant levels at 1%, 5% and 10%, respectively.

$$LM = T\sum_{i=1}^{N-1}\sum_{j-i+1}^{N}\rho_{ij} \quad \text{Eq.7}$$

Regardless, the LM test could be skewed. As a result, (Pesaran et al., 2004), adjusted it by adjusting for biases based on the LM statistic given in as follows in Eq.8:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\Sigma_{t=0}^{N-1}\Sigma_{j=i+t}^{N}\rho_{ij}\right) \quad \text{Eq.8}$$

3.2.2. *Unit root test*

After cross-sectional dependency is revealed, the next step is to evaluate the integration order of the tested parameters. We do not apply the first-generation unit root test because of the CSD in our data, which may lead to biased outcomes. Furthermore, we used the IPS (i.e. CADF) and CIPS (i.e. CIPS), the second-generation unit root, test to confirm the stationarity of the indicators (Pesaran, 2007). The unit root test is used to determine whether a variable is stationary at a level I (0) or at first difference I. (1). To calculate the CADF and CIPS unit root test, apply the following Eq. 9 and Eq.10:

$$CO_2\_Ems_{it} = \alpha_{it} + \beta_i x_{it-1} + \rho_i T + \sum_{j=0}^{n}\theta_{it}\Delta x_{it-j} + \varepsilon_{it} \quad \text{Eq.9}$$

CIPS computed by averaging the $CADF_i$ was introduced by (Pesaran, 2007) as follows:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N}CADF_i \quad \text{Eq.10}$$

3.2.3. *Westerlund panel cointegration*

'After the unit root analysis, the panel co-integration analysis is used to assess if the indicators have long-run correlations. The adoption of first-generation panel co-integration methods is not acceptable, as it was in the case of unit root analysis. Our study used the Westerlund (2007), panel co-integration test, this technique is preferable over traditional co-integration tests and is widely used in CD' (Westerlund, 2007). The Westerlund panel co-integration method findings are shown in Table 3.

3.2.4. *Dumitrescu and Hurlin Causality test*

After the validation of CD-Test, the causality test was used, which was defined as the individual Wald statistic of the Granger-Wald statistic of the Granger test. The empirical interpretation of the test is as follows in Eq.11:

$$CO_2\_Ems_{it} = \alpha_i + \sum_{j=1}^{j}\lambda_{ij}y_{i(t-j)} + \sum_{j=1}^{j}\beta_{ij}X_{i(t-j)} + \varepsilon_{it} \quad \text{Eq.11}$$

Where in Eq.11, $CO_2\_Ems_{it} =$ carbon emission, x and y= number of observations, λ_{ij} and β_{ij}= coefficient of the indicators. The null hypothesis indicates no causal relationship between the dimensions and demonstrates a casual association among the indicators.

3.2.5. *Sequential estimation of linear panel data model and the system-GMM*

This study examined the effects of EPU, FDV, and GIT on CO_2_Ems, the Eq.5 is in the form of dynamic panel data, and our research estimates dynamic unbalanced panel data using the SELPDM and SYS-GMM techniques, for 35 OECD economies over the period, 2003 to 2019.

We conduct our analyses on a large volume of data, which enables us to create a dynamic panel for the uses of the SELPDM and SYS-GMM techniques. These approaches are more effective than the traditional two-way fixed effect model estimate approach. The SYS-GMM estimation method more accurately addresses the endogeneity problem by employing internal instruments for endogenous indicators. It evaluates the equation simultaneously in the first difference and levels in the first difference, using lagged levels of the core and independent dimensions', and in levels, using the first differences of the regression equations. Additionally, according to the study of (Roodman, 2009), this approach is well suited for short-time frames with a large number of cross-sectional units, which was met in this study's sample, with T = 17 and N = 35 (N>T). The Eq.5 is estimated the SELPDM proposed by (Kripfganz, 2017) for benchmark estimation. To address this issue, the SELPDM is a new method presented by (Kripfganz, 2017), and

Table 3. Results of cross-section dependency test.

	Breusch-Pagan LM		Pesaran Scaled LM		Bias-corrected scaled LM		Pesaran CD	
Indicators	Statistic	Prob	Statistic	Prob	Statistic	Prob	Statistic	Prob
CO_2	2646.341***	0.000	121.521	0.000	119.623	0.000	18.056	0.150
EPU	1915.210***	0.000	65.854	0.000	64.425	0.000	22.542***	0.000
FDV	983.825***	0.000	114.523	0.000	112.706	0.000	36.231***	0.000
GTI	753.247***	0.000	87.547	0.000	85.541	0.000	9.824***	0.000
IQT	986.145***	0.000	97.357	0.000	95.478	0.000	7.964***	0.000
ECG	4575.175***	0.000	148.231	0.000	148.053	0.000	36.254***	0.000
ENC	2869.706***	0.000	143.509	0.000	141.754	0.000	3.841***	0.000
FDI	748.249***	0.000	9.649	0.000	7.847	0.000	5.853***	0.000
TRD	2014.763***	0.000	89.654	0.000	88.579	0.000	19.873***	0.000

Note: ***, **, and * are significant levels at 1%, 5% and 10%, respectively.

investigated that when the residuals from the first stage are regressed on another set of (often time-invariant) independent indicators in the second stage, the traditional standard errors become invalid. As a result, our study follows the latest (Ali et al., 2023) used the SELPDM estimation. Additionally, we used SYS-GMM estimation for robustness purposes, and SYS-GMM addresses heteroscedasticity and autocorrection issues more effectively than one-step GMM (Blundell & Bond, 1998). Therefore, as a result, we used a dynamic panel model (SYS-GMM) for an estimate to accomplish the study's aims.

4. Results discussion

The descriptive statistics, pair-wise correlation matrix, and test for multicollinearity, which is provided in Table 2. The mean value of quality of the environment measured by CO_2_Ems is 2.967 with minimum and maximum values of 0.835 and 3.426 metric tons CO_2 per capita, with a Std, dev of 0.763, respectively. While the average values of explanatory indicators EPU measured by WUI, and FDV index range from 4.125, and 13.0182 with the Std, dev 0.524, and 38.012, respectively. We also summarised the moderation indicator GTI and IQT has a mean of 2432.108 and 2.986 with Std, dev 6547.257 and 20.350. Similarly, other macro-level control indicators also indicate significant variation around the sample means.

Table 2 also reports the correlation analysis, which shows how our variables are associated. The correlation analysis indicates a positive correlation between CO_2_Ems, EPU, FDV, FDI, ECG, ENC, and TRD are positively correlated with each other. While CO_2_Ems, GTI and IQT have a negative correlation.

The correlation coefficients amid the variables are low, indicating no multicollinearity problem. To be free of a multicollinearity problem, a variable must have a VIF value of less than 10 and a tolerance value greater than 0.10. If the coefficient values of a variable are less than 0.85, it is usually considered that the model has no multicollinearity concerns. (Sheraz et al., 2021). As indicated in Table 2, all our variables fulfil the VIF analysis conditions, hence the absence of multicollinearity.

The CD can exist in panel data regression because to interactions across nations in the same economic-social network, geographical factors, and other unobserved variables. Table 3 we performed the cross-sectional dependency (CD) test and revealed that all the indicators are statistically significant at the 1% level, except CO_2 in column 4. The findings of all the CSD-tests reveal that we reject H_0-the null hypothesis that there is no CSD in panels by extremely low *p* values, the outcomes of column 4 in Table 3 except for CO_2 findings. The probability values for CO_2 in columns 1, 2, and 3, as well as for other independent and control variables in all four columns, demonstrate that all parameters are cross-sectionally dependent. It indicates that one country's uncertainty or disruption upsets others in the OECD economies panel. Failure to address CD in panel data will produce biased and inconsistent estimation results (Shabir et al., 2021).

The stationarity of the variables was checked using the IPS (i.e. CADF) and CIPS, the second-generation unit root test in the presence of CD and heterogeneity and the CIPS unit root test. Table 4 Investigates the CPIS and CADF outcomes, after CD is examined now, we will investigate the findings of CIPS and CADF unit root techniques. Regarding the CPIS test, CO_2, GTI, IQT, ECG, ENC, and TRD, are stationary at level; however, EPU and FDV are stationary at first difference. The order of integration in the CADF unit root test is mixed, as GTI, IQT, ECG, ENC, and TRD are stationary at level; however, CO_2, EPU, FDV, and FDI are stationary at first difference. After considering the first difference, CIPS and CADF both provide sufficient evidence to reject the null hypothesis (H0 = panel contains unit root). Thus, all variables are integrated at order one I (1), demonstrating that all parameters satisfy the co-integration test's presumption. Our study findings are similar (Shabir et al., 2021; Sheraz et al., 2021).

Table 5 shows the Westerlund panel co-integration test results. The results confirm the model's co-integrating equations. Thus, there are long-run

Table 4. Panel-unit root test.

	CPIS			CADF		
Indicators	Level	1^{st} difference	Order	Level	1^{st} difference	Order
CO_2	−0.538*	-	I(0)	−0.593	−2.593***	I(1)
EPU	−2.489	−3.852***	I(1)	−3.193	−4.607**	I(1)
FDV	−3.536	−2.957***	I(1)	−2.147	−2.582***	I(1)
GTI	−2.839***	-	I(0)	−1.819*	-	I(0)
IQT	−2.635***	-	I(0)	−2.157***	-	I(0)
ECG	−4.049***	-	I(0)	−1.816*	-	I(0)
ENC	−3.173***	-	I(0)	−2.497***	-	I(0)
FDI	−2.694**	-	I(0)	−3.019	−4.523**	I(1)
TRD	−1.539*	-	I(0)	−2.658**	-	I(0)

Note: ***, **, and * are significant levels at 1%, 5% and 10%, respectively.

relationships between environmental quality indicators and the independent dimensions obtained in this research. Our result shows that one group (Gt) and one panel (Pt) test provide significant statistics. Based on these findings, our model's variables are cointegrated.

After confirming a long-run correlation among indicators through Westerlund (2007) panel co-integration test, the long-run coefficients of the explanatory indicators are estimated by two Step-Sequential estimations of the linear panel data model (SELPDM).

The SELPDM model's results are provided in Table 6, while Table Appendix-A2 provides the findings of our two-step GMM (for robustness purposes), linked with empirical relations between EPU, FDV on CO_2_Ems, with the conditioning effect of GTI and IQT. Different information criteria must be checked for each specification. First, the absence of Arellano and Bond autocorrelation (first-order AR1 and second-order AR2) must be confirmed. Second, the instrumental variables were uncorrelated with the error term. The Hansen and Saran over-identification restriction test, which is expected to be insignificant, shows that our outcomes are reliable and impartial (Roodman, 2009).

Table 6 provides the SELPDM findings for Eq.5 using the WUI of OECD economies as a proxy for EPU. The results indicate that increasing the EPU in OECD countries dramatically increases CO_2 Ems in those economies. The coefficient of EPU has a positive and significant relationship on CO_2_Ems; According to estimation results of Eq. 5, increasing EPU causes an increase in CO_2_Ems. This result is consistent with the hypothesis that a high EPU has a positive effect on CO_2 _Ems, due to (i) EPU encouraging producers to use environmentally hazardous production practices, resulting in increased CO_2_Ems because reduced utilisation of renewable energy and R&D may increase CO_2 _Ems due to higher EPU. (ii) EPU, according to economic intuition, distorts the economic environment, restricting household consumption and corporate investment, particularly in the development of renewable energy. (iii) Increasing EPU can affect industrial transformation, economic diversification, and

Table 5. The Westerlund Panel Co-Integration Results.

Statistics	Values	Z-value	Robust p-value
Gt	−3.948**	−2.245	0.041
Ga	−19.463	−4.349	0.724
Pt	−7.842**	−0.178	0.025
Pa	−9.149	−2.329	0.573

Note: ** Indicate rejection of the null hypothesis of no co-integration at 5% levels respectively.

Table 6. The SELPDM- estimation of the linear panel-data model.

			GTI*EPU	GTI*FDV	IQT*EPU	IQT*FDV
Independent variables	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
	I	II	III	IV	V	VI
CO_2	0.924***	0.617**	0.809***	0.758**	0.354***	0.438*
	(9.045)	(2.514)	(6.524)	(2.509)	(3.990)	(1.365)
EPU	7.589***	5.749**	5.248***		4.501**	
	(11.458)	(2.657)	(7.587)		(2.583)	
FDV	0.923***	0.357***		0.786***		0.690**
	(5.247)	(5.526)		(3.997)		(2.968)
ECG	0.009*	0.863***	0.087	0.428**	0.268*	0.947***
	(1.719)	(3.968)	(0.528)	(2.987)	(1.237)	(7.583)
ENU	0.689***	0.0749*	0.578***	0.967***	0.526	0.237
	(7.480)	(1.489)	(9.570)	(5.118)	(0.968)	(0.827)
FDI	0.657**	0.247**	0.529***	0.780***	0.472	0.632*
	(2.859)	(2.479)	(3.897)	(7.547)	(0.254)	(1.901)
TRD	0.893**	0.489*	0.587*	0.483***	0.639*	0.352
	(2.236)	(1.367)	(1.057)	(3.924)	(1.523)	(0.991)
GTI	−0.986***	−0719**	−0.324*	−0.694***		
	(−9.478)	(−2.965)	(−1.058)	(−7.657)		
GTI*EPU			−0.978***			
			(−3.879)			
GTI*FDV				− 0.557**		
				(−2.698)		
IQT	−0.953***	−0.587**			−0.826***	−0.968***
	(−7.365)	(−2.987)			(−9.213)	(−3.528)
IQT*EPU					−0.964*	
					(−1.952)	
IQT*FDV						− 0.751***
						(−4.807)
Constant	Yes	Yes	Yes	Yes	Yes	Yes
Obs	629	629	623	619	619	619
S. Period	2003–2019	2003–2019	2003–2019	2003–2019	2003–2019	2003–2019
No, of countries	35	35	35	35	35	35
No of IV	29	29	27	25	25	25
No of time	17	17	17	17	17	17
AR-1	0.0362	0.068	0.042	0.021	0.046	0.023
AR-2	0.764	0.826	0.668	0.564	0.382	0.483
Sargan. T, P-values	0.893	0.982	1.000	0.905	1.000	0.912
Hansen, P-Values	0.462	0.886	0.912	0.683	0.917	0.896

Note: t statistics are in parenthesis, ***, **, and * are significant levels at 1%, 5% and 10%, respectively.

investment in green innovation projects, increasing CO_2_Ems as the EPU increases. Our findings are consistent with (Amin & Dogan, 2021; Lei et al., 2021; Q. Wang et al., 2020; Zakari et al., 2021).

The result of our study concerning the effect of FDV on CO_2_Ems has been positive and significant. At a 1% significance level, the coefficient FDV becomes statistically significant and positively impacts on CO_2_Ems, showing that a 1% rise in FDV can boost CO_2_Ems in OECD economies. This suggests that when FDV progresses, CO_2_Ems will increase as well. This implies that the development of OECD economies' financial sectors may stimulate new projects and activities but has not yet achieved success in allocating finance for environmentally friendly projects, resulting in increased pollution, energy consumption, and CO_2_Ems. Similarly, the development of the financial sector will also increase consumer credit, which will encourage people to invest in new enterprises, acquire machinery and equipment, or spend on autos, household items, and so on. As a result, carbon emissions will rise. Thus, the FDV relationship with lower environmental quality in OECD economies, as predicted. Our results are similar to most recent research (Ali et al., 2020; Bayar & Maxim, 2020; Le & Ozturk, 2020; Sheraz et al., 2021) these studies report that FDV decreases environmental quality to increase CO_2_Ems in OECD economies.

GTI has an adverse relationship with CO_2_Ems. The coefficient of GTI is negative, indicating that the level of GTI in a region can decrease CO_2_Ems; thus, it is recommended that policies to encourage innovation will play a significant role in minimising CO_2 emissions. This is mainly because GTI, (i) Improves operational capabilities while decreasing negative impacts on the environment, is the key to addressing the economic – environmental issue. (ii) GTI improves resource use efficiency, encourages the development and use of sustainable energy, and reduces environmental pollution. (iii) Through advanced technology, efficient energy usage minimises energy consumption and improves financial development and environmental quality by decreasing CO_2_Ems. For a better green society increase environment quality in OECD economies; promote green economic growth, and green finance strategies, enable and transfer technology to green investment and trade, focus on R & D, ICT, biotechnology, nanotechnology, and introduce policies that reinforce green innovation in global markets. However, technological innovation is important in OECD economies for reducing emissions and environmental deterioration. This finding is consistent with the most recent research of (Guo et al., 2021; Shan et al., 2021).

We used the most relevant components of the overall Institutional Quality index. IQT has a significant adverse effect on CO_2_Ems. Second, in terms of the relationship between IQT and CO_2_Ems, the sign and coefficient of IQT have a statistically significant and negative impact on the environment, except for models (1) and (2); when the IQT in the host economy rises, it results in a decrease in CO_2_Ems, ranging from 0.953 to 0.587 as a percentage term. In other words, a more effective and efficient institutional environment can reduce CO_2_Ems in the country and, as a result, preserve the environment from deterioration. Our outcomes are also consistent with past study, (Bakhsh et al., 2021) have claimed that stronger formation of institutions may pave the way for the sustainable use of natural resources, which, in turn, can reduce the CO_2 _Ems. It is worth noting that we used principal component analysis (PCA) to build the IQT index and examine its overall effect on CO_2_Ems: In accordance with our primary result, our findings are as follows in terms of robustness (see Appendix Table A1).

Our result also explains a fundamental gap in the existing literature, analysing the mediating term between GTI*EPU, GTI*FDV and IQT*EPU, IQT*FDV on the environmental dimensions of CO_2_Ems. Table 6 shows the interaction between GTI*EPU on CO_2_Ems, our result reveals the mediating effect of GTI*EPU on CO_2_Ems, the regression coefficient of GTI is negative and statistically significant at the 1% level, in column (3) Table 6. The inverse relation has been found between GTI and EPU on CO_2_Ems. This implies the development of GIT in host nations is the important factor for which EPU outcomes to mitigate CO_2_Ems in OECD countries, where GTI has environmentally friendly effects on CO_2_Ems. (Zhao et al., 2021) the result reveals the interactive impact of GTI on CO_2 _Ems, the indirect effect of CO_2_Ems mitigates by improving technological innovation. This outcome is similar with Bakhsh et al., (2021), who have recognised that investing in technology innovation helps reduce CO_2_Ems.

The interaction term of FDV*GTI was introduced in the regression equation (3) of this study to investigate the comprehensive impact of FDV and technological innovation on the environment. The coefficient of GTI is positive, indicating that the level of technological innovation in a region can reduce CO_2_Ems. The advancement of technology has a healthy and positive impact on the environment due to its involvement in decreasing pollution; According to (Hao et al., 2020) Technological innovation can also reduce emissions of gaseous pollutants, such as SO_2 emissions and smoke dust. The present study's findings are consistent with those of prior investigations by (Bakhsh et al., 2021; Tamazian & Rao, 2010). In accordance with the technological effect, increasing financial resources, and providing low-cost financing which helps to mitigate pollution and promote environmentally friendly initiatives.

The interpretation of interaction terms in this context would involve examining how the relationships between the variables impact the environmental dimensions of CO_2 emissions. Specifically, the study aims to identify the mediating term, which is the mechanism through which the relationships between the variables occur. For example, the interaction between Green technological innovation and Economic policy uncertainty could be examined to see how changes in economic policy uncertainty affect the relationship between Green technological innovation and CO_2 emissions. If economic policy uncertainty decreases, it may lead to an increase in the impact of Green technological innovation on reducing CO_2 emissions, while an increase in economic policy uncertainty may diminish the impact of Green technological innovation. Similarly, the interaction between Institution quality and financial development could be examined to see how changes in financial development impact the relationship between Institution quality and CO_2 emissions. If financial development increases, it may lead to an increase in the impact of Institution quality on reducing CO_2 emissions, while a decrease in financial development may diminish the impact of Institution quality.

Moreover, in Table 6, the moderating effect of IQT on CO_2_Ems via EPU an interaction term IQT*EPU takes a negative sign. An increase in IQT will mitigate the effect of uncertainties. IQT develops a sustainable environment in the country. Our study examines the ability of strong institutions to decrease the negative outcome of EPU on CO_2-Ems. This means that efficient institutions can help decrease the environmental cost of increased economic development thus; strong institutional structure, policy and regulations can be used efficiently which will to mitigate the environmental pollution (Ali et al., 2022).

In order to evaluate the interaction effects of IQT*FDV on CO_2_Ems, in the Table 6. The outcome shows a statistically significant and adverse impact on CO_2_Ems. Thus, in order to investigate the conditioning role of IQT on the relationship between FDV and environmental degradation, we have incorporated an interaction term IQT*FDV in column (6). This interaction term's β_5 coefficient is likely to show a negative sign. A better institutional quality environment will encourage FDV to attract FDI and it will also stimulate foreign investment in high-tech sectors. It will have a significant impact on the overall quality of the environment. The moderating term IQT*FDV is included in the model to bring this effect into the analysis. As expected, the coefficient on this interaction term is likewise projected to be negative because weak institutions harm the environment while strong institutions enhance the environment in OECD nations. Our results for the robustness check are in line with our core conclusion (see Appendix Table A1).

Table 7 summarises the findings of a non-causality test conducted by Dumitrescu and Hurlin to investigate the relation of CO_2_Ems with EPU, FDV, GIT, IQT, FDI, ECG, ENC, and TRD. The findings show that there is a bidirectional or reverse causal relationship between FDV and CO_2 and CO_2 to FDV; similarly, in the case of IQT to CO_2, and FDI to CO_2, and ENC to CO_2 we also recognised a bidirectional connection running from IQT to CO_2, and CO_2 to IQT, and FDI to CO_2 and CO_2 to FDI, and ENC to CO_2, and CO_2 to ENC. However, CO_2 is Granger caused by EPU and ECG which show a unidirectional causality relationship. There is a bidirectional causality nexus GTI-CO_2 and TRD-CO_2 for OECD economies. Our outcomes in line with previous findings (Shabir et al., 2021; Sheraz et al., 2021). The findings supported our primary outcome robustness check (see Appendix Table A1).

5. Conclusion

A large number of investigations have been carried out in order to ascertain the factors which influence environmental quality. However, prior research has neglected the importance of economic policy uncertainty, the economic implications of the economic policy uncertainty, and environmental consequences, particularly in the 35 OECD nations. The major purpose

Table 7. Results of Dumitrescu and Hurlin panel causality test.

Null Hypothesis	W-Stat	Zbar-Stat	P-Value
EPU to CO_2	4.627***	5.247	0.000
CO_2 to EPU	2.436	0.267	0.549
FDV to CO_2	5.214***	6.589	0.000
CO_2 to FDV	4.563***	4.265	0.000
FDI to CO_2	5.324***	4.235	0.000
CO_2 to FDI	4.638***	3.657	0.000
GTI to CO_2	4.089***	3.685	0.000
CO_2 to GTI	4.547***	4.687	0.000
CO_2 to IQT	5.213***	6.018	0.000
IQT to CO_2	4.680***	3.894	0.000
ECG to CO_2	3.347**	2.047	0.040
CO_2 to ECG	2.824	0.289	0.652
ENC to CO_2	4.859***	4.863	0.000
CO_2 to ENC	4.632***	4.987	0.000
TRD to CO_2	5.869***	6.487	0.000
CO_2 to TRD	2.479**	0.285	0.048

Note; ***, **, and * are significant levels at 1%, 5% and 10%, respectively.

of the study for these reasons was to determine the impact of economic policy uncertainty (measured by the world uncertainty index), and financial development on CO_2 emissions, followed by green technological innovation and Institutional quality (as mediator indicators), and economic growth, foreign direct investment, energy consumption, and trade (as control variables) by carrying out the methodologies, To assess the interaction between explanatory indicators and CO_2 emissions, the two-stage sequential techniques of the linear panel data model (SELPDM) adopted for benchmark estimations. We also applied SYS-GMM robustness econometrics techniques. Specifically, our findings reveal the conditioning role of green technological innovation and institutional quality on relations between economic policy uncertainty and financial development on CO_2 emissions. Our study used green technological innovation and a good institutional environment as policy indicators to stimulate economic policy uncertainty and financial development to escalate environment quality by mitigating CO_2 emissions.

We examined that economic policy uncertainty, financial development, economic growth, energy consumption, and trade are damaging to CO_2 emissions, while green technological innovation and institutional quality enhance the performance of the CO_2 emissions of the sample countries. Our empirical research revealed that the high releasing CO_2 emitter countries in the OECD region, such as (Australia 14.63%, Canada 13.77%, and the U.S.A 12.98%), should be played an active task in enhancing the capability to find out from the other higher-income economies in OECD region as well in the other advanced global region in terms to adopting a better institutional quality environment, green financing, green technological advancement and other sustainable environmental initiatives to address the OECD region's present environmental issues.

Based on the findings of the interaction terms, there are several policy implications that can be derived. Firstly, the study found that technological innovation has a significant and favourable impact on mitigating CO_2 emissions. Thus, policymakers should focus on promoting and investing in green technological innovations to reduce the carbon footprint of industries and improve environmental outcomes. Additionally, it is essential to reduce economic policy uncertainty to achieve the maximum potential of green technological innovation in reducing CO_2 emissions. This can be done by providing a stable and predictable regulatory environment for businesses, promoting investment in research and development, and supporting green industries. Secondly, the study found that financial development plays a vital role in environmental degradation, particularly in regions with high institution quality. Thus, policymakers should prioritise financial sector reforms and encourage financial institutions to provide low-cost financing for environmentally friendly initiatives. This can be done by introducing policies that incentivise banks to provide loans for green investments, such as reducing interest rates on loans for sustainable projects, providing tax breaks for investments in renewable energy, and introducing regulations that require banks to disclose their environmental impact.

Therefore, the study highlights the importance of technological innovation, economic policy certainty, financial development, and institution quality in mitigating CO2 emissions. By focusing on these factors, policymakers can promote sustainable development, reduce greenhouse gas emissions, and achieve environmental goals.

The study addresses some of our study's limitations. The scope of our analysis is confined to one indication of green technological innovation; however, other variables, such as government R&d expenditures, the number of research publications produced per 1000 residents in the country, and the global innovation index, can be employed in future research projects. In our paper, we used only one dimension of environmental quality. Hence, the researcher may use different environmental indicators, such as ($CO_{2HE,}$ from heat and electricity production, $CO_{2FL,}$ fuel liquid), Nitrogen Oxide and Sulfur Dioxide for further research. We also used institutional quality as a principal component index PCA; scholars may use the different dimensions of institutional quality (the rule of law, Political stability, Control of Corruption, Government effectiveness, and voice and accountability) for interesting results.

Notes

1. Name of the 35-OECD economies; 'Australia, Austria, Belgium, Canada, Switzerland, Chile, Colombia, Costa Rica, Czech Republic, Germany, Denmark, Spain, Finland, France, UK, Greece, Hungry, Ireland, Israel, Italy, Japan, Korea, Lithuania, Latvia, Mexico, Netherlands, Norway, Newzeland, Poland, Portugal, Slovak Republic, Slovenia, Sweden, Turkey, U.S.A' (OECD, 2022).
2. The world uncertainty index developed for143 countries, the data available on a quarterly basis; As a result, to get a yearly frequency out of the data, we average out the last four quarters. http//www.worlduncertinityindex.com.
3. For the OECD economies, there are no data of the Luxembourg, Estonia and Iceland in WUI. We exclude them in the empirical analysis.

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Disclosure statement

No potential conflict of interest was reported by the author (s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Appendix

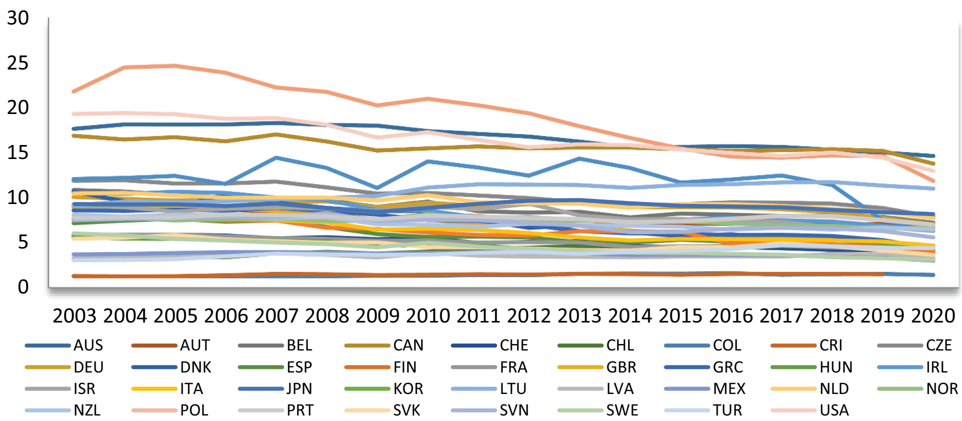

Figure A1. Trends in the CO_2_Ems (Metric tons/capita) in OECD economies from 2003 to 2020. Source: Authors own calculations based on OECD database

Table A1. SYS-GMM, Robustness test.

			GTI*EPU	GTI*FDV	IQT*EPU	IQT*FDV
Independent variables	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
	I	II	III	IV	V	VI
CO_2	0.715***	0.428***	0.615**	0.398*	0.296***	0.179**
	(5.154)	(3.992)	(2.529)	(1.996)	(3.981)	(2.053)
EPU	5.364***	4.289**	7.264***		2.098**	
	(9.015)	(2.547)	(2.587)		(2.689)	
FDV	0.852***	0.593***		0.402***		0.675***
	(7.251)	(5.842)		(5.214)		(3.997)
ECG	0.021*	0.153**	0.815	0.987*	0.198**	0.746**
	(1.850)	(2.927)	(0.624)	(1.659)	(2.059)	(2.862)
ENC	0.152***	0.346*	0.089*	0.358**	0.489*	0.382
	(5.810)	(1.993)	(1.928)	(2.620)	(1.563)	(0.567)
FDI	0.110**	0.256**	0.209***	0.419***	0.382	0.461*
	(2.520)	(2.826)	(4.109)	(3.990)	(0.179)	(1.990)
TRD	0.368***	0.664	0.589**	0.052***	0.537*	0.289
	(4.098)	(0.995)	(2.957)	(5.210)	(1.890)	(0.150)
GTI	−0.946***	−0.658***	−0.352**	−0.089***		
	(−3.998)	(−5.010)	(−2.059)	(−3.892)		
GTI*EPU			−0.098***			
			(−5.214)			
GTI*FDV				−0.352**		
				(−2.581)		
IQT	−0.825***	−0.488**			−0.639***	−0.896***
	(−4.639)	(−0.289)			(−9.528)	(−3.998)
IQT*EPU					−0.996**	
					(−2.928)	
IQT*FDV						−0.759***
						(−5.648)
Constant	Yes	Yes	Yes	Yes	Yes	Yes
Obs	629	629	625	629	625	625
S. Period	2003–2019		2003–2019	2003–2019	2003–2019	2003–2019
No, of countries	35	35	35	35	35	35
No of IV	27	27	25	23	27	21
No of time	17	17	17	17	17	17
AR-1	0.046	0.183	0.028	0.010	0.569	0.389
AR-2	0.647	0.896	0.589	0.464	0.289	0.543
Sargan. T, P-values	0.908	0.994	0.849	1.000	0.876	0.993
Hansen, P-Values	0.569	0.948	0.602	0.941	0.864	0.910

t statistics are in parenthesis, ***, **, and * are significant levels at 1%, 5% and 10%, respectively.