






“Economic policy uncertainty and the climate challenge: Moderating effects on the innovation–emissions nexus in G20 nations”

AUTHORS	Dharmendra Singh  Muhammad Naeem  Shikha Daga  Umar Ahmed 
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Dharmendra Singh, Dr., Associate Professor, Department of Business and Economics, Modern College of Business and Science, Oman.

Muhammad Naeem, Dr., Assistant Professor, Modern College of Business and Science, Oman.

Shikha Daga, Dr., Associate Professor, Department of Commerce, PGDAV College, University of Delhi, India. (Corresponding author)

Umar Ahmed, Dr., Associate Professor, Modern College of Business and Science, Oman.



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Dharmendra Singh (Oman), Muhammad Naeem (Oman), Shikha Daga (India), Umar Ahmed (Oman)

ECONOMIC POLICY UNCERTAINTY AND THE CLIMATE CHALLENGE: MODERATING EFFECTS ON THE INNOVATION–EMISSIONS NEXUS IN G20 NATIONS

Abstract

This study aims to examine the impact of technological innovation on the carbon emissions of the G20 economies while accounting for the moderating role of economic policy uncertainty. To analyze the relationship between emissions and technological innovation in the presence of economic vulnerabilities, the study used the annual data from 2000 to 2023. Panel and quantile regression are used to test the heterogeneous relationship. The results reveal that research and development expenditure (R&D) has a positive and statistically significant impact on emissions at certain quantiles, suggesting that innovation alone may not uniformly contribute to emission reductions. Economic policy uncertainty is documented to have a heterogeneous relationship with emissions, wherein it reduces emissions at lower quantiles, with a positive relationship exhibited at higher quantiles. Similar results are obtained when economic policy uncertainty and R&D interact and are able to reduce emissions at all levels, as shown by quantile regression. The results provide valuable implications for policymakers, emphasizing the importance of fostering innovation while managing policy uncertainty to achieve carbon mitigation goals across varying emission levels within the G20.

Keywords

economic policy uncertainty, research and development expenditure, carbon emission, quantile regression, moderation

JEL Classification

Q55, C21, O32, Q54

INTRODUCTION

In the contemporary era, economies are increasingly navigating a dual pathway: pursuing economic growth while simultaneously addressing the pressing need for environmental preservation. The intensifying threat of environmental degradation has compelled nations to seek a sustainable equilibrium between development and ecological stewardship. In response, institutions, corporations, and governments have introduced strategic measures to enhance energy efficiency and promote a transition toward low-emission, green energy sources. At the global level, the adoption of the Sustainable Development Goals (SDGs) and, at the corporate level, the implementation of Environmental, Social, and Governance (ESG) frameworks underscore a collective commitment to aligning economic advancement with environmental integrity and social accountability. These efforts reflect a broader paradigm shift toward resilient, inclusive, and sustainable development models that are essential for long-term global stability. While technological innovation, primarily driven by research and development (R&D), is often viewed as a key mechanism for emission reduction, its effectiveness is influenced by multiple economic and policy-related factors. The policy-driven efforts undertaken by economies fail to deliver the

results when faced with economic and political vulnerabilities. The last decade has witnessed multiple global events like the COVID-19 pandemic, the Russian-Ukrainian war, inflationary pressures, and the recent tariff wars. These episodes of economic uncertainty have diverted policy focus and resource allocation away from environmental initiatives, thereby undermining the momentum required for sustained progress in climate action and sustainable development. While understanding how technological innovation, fostered by enhanced R&D expenditure, can lead to reduced emissions is necessary, it is also essential to recognize how it is moderated by factors that impact economic stability.

Economic instability can alter investment patterns, disrupt innovation cycles, and influence the pace at which new technologies are developed and deployed. The extent to which economic policy uncertainty moderates the R&D-emission relationship remains an open scientific question, particularly across economies with varying emission levels and technological capabilities. The potential heterogeneity in this relationship adds complexity to assessing whether R&D consistently contributes to emission reductions or whether its effects vary according to differing economic contexts.

Despite extensive research on emissions and their economic determinants, there is limited understanding of how economic policy interacts with R&D in shaping emission trajectories. Addressing this gap is crucial for designing effective policies that promote innovation while ensuring economic stability, thereby advancing the broader agenda of sustainable development.

1. LITERATURE REVIEW AND HYPOTHESES

Economies worldwide are battling the dilemma of increasing economic wealth along with maintaining their environment. The relationship between the two has garnered the attention of academics and policymakers alike. To decouple growth from emissions, various policies have been undertaken at both the macro and micro levels (Addai et al., 2023). Economies worldwide are intensifying their efforts to achieve the Sustainable Development Goals (SDGs). For this, it is necessary to make a transition toward varied principles of circular economy to ensure that there is a decoupling of growth from emissions (Agrawal et al., 2025). The conventional theory of the Environmental Kuznets Curve (EKC) documents how technological development in economies transitioning toward wealth generation experiences a decline in emissions after a certain income level (Grossman & Krueger, 1991). The inverted U-shaped EKC, though well accepted across developed economies, found varied transitions across their developing and low-income counterparts (Abuolien et al., 2024; Ali, 2021). This is because emission reduction requires a paradigm shift and conscious effort toward using cleaner sources of energy, which is heavily dependent on technological upgradation across economies that are generally lacking in the

latter (Abdullah et al., 2024). Technological innovation is thus a crucial factor that is hypothesized to assist in emission mitigation and promote green growth.

SDG 7 (affordable and clean energy) and its attainment are not only heavily dependent on R&D but are also closely interlinked with other SDGs, namely SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action). The role of R&D in reducing emissions and advancing the Sustainable Development Goals (SDGs) is well established in the literature. Empirical evidence suggests that technologically advanced economies are more capable of decoupling economic growth from environmental degradation, thereby accelerating progress toward global sustainability objectives (Deka, 2024). The impact of R&D, however, on emission reduction is not similar across all economies and is documented to be dependent on various other factors that moderate the relationship (Xie et al., 2024).

For instance, Amin et al. (2025), Li and Liu (2025), and Xie et al. (2024) highlight a positive impact of R&D on green innovation and emission reduction across different emerging economies. In contrast, Fatima et al. (2024) and Anser et al. (2021) document a positive impact across G-7 economies, with Erdogan et al. (2024) providing similar results for

developed countries. These studies highlight how R&D can help in decoupling economic development from emissions, thereby helping economies in attaining the goal of sustainable development. The results, however, are not synonymous across all studies. Yeboah et al. (2024) highlighted mixed results in African nations, with Azam Khan et al. (2024) documenting the same across the 12 Asian economies. Bilgili et al. (2024) also asserted mixed results and indicated how the relationship is not linear but is U-shaped, thereby supporting the Kuznets curve hypothesis across the nine European nations. The study thereby supports how the effectiveness of R&D in reducing emissions is heavily dependent on regional economic structures, policy frameworks, and technological capabilities.

The mixed results identified between R&D and emissions highlight the presence of a heterogeneous relationship between technological innovation and the mitigation of emissions. This is mainly because the relationship is not bivariate, as the presence of other factors has a direct and/or indirect influence on the relationship (Azam Khan et al., 2024). Other than this, the relationship might vary at different stages of emissions and at varied points of time (Esquivias et al., 2022). The relationship is also documented to be influenced by various macro- and micro-level factors, including financial development, trade openness, population growth, urbanization, and economic uncertainty, which can impact emission reduction efforts by diverting attention away from environmental concerns (Menyari, 2024). The gap in the literature between R&D and its role in emission reduction is thus the main motivation behind this study.

Out of the various factors that are crucial for identifying the true innovation emission nexus, the one that has caught the attention of policymakers, academicians, and practitioners is the stability across the economy (Ali et al., 2022). This is because crises or uncertainty at the micro and/or macro level can delay the impact and make the relationship ineffective. The last decade has witnessed multiple instances of economic and political turbulence that have significantly hindered sustainability efforts globally (Adams & Abhayawansa, 2022). The 2008 Global financial crisis, the Russia-Ukraine war, and the USA-China trade tariffs have disrupted global supply chains, strained diplomatic rela-

tions, and diverted critical resources away from climate action and sustainable development initiatives (Ahmed et al., 2024). All these macro-level events depict how global integration has a strong spillover across various economies, along with highlighting the importance of macro-level stability in promoting global sustainability efforts. It is therefore necessary to identify the role that global uncertainty plays in emission mitigation efforts.

Studies have also revealed how a high level of economic uncertainty discourages long-term investments in sustainability due to unpredictable policy changes, market volatility, and increased business risks (T. Yuen & W. Yuen, 2024). There are varied proxies that can be used for measuring the global uncertainty, and the most commonly used in the literature and theoretically justified is the economic policy uncertainty (Abakah et al., 2024). The role of economic policy uncertainty in influencing global sustainability efforts can be examined at both the direct and indirect levels. It is hypothesized to have a direct impact on decarbonization efforts by influencing investment decisions, delaying the adoption of green technology, and altering policy priorities. Additionally, economic policy uncertainty is theorized to have spillover effects by creating market volatility, disrupting supply chains, and indirectly influencing other economic variables that are crucial for sustainable development (Ali et al., 2022).

To address the uncertainty around the emission and technological innovation nexus, the study has used R&D expenditure as the main independent variable, along with economic policy uncertainty acting as the independent and the moderator across two different models in the study. Recent studies suggest that the impact of economic policy uncertainty on emissions is heterogeneous across economies. Anser et al. (2021) found that in developed nations with stable regulatory environments, the negative impact of uncertainty on R&D investment is less pronounced. In contrast, emerging economies experience more volatility, leading to inconsistent progress in green technology adoption (Chopra et al., 2024).

Furthermore, the interaction between economic policy uncertainty and R&D in influencing emissions is largely unexplored. While studies have ex-

amined how economic policy uncertainty affects business confidence and investment decisions, there is limited empirical research on whether it amplifies or weakens the relationship between R&D and emissions across different economic conditions.

While analyzing the relationship between the variables of interest, it is important to control for variables that are documented to have an impact on emissions.

One variable commonly used in studies is economic growth, proxied by GDP, which reflects the economic health of an economy and provides support for technological upgradation, thereby promoting energy efficiency and, in turn, emission reduction (Zahra et al., 2025). The results, however, are found to be mixed. Grossman and Krueger (1991) highlighted how economies on the path of development with increased industrialization are not always high emitters. Initially, when the economy grows, there is a corresponding increase in emissions, while with a further rise in the GDP, the economy transitions to enhanced technological innovation that leads to energy efficiency and hence helps in reducing emissions. Safi et al. (2024) documented how an increase in economic growth leads to a rise in emissions in the OECD economies. Al-Taei et al. (2024) asserted a bi-directional causality between emissions and economic growth in the Gulf countries. It is therefore necessary that while studying the R&D and emission nexus, the study controls for the economic status of the different economies to ensure that its impact is accurately captured, thereby preventing biases that may arise due to variations in income levels, industrial structures, and technological capabilities across different nations.

Trade openness is another factor that is documented to have a significant impact on global emissions. Backed by the pollution haven hypothesis, the studies assert that liberal trade can lead to the relocation of high-carbon-emitting industries to countries with lax environmental regulations, thereby increasing emissions in those economies. However, Ramizo et al. (2025) and Menyari (2024) demonstrate how trade openness facilitates the transmission of green technology across countries, leading to increased energy efficiency and reduced

emissions. The heterogeneous results thus make it necessary to control for trade variables to identify the actual impact of R&D and EPU on emissions (Baker et al., 2016).

As an economy grows, it transitions from financial repression to financial development, where financial institutions become more efficient, diversified, and accessible. This progression enhances capital allocation, promotes investment in productive sectors, and supports overall economic growth. An economy characterized by well-developed financial markets is also documented to enhance energy efficiency and hence bring a reduction in emissions, thereby supporting the promotion of sustainable development (Azam Khan et al., 2024). However, not all studies document similar results, and there are instances wherein economies have reported increased emissions that correspond to improved financial status (Yuan et al., 2025).

Population growth is another determinant of emissions across countries. This is because as the population of an economy increases, it leads to a rise in demand for energy consumption that ultimately generates greater emissions if rising energy demand is not backed by green and/or renewable energy (Erdogan et al., 2024).

In summary, the existing literature underscores the complex, heterogeneous, and often context-dependent relationships between technological innovation, economic policy uncertainty, and carbon emissions. While technological innovation is asserted to have a significant impact on environmental sustainability, the impact is often disrupted by economic vulnerabilities and other related factors. The gap in the existing studies motivated the present study to explore the interaction between economic policy uncertainty and R&D, especially within a heterogeneous group of G20, as the influence of economic policy uncertainty can disrupt the entire relationship by delaying investments in green technologies (Anser et al., 2021).

This paper examines the heterogeneous and moderating effects of economic policy uncertainty on the relationship between research and development (R&D) and carbon emissions in G20 economies, a diverse group of countries with varying macroeconomic foundations. Although existing

literature has highlighted the role of R&D in the mitigation of environmental degradation, these studies have remained silent regarding how policy uncertainty can influence the efficacy of innovation-led sustainability policies. Pioneering this gap in knowledge, the paper systematically investigates the direct and interactive effects of economic policy uncertainty on the link between R&D and emissions, incorporating several control variables to enhance the rigor of the analysis. Based on the above literature and gap identification, the following research hypotheses (Figure 1) were formulated:

- H1: *R&D expenditure has a negative impact on carbon emissions across G20 economies.*
- H2: *The impact of R&D on emissions is heterogeneous at different emission levels.*
- H3: *Economic policy uncertainty has a positive impact on carbon emissions across G20 economies.*
- H4: *Economic policy uncertainty moderates the relationship between R&D and carbon emissions.*
- H5: *The moderating effect of economic policy uncertainty on the relationship between R&D and emissions is heterogeneous across different emission levels.*

2. METHOD

Literature has highlighted how technological innovation, proxied by R&D expenditure, has a mixed impact on carbon emissions (Bilgili et al., 2024; Zahra et al., 2025). While a few studies document a positive relation, others provide a negative or non-linear impact. The research gap in this study is to identify the relationship at different levels of emissions using quantile regression, which is a novel approach. The study has considered 15 economies (Table 1) that are a subset of the G20 economies, as their contribution to global wealth generation, trade, and emissions is well recognized.

All data used in the study are freely available from the World Development Indicators (WDI) Database and the Economic Policy Uncertainty (EPU) website.

The G20 contributes around 80% to global wealth and emissions; hence, mitigating these impacts across these economies is a necessary and important policy requirement. The study has used annual data of the G20 countries from 2000 to 2023, generating enough panel observations for the analysis. However, due to the absence of data on economic policy uncertainty for countries such as Argentina, Indonesia, Saudi Arabia, South Africa, and Turkey, the dataset comprises only the remaining G20 economies with complete and reliable information. The final set of countries thus comprises Australia,

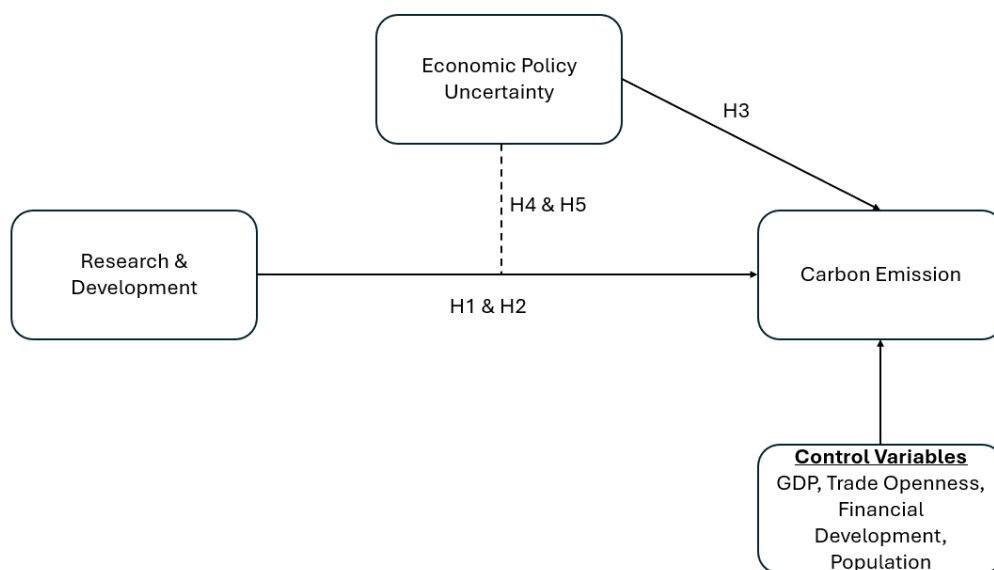


Figure 1. Conceptual model

Table 1. Description of sample countries and variables

Variable	Description	Literature	Source
Dependent Variable			
Carbon Emissions	Carbon dioxide (CO ₂) emissions (total) (Mt CO ₂ e)	Amin et al. (2025), Xie et al. (2024)	WDI
Independent Variable			
Expenditure on R&D	Research and development expenditure (% of GDP)	Azam Khan et al. (2024), Bilgili et al. (2024)	WDI
Economic Policy Uncertainty*	Level of uncertainty regarding economic and policy-related decisions	Anser et al. (2021), Ali et al. (2022)	Policy Uncertainty Database
Moderating Variables			
Economic Policy Uncertainty	Level of uncertainty regarding economic and policy-related decisions	Anser et al. (2021), Ali et al. (2022)	Policy Uncertainty Database
Control Variables			
GDP	GDP (constant 2015 US\$)	Al-Taei et al. (2024), Caldera et al. (2024)	WDI
Trade Openness	Trade (% of GDP)	Menyari (2024), Adebayo et al. (2023)	WDI
Financial Development	Domestic credit to private sector (% of GDP)	Azam Khan et al. (2024), Yuan et al. (2025)	WDI
Population	Population, total	Erdogan et al. (2024), Appiah et al. (2022)	WDI
Countries used in the Study			
Australia	Brazil	Canada	China
France	Germany	India	Italy
Japan	Mexico	Russia	South Korea
The UK	The USA	European Union	–

Note: * Baker et al. (2016).

Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russia, South Korea, the UK, the USA, and the European Union. Additionally, due to the lack of a unified EU-level Economic Policy Uncertainty Index, the study employed the Europe-wide Economic Policy Uncertainty Index as a proxy for EU economic policy uncertainty. This is because European economic policy uncertainty is a reasonable approximation, especially in macro-level panel studies.

The following is the relationship that is tested in the study

$$CO_2 = f\left(\begin{matrix} R \& D, EPU, GDP, \\ TO, POP, FD \end{matrix}\right), \quad (1)$$

where CO₂ is the carbon emissions of the G20 economies; R&D is the expenditure on R&D as a % of GDP; EPU measures the economic policy uncertainty; GDP is the proxy for economic growth; TO is the trade openness measured by total trade as a % of GDP; POP is the total population; FD depicts the level of financial development measured by domestic credit to the private sector as a % of GDP.

The variables that are in their absolute term are converted to log to ensure robust calculations before proceeding with further analysis. As the first step toward panel regression, descriptive statistics and correlation are calculated to ensure the fit of the data, after which advanced panel and quantile regression are used. The various models that are tested in the papers are given below:

Model 1: Direct impact of EPU on CO₂ emissions

$$\begin{aligned} CO_{2it} = & \beta_0 + \beta_1 EPU_{it} + \beta_2 R \& D_{it} \\ & + \beta_3 GDP_{it} + \beta_4 TO_{it} \\ & + \beta_5 FD_{it} + \beta_6 POP_{it} + \varepsilon_{it}. \end{aligned} \quad (2)$$

Model 2: Moderating role of EPU in the relationship between R&D and CO₂ emissions

$$\begin{aligned} CO_{2it} = & \beta_0 + \beta_1 R \& D_{it} + \beta_2 EPU_{it} \\ & + \beta_3 (R \& D_{it} \cdot EPU_{it}) + \beta_4 GDP_{it} \\ & + \beta_5 TO_{it} + \beta_6 FD_{it} + \beta_7 POP_{it} + \varepsilon_{it}. \end{aligned} \quad (3)$$

Robustness check: Quantile regression model

$$\begin{aligned}
 Q_{\tau}(CO_{2it}) = & \beta_0(\tau) + \beta_1(\tau)R \& D_{it} \\
 & + \beta_2(\tau)EPU_{it} + \beta_3(\tau)(R \& D_{it} \cdot EPU_{it}) \\
 & + \beta_4(\tau)GDP_{it} + \beta_5(\tau)TO_{it} + \beta_6(\tau)FD_{it} \\
 & + \beta_7(\tau)POP_{it} + \varepsilon_{it},
 \end{aligned} \tag{4}$$

where Q_{τ} represents the conditional quantile function for different percentiles τ of CO_2 emissions.

3. RESULTS

The first step in the panel regression is to provide the descriptive statistics of the various variables used in the study, which provides a comprehensive analysis of the variables (Table 2). The analysis provides for varied dispersion across different variables, emissions, GDP, population, trade, and

financial development are found to exhibit lesser variations vis-à-vis economic policy uncertainty and R&D, wherein countries exhibit extreme variations showing differing levels of technological innovation and economic policy uncertainty.

After the computation of basic statistics, the next step is to identify the correlation to determine the level of interconnection among the variables. It is provided in Figure 2, wherein a few variables like R&D and financial development depict a moderate level of correlation; however, the VIF being less than 10 rules out the possibility of multicollinearity.

Panel regression using fixed and random effects for the two models (model 1: using economic policy uncertainty as the independent variable; and model 2: using economic policy uncertainty as the moderating variable in the R&D and emission nexus) highlights the role of economic policy un-

Table 2. Descriptive statistics

Descriptive Statistics	LCO	LGDP	LPOP	R&D	TRADE	FD	EPU
Mean	3.014184	12.44228	8.166314	1.903796	53.29062	100.9013	146.2051
Median	2.822077	12.35654	8.101908	1.931875	53.89181	95.86205	122.9006
Maximum	4.101115	13.32052	9.149945	4.93012	105.5663	220.3156	792.000
Minimum	2.458372	11.90251	7.279411	0.26855	19.5596	12.24098	27.00091
Std. Dev.	0.444678	0.388901	0.489612	0.953707	19.08426	50.78466	98.51755
Skewness	0.786129	0.842365	0.666515	0.395098	0.182834	0.209313	2.824840
Kurtosis	2.402901	2.563274	2.583737	2.811973	2.362429	2.135818	14.82671

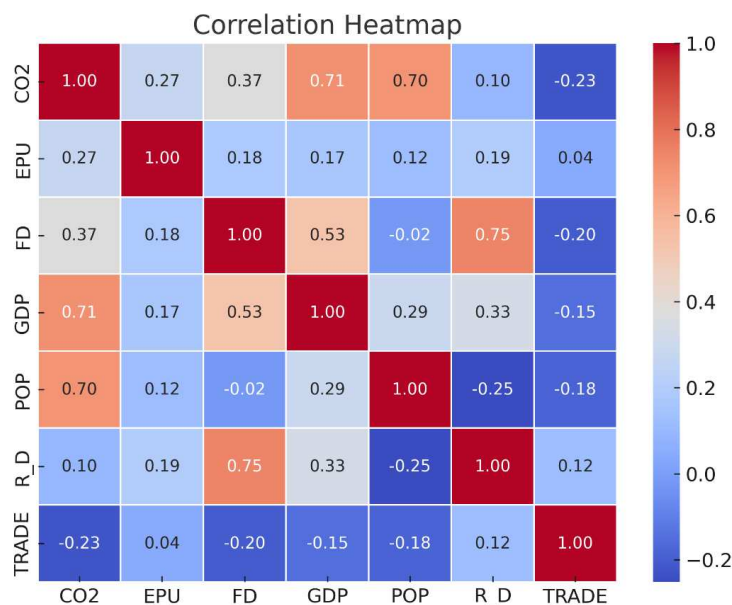


Figure 2. Correlation heatmap

certainty as a significant independent variable. It has a significant impact in mitigating emissions across the G20 countries, along with the R&D expenditure. The results from the panel regression (Table 3) indicate a statistically significant negative relationship between R&D expenditure and carbon emissions across G20 economies, justifying the first research hypothesis. Specifically, the coefficient for R&D is -0.0618 ($p < 0.01$) under the fixed effects model, suggesting that increased investment in R&D contributes to lower emissions. Results support the existing literature, wherein technological innovation is documented to reduce emissions (Adebayo et al., 2022).

Testing the third and fourth hypotheses related to economic policy uncertainty and its impact on emissions is provided in Table 3 (linear relationship) and Table 4 (heterogeneous relationship). The linear relationship provides for a negative impact of economic policy uncertainty on emissions using fixed and random effects. The results, however, are found to be contradictory to the existing studies, which call for a robust analysis using quantile regression (Table 4).

Table 3. Panel regression

Variable	FE	RE	FE	RE
	Model 1		Model 2	
C	0.2472 (0.8498)	-6.2582*** (0.0000)	0.1395 (0.9164)	-6.7125*** (0.0000)
R&D	-0.0618*** (0.0000)	-0.0586*** (0.0000)	-0.0570*** (0.000)	-0.0435*** (0.0011)
EPU	-0.0002** (0.0000)	-0.0002*** (0.0000)	-0.0002 (0.3208)	-0.0001 (0.2436)
GDP	0.9829*** (0.0000)	0.8706*** (0.0000)	0.9799*** (0.0000)	0.8571*** (0.0000)
TO	-0.0003 (0.3881)	-0.0012*** (0.0004)	-0.0003 (0.3675)	-0.0012* (0.0002)
POP	-1.1388*** (0.0000)	-0.1627 (0.1335)	-1.1217*** (0.0000)	-0.0870 (0.3980)
FD	0.0001 (0.6136)	-0.0003 (0.1952)	0.0000 (0.6735)	-0.0003 (0.1170)
R&D*EPU	-	-	-0.0000 (0.6536)	-0.0000 (0.1330)
Hausman Test				
Statistics	t-Statistic	Prob.	t-Statistic	Prob.
Values	44.532	0.0000	47.834	0.00000

Note: ***, **, * represent statistically significant level at 1%, 5%, and 10%, respectively.

While the panel regression results indicate that economic policy uncertainty has a contradictory effect on emissions compared to existing literature,

it is crucial to account for distributional heterogeneity. Traditional mean-based estimators (such as fixed effects and random effects models) assume a uniform impact of economic policy uncertainty and R&D across all emission levels. However, the relationship between these variables may vary across different quantiles of emissions, necessitating the use of quantile regression. Results of the same are provided in Table 4. The quantile regression estimates provide evidence of a heterogeneous relationship between R&D expenditure, economic policy uncertainty, and emissions, thereby leading to the justification of the second research hypothesis. In economies with lower emissions, uncertainty may lead to industrial slowdowns, reducing carbon output. However, in high-emission economies, policy uncertainty may deter long-term green investments, exacerbating environmental degradation, as shown by the individual impact of economic policy uncertainty on emissions through the use of quantile regression.

While the impact of R&D on emissions is positive at all quantiles, it is significant only at lower (Q10) and higher quantiles (Q80). This pattern suggests that R&D investments may initially lead to increased emissions, possibly due to the energy-intensive nature of early-stage innovation. Also, the contrasting results between the fixed effects and quantile regression models depict how each model captures the relationship between the variables of interest. While the fixed effects model estimates an average effect across all countries and time periods, revealing a negative association, it depicts the overall intention of R&D to support emission reduction through innovation. However, the quantile regression approach, which captures the heterogeneity across the emissions distribution, shows a positive relationship between R&D and emissions at all quantiles, though this relationship is statistically significant only at the 10th and 80th quantiles. This suggests that in countries with very low and very high emission levels, R&D may be contributing to emission increases, possibly due to a focus on industrial or productivity-enhancing innovation rather than clean technology. In the middle quantiles, the relationship remains positive but insignificant, indicating weaker or mixed effects of R&D on emissions. These findings underscore the importance of employing distributional methods, such as quantile regression, to uncover hidden patterns that average models may overlook.

Table 4. Robustness check: Quantile regression

Variables	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90
R&D	0.1099**	0.0528	0.0479	0.0218	0.0233	0.0313	0.0597	0.1285**	0.0470
	0.0148	0.1673	0.1958	0.4732	0.4458	0.5506	0.3649	0.0219	0.4355
EPU	-0.0000	-0.0008	-0.0008	-0.0008*	-0.0005	0.0006	0.0012*	0.0022***	0.0004
	0.9347	0.1809	0.1405	0.0753	0.1794	0.5709	0.0432	0.0000	0.4124
GDP	0.4232***	0.3981***	0.3756***	0.3869***	0.3894***	0.3511***	0.2537***	0.1914***	0.1161*
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0029	0.0099	0.0551
FD	0.0016***	0.0019***	0.0021***	0.0025***	0.0024***	0.0025***	0.0027***	0.0021**	0.0003
	0.0000	0.0000	0.0000	0.0000	0.0002	0.0043	0.0045	0.0134	0.5918
TO	0.0030***	0.0032***	0.0035***	0.0032***	0.0026***	0.0018	0.0011	-0.0007	-0.0047***
	0.0001	0.0000	0.0000	0.0000	0.0001	0.1258	0.5941	0.6751	0.0000
POP	0.6446***	0.6410***	0.6405***	0.6246***	0.5919***	0.5523***	0.6517***	0.6565***	0.6555***
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R&D*EPU	-0.0005	-0.0001	-0.0001	0.0000	-0.0000	-0.0003	-0.0005**	-0.0010***	-0.0002
	0.2094	0.7695	0.8623	0.9439	0.7716	0.1647	0.0308	0.0000	0.3472
Pseudo R-squared	0.5552	0.5748	0.586	0.6030	0.6190	0.6289	0.6356	0.6364	0.6459

Note: ***, **, * represent statistically significant level at 1%, 5%, and 10%, respectively.

The results of quantile regression highlighted interesting facts about the R&D emission nexus and the role of economic policy uncertainty in impacting the relationship. The heterogeneous nature of the relationship is visible at different quantiles wherein the p -values significance and direction both change at higher quantiles vis-à-vis the lower emission levels for economic policy uncertainty as an individual variable. Not only does the study document the individual effect to be different at various levels, but their interaction effect too is found to be significant at higher quantiles (70–80 percentiles). A negative relationship between economic policy uncertainty and emissions at lower quantiles that turns positive at higher quantiles demonstrates that the relationship is strictly heterogeneous, which also justifies the research hypotheses. The interaction term (R&D * EPU) in the panel regression (Table 3) is statistically insignificant, indicating no significant moderating effect at the mean level. However, quantile regression results (Table 4) show that economic policy uncertainty significantly amplifies the negative impact of R&D on emissions at higher quantiles (Q70–Q90), leading to the acceptance of H3. The reason for the same can be that in high-emission economies, heightened policy uncertainty may push firms to prioritize sustainable R&D investments, as future regulatory risks make green innovation a more attractive long-term strategy. The heterogeneous nature of the relationship between R&D, emissions, and economic policy uncertain-

ty underscores the importance of policy stability in ensuring effective environmental and technological advancements. The combined results highlighting the hypotheses testing and its results are presented in Table 5.

The hypotheses testing using panel and quantile regression provides useful insights into the technological and emission nexus impacted by policy uncertainty across the G20 economies. Regarding the testing of the five hypotheses, the results are found to be heterogeneous. For instance, the empirical results of the study highlight how contrary to expectations, R&D expenditure shows a positive and significant relationship with carbon emissions at higher quantiles, while its impact is insignificant at lower quantiles, thereby leading to rejection of the first hypothesis. This is in contrast to the results obtained via panel regression, wherein R&D is found to have a negative and significant impact on emissions. The results depict how excessive reliance on a homogeneous and linear model can produce biased results. R&D thus is found to possess a heterogeneous relationship with emissions that needs to be captured using advanced econometric models rather than the contemporary linear regression models. These results add to the existing literature and are helpful for policy formulation.

Regarding the second hypothesis, which concerns the presence of a heterogeneous relationship be-

Table 5. Summarized results of hypotheses testing

Hypothesis	Statement	Result	Explanation
<i>H1</i>	R&D reduces carbon emissions	Positive effect at high quantiles	R&D in high-emission countries supports growth, increasing emissions in the short term
<i>H2</i>	R&D impact varies across emission levels	Heterogeneous effect confirmed	Impact is stronger (positive) in high-emission economies
<i>H3</i>	Economic policy uncertainty increases carbon emissions	Mixed: negative at low, positive at high quantiles	Economic policy uncertainty delays green investments in high-emission economies
<i>H4</i>	Economic policy uncertainty weakens R&D's positive impact on emissions	Negative interaction term, significant	Economic policy uncertainty moderates R&D impact by forcing cautious investment
<i>H5</i>	Economic policy uncertainty's moderating effect varies by emission level	Stronger moderation at high quantiles	Economic policy uncertainty has a greater effect in high-emission countries

tween R&D and emissions, the relationship receives support from quantile regression, as R&D is documented to have a non-uniform impact across economies. For countries with already high emissions, R&D may initially support economic growth (and emissions), whereas its long-term environmental benefits are found to be less immediate. The results are thus supportive of promoting tailored policies for a diverse set of countries depending on their level of emissions and technological advancement.

The third hypothesis related to economic policy uncertainty and emissions is partially supported as the findings provide a mixed effect wherein the relationship is found to be negative at lower quantiles that turn positive at higher quantiles. The results provide support for economic policy uncertainty in low-emitting countries, wherein policy uncertainty further reduces industrial activity, thereby indirectly reducing emissions, while the high emitters are stuck in a ripple effect wherein uncertainty delays green investments and enforcement of environmental regulations, leading to increased emissions. However, when a traditional panel regression approach is applied, economic policy uncertainty exhibits a consistent negative impact on emissions across the full sample of fifteen countries. This discrepancy highlights the limitations of mean-based estimations, which fail to capture the distributional variations observed in quantile regressions. The contrast between panel and quantile regression results underscores the importance of accounting for heterogeneity in emissions data, as the impact of economic policy uncertainty is not uniform across countries with varying emission levels. Therefore, while the hy-

pothesis is partially validated, the findings advocate for the use of distributional analysis methods to uncover nuanced policy implications.

The testing of the fourth hypothesis using the moderation analysis provides that the economic policy uncertainty as a moderator has a partial impact on the emissions. In the panel regression, the interaction term between R&D and economic policy uncertainty is found to be statistically insignificant, indicating that the mean model is unable to produce any significant results. The quantile regression results, however, provide a different output wherein the interaction term not only turns negative but is also found to be statistically significant at the higher quantiles (Q70 and Q80), thereby supporting the presence of a heterogeneous relationship. The findings underscore the importance of contextualizing the moderating role of economic policy uncertainty, where its influence is more pronounced in emission-intensive economies, validating the fifth hypothesis in a heterogeneous framework. This indicates that the ability of economic policy uncertainty to influence the effectiveness of R&D in reducing emissions is not uniform across countries. Specifically, in high-emission economies, policy uncertainty acts as a catalyst, driving firms to adopt cleaner technologies and more environmentally conscious R&D strategies, possibly due to heightened pressure from policymakers, global stakeholders, and future regulatory expectations.

The findings offer policymakers actionable insights to mitigate emissions by promoting policy certainty and incentivizing long-term green research and development investments.

4. DISCUSSION

Panel and quantile regression used in the study provide important implications for the global economy. Based on the results of G20 economies, other countries can take the necessary steps to contribute toward mitigating emissions. The findings of panel regression provide for a significant negative impact of technological innovation, proxied by R&D expenditure, on carbon emissions, indicating that a paradigm shift toward energy efficiency, due to increased R&D expenditure, leads to a reduction in emissions. This aligns with the argument that technological advancements and innovation play a crucial role in driving sustainable development (Abid et al., 2022). However, this finding should be interpreted in light of the broader innovation literature, which often distinguishes between “dirty innovation” (which enhances productivity but may increase emissions initially) and “clean innovation” focused on environmental gains. The results suggest that policy frameworks are essential in steering R&D investments toward environmentally beneficial outcomes (Awaworyi Churchill et al., 2019).

Similar results are obtained in the cases of economic policy uncertainty and emissions, wherein rising uncertainty across economies leads to a reduction in emissions. When economies face uncertain times, it leads to decreased demand and industrial production, which brings a reduction in emissions (Ali et al., 2022). Nonetheless, this contrasts with studies that emphasize how prolonged policy uncertainty can discourage green investments (Baker et al., 2016). Hence, while short-term industrial slowdowns may reduce emissions, long-term policy inconsistency can derail sustainability goals. However, when interaction terms between R&D and economic policy uncertainty are introduced, their effects become statistically insignificant, implying that economic policy uncertainty does not significantly moderate the relationship between R&D and emissions in a panel setting (Alam, 2025). This supports the argument of “scale effects” in environmental economics, where innovation can initially drive emissions through industrial expansion before yielding environmental benefits. Such dynamics underscore the importance of innovation type and sectoral focus.

To provide a robust understanding of the results, the study has used quantile regression that provides deeper insights into the innovation and emission nexus. While panel regression indicates a negative impact of R&D on emissions, the results vary significantly across different quantiles, both in terms of direction and significance. In comparison, technological innovation leads to increased emissions at all quantiles, supporting the viewpoint that a shift toward advanced technology leads to expansion in emissions. This is later reversed when economic policy uncertainty is used as a moderator. When economies ultimately shift toward energy-efficient technology, it ultimately reduces emissions (Mani Upadhyaya et al., 2025). Economic policy uncertainty also shows a varied impact at different quantiles, with economic policy uncertainty increasing emissions in highly polluting economies, as it may deter firms from investing in long-term sustainability efforts. This suggests that while short-term uncertainty may lead to temporary emission reductions, its prolonged presence in high-emission countries may hinder green investments, emphasizing the need for stable and supportive policy environments. The results thereby add to the existing literature wherein economic policy uncertainty has been used as an explanatory variable in the mean model, thereby excluding the heterogeneous impact (Alam, 2025).

The interaction term between R&D and economic policy uncertainty, which was insignificant in the panel regressions, turns significantly negative at higher quantiles, implying that the combined effect of innovation and economic uncertainty plays a more crucial role in heavily polluting countries (Abid et al., 2022). This suggests that while R&D alone may not always lead to emission reductions, its impact is strengthened in high-emission nations when economic uncertainty is low. Thus, stable policy environments can enhance the effectiveness of technological innovations in mitigating emissions, reinforcing the importance of policy consistency in climate action strategies.

As far as control variables are concerned, GDP, trade openness, population, and financial development are found to be significant across the various quantiles, determining their impor-

tance in the R&D–emissions nexus. In fact, all the variables are found to significantly increase emissions at all quantile levels, determining the importance of these factors.

Overall, these findings provide strong evidence that while economic growth and population expansion continue to be major contributors to carbon emissions, R&D investments have the potential to mitigate environmental degradation, particularly in highly polluting economies, while controlling for economic policy uncertainty. However, the effectiveness of such investments is contingent upon stable economic policies, as uncertainty can diminish the incentives for firms to engage in long-term sustainable innovation. Financial development and trade openness show non-uniform effects, highlighting the complexity of their roles in influencing emissions. These insights emphasize the need for nuanced, country-specific policy approaches that balance economic development with sustainability goals. Encouraging R&D while ensuring stable economic policies, promoting green financial mechanisms, and implementing effective trade policies are crucial in steering G20 countries toward a low-carbon future.

The results of the study, however, support existing studies in highlighting the relationship between technological innovation and emissions. The novelty of the study lies in identifying the heterogeneity of this relationship by using quantile regression, which reveals that the impact of R&D on emissions is not uniform across all emission levels. Another novelty of the study lies in testing the impact of economic policy uncertainty as an independent as well as a moderating variable, which has not been used in any of the earlier studies.

Future research can further expand on these findings by incorporating sector-specific analyses, as the impact of R&D and economic policy uncertainty may vary across industries. Moreover, extending the analysis to a broader set of countries, including emerging economies outside the G20, can offer a more comprehensive understanding of global decarbonization strategies. By addressing these gaps, future research can contribute to more effective policy-making, ensuring that technological advancements and economic policies align with global sustainability goals.

CONCLUSION

The study aimed to empirically test the impact of economic policy uncertainty on the R&D–emissions nexus across the G20 economies. The paper examined the dual impact of economic policy uncertainty, first as an individual explanatory variable and secondly as a moderator in the relationship between technological innovation and emissions. To test the traditional linear and advanced heterogeneous relationship between the variables, the study used quantile regression in addition to the linear panel regression to test the robustness of the results.

The analysis revealed a heterogeneous relationship between R&D and carbon emissions across the sample economies, with significant effects at both lower and higher quantiles. The results showed that though technological innovation is theoretically associated with green growth, the environmental benefits are not found to be uniform across all the economies, biased toward the existing level of emissions. In certain contexts, especially in high-emission countries, R&D may initially contribute to increased emissions due to its association with industrial expansion and productivity enhancements.

Regarding the impact of economic policy uncertainty on the relationship between R&D and emissions, the results are found to be quantile-dependent. While short-term policy vulnerability can assist in reducing emissions by dampening economic activity, prolonged uncertainty discourages long-term green investments, particularly in economies with higher emission levels. The results highlighted a significant negative relationship at the higher quantiles, providing for a strong impact of economic policy uncertainty on the emission reduction potential of technological innovation, especially in the emission-intensive economies.

The results thereby highlight the context-specific impact of R&D on emission reduction that is not only dependent on the existing level of carbon footprints across the economies but also on the present state of the economic policy environment. The study highlights the importance of stable and consistent policy frameworks to ensure that technological innovation is effectively translated into environmental benefits.

These findings underscore the critical role that policy consistency plays in fostering environmental innovation. In particular, the stability and predictability of economic and regulatory frameworks are essential for encouraging firms to undertake long-term investments in clean and sustainable technologies. When businesses operate in environments characterized by frequent policy shifts, ambiguity, or economic uncertainty, they may be less inclined to allocate resources toward innovation, especially in areas that require substantial upfront investment and yield long-term benefits, such as renewable energy, green infrastructure, or carbon-reducing technologies.

Governments must, therefore, prioritize the development of clear, coherent, and stable environmental and economic policies that provide strong and sustained signals to the private sector. This includes setting long-term emission reduction targets, offering consistent tax incentives or subsidies for the adoption of clean technology, and minimizing abrupt regulatory changes that could disrupt investment planning. Stable policies not only reduce perceived risks but also build investor and industry confidence, which is vital for the diffusion of green innovation across sectors. Moreover, a predictable policy environment can enable better coordination between public institutions, private enterprises, and international partners, creating an ecosystem where sustainable innovation thrives. Such an approach is especially relevant for G20 nations, whose economic and environmental decisions have global spillover effects. By aligning economic stability with climate goals, governments can ensure that environmental progress is not undermined by short-term uncertainty, thereby reinforcing the innovation–emissions reduction nexus at both national and international levels.

Future research could explore sectoral variations and the role of financial incentives in mitigating the adverse effects of uncertainty on green investments. By fostering policy stability and supporting R&D-driven innovation, economies can accelerate their transition toward a low-carbon future. By addressing these avenues, future studies can provide more targeted policy recommendations, ensuring that technological progress and economic policy align effectively with global sustainability objectives.

AUTHOR CONTRIBUTIONS

Conceptualization: Dharmendra Singh, Shikha Daga.

Data curation: Shikha Daga, Umar Ahmed.

Formal analysis: Dharmendra Singh, Shikha Daga.

Investigation: Shikha Daga.

Methodology: Shikha Daga, Umar Ahmed.

Project administration: Shikha Daga.

Resources: Shikha Daga.

Software: Dharmendra Singh.

Supervision: Muhammad Naeem, Shikha Daga.

Validation: Muhammad Naeem, Shikha Daga.

Visualization: Muhammad Naeem, Shikha Daga.

Writing – original draft: Dharmendra Singh, Muhammad Naeem, Shikha Daga, Umar Ahmed.

Writing – review & editing: Dharmendra Singh, Muhammad Naeem, Shikha Daga, Umar Ahmed.

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