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Effects of economic policy uncertainty, economic growth and green technologies on environmental degradation in India

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Abstract

Past studies have overlooked the asymmetric influence of EPU and green technologies on environmental quality in India. This gap limits our understanding of how these factors impact emissions. As a result, this study aims at addressing this gap by examining the impact of green technologies (GT), economic growth (GDP) and EPU on CO₂ emissions in India using advanced techniques including wavelet quantile regression and quantile on quantile Granger causality from 1990 to 2023. The results highlight that GT and EPU consistently reduce CO₂ emissions across major quantiles and all frequencies, while increases in economic development are connected to increases in CO₂ emissions in this economy. In addition, the causality estimates point out that all predictors, namely GT, GDP and EPU, remarkably predict CO₂ emissions across the distribution. These outcomes emphasize the importance of integrating GT into economic development and carrying out strategic economic policies to support carbon reduction and long-term environmental sustainability in India.

Keywords Green technology, EPU, GDP, CO₂ emissions, Quantile analysis

JEL Classification Q53, Q55, Q56

1 Introduction

Environmental degradation (ED) has become a critical challenge for sustainable development, particularly in emerging economies where rapid economic expansion continues to rely heavily on fossil fuels [11, 12, 36, 38]. India, one of the world's fastest-growing economies and third-largest CO₂ emitter, faces pressure to balance industrialization with environmental protection [25]. Despite strong national commitments to sustainable development and clean energy transitions, the country still exhibits high dependence on carbon-intensive energy sources, making it vulnerable to rising emissions and climate-related risks.

Although an increasing body of research addresses environmental issues, somewhat few recent studies have centered particularly on the influence of EPU and economic development on climate change across countries [4, 18, 33, 35, 36]. In India, works by



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Iqbal et al. [25], Chen et al. [17], Oprea et al. [39] and Albassam et al. [6], investigate how EPU affects the environment. Meanwhile, increasing scholarly attention has been directed toward the role of GT in decreasing environmental pollution [6, 19, 23]. Recognizing the diverse environmental consequences of economic activity, a change from fossil fuels to renewable energy is often recommended to mitigate CO₂ emissions in connection with energy consumption. This study aims to estimate the remarkable influence of both EPU and green technologies on environmental pollution, providing valuable insights into the complex interaction between economic governance and environmental sustainability.

In this context, green technology development and transfer are vital for achieving the 2030 SDGs, as they boost social, economic, and environmental sustainability [3, 39]. In light of growing environmental concerns, India has actively pursued strategies aimed at transitioning from environmentally detrimental energy sources to more sustainable alternatives [14, 17]. This change is particularly critical given that the energy sector remains the primary source of the country's greenhouse gas emissions. In India, conducting such technologies calls for structural changes in production, backed by economic incentives and policies suited to local socio-economic conditions. The transition to a green economy entails the substitution of environmentally damaging industrial technologies with green alternatives, thereby fostering economic development while reducing ecological issues [25]. Although a growing body of literature has examined these relationships globally, empirical evidence for India, especially regarding asymmetric, nonlinear, and time-varying effects, remains limited.

Furthermore, India has recently become a focal point in the global discourse on achieving the Sustainable Development Goals, which encompass social, economic, and environmental dimensions [6, 24, 28]. The worldwide challenges posed by environmental matters like climate change, global warming, and air pollution adversely affect economic development. In this context, the present study contributes to the ongoing policy debate on environmental sustainability. Specifically, this study addresses the following research questions:

(1) How does EPU influence CO₂ emissions? (2) What roles do GT and GDP play in determining CO₂ emissions? (3) Are there variations in these interactions across different quantiles and timescales?

Therefore, this study contributes meaningfully to the existing literature in multiple ways. First, there is limited empirical evidence on the influence of the aforementioned factors on ED in the Indian context. Second, to address this research gap, the study employs two advanced quantile-based empirical methods, wavelet quantile regression (WQR) and quantile-on-quantile Granger causality (QQGC) to provide nuanced insights into the associations between CO₂ emissions and its determinants under conditions of heterogeneity [2, 5]. These approaches are particularly well-suited for capturing asymmetries and nonlinear dynamics, given their robustness to diverse data distributions [1]. Finally, the results of this research are expected to provide valuable guidance for policymakers in designing or revising sustainable development strategies.

The rest of the paper is organized as follows: Sect. 2 offers a review of the relevant literature. Section 3 details the data and methodology. Section 4 represents empirical results and discusses them in the context of existing research. Lastly, Sect. 5 concludes the study by summarizing the key findings and their implications.

2 Literature review

2.1 EPU and CO₂ emissions

Policy uncertainty tends to raise production costs and dampen investment activity [29, 30]. It significantly influences manufacturing decisions. Besides, elevated economic uncertainty serves as an early indicator of recessions, as firms typically delay or reduce investment and spending under uncertain conditions [7]. This uncertainty can disrupt production schedules, thereby affecting CO₂ emissions. EPU, in particular, would impact pollution indirectly through its impact on economic growth. EPU also reduces corporate hiring and capital investment, hindering overall economic performance [46]. Increased policy uncertainty leads firms to adopt more conservative investment strategies due to concerns about future government regulations and tax reforms.

Mushtaq et al. [34] report that both the direct and indirect effects of EPU on CO₂ emissions via the investment channel are positive, supporting the Environmental Kuznets Curve hypothesis. Additionally, their results indicate that fossil fuel consumption contributes to rising CO₂ emissions. Wang et al. [46] argue that both increases and decreases in economic policy uncertainty significantly reduce transport CO₂ emissions, suggesting that uncertainty, regardless of its nature, dampens activity in the transport sector. In their analysis of energy uncertainty and its effects on pollution and energy consumption, Ma et al. [29] report a significant positive interplay between the Energy Uncertainty Index and CO₂ emissions, emphasizing how policy unpredictability can intensify environmental degradation. Similarly, according to Aslan et al. [7], long-term analysis shows that economic policy uncertainty lowers emissions at all quantile levels in G7 countries when fossil fuel energy consumption is used as the measure of energy use. Dunyo et al. [20] demonstrate that uncertainty exerts a direct, negative, and statistically significant effect on emissions.

Wang et al. [45] demonstrate that the quantiles of green energy transition exhibit a positive relationship across all CO₂ quantiles. Additionally, while the relationship between eco-innovation and CO₂ appears modestly beneficial across the distribution, the presence of positive slope coefficients highlights the influence of EPU on CO₂ emissions within the 0.2–0.95 quantile range. Mohanty et al. [33] emphasize that the combined influence of rising nuclear energy usage and declining EPU contributes to a reduction in emissions. According to Chiou et al. [18], CO₂ emissions are significantly influenced over the long term by political variables, including economic policy uncertainty and the prevailing political environment. Recently, Albassam et al. [6] confirm the EKC hypothesis: GDP growth first increases and later reduces CO₂ emissions. EPU, however, worsens environmental quality by raising CO₂ levels.

2.2 GDP and CO₂ emissions

Numerous empirical investigations have independently explored the interaction between ED and GDP [8, 22, 32, 35]. These studies consistently identify an inverted U-shaped nexus between pollution indicators and per capita income, commonly referred to as the Environmental Kuznets Curve (EKC) due to its similarity to the Kuznets Curve introduced by Kuznets [26] in the context of income inequality. Focusing on India, this study examines the interplay between green energy, GDP, and environmental sustainability. It employs the EKC framework to assess how innovation and policy can decouple emissions from growth. The findings are intended to guide policymakers in crafting

sustainable development strategies, supported by a solid theoretical model. For example, in a study of the 27 EU countries, Onofrei et al. [38] identify a long-term cointegrating linkage between GDP and CO₂ emissions. The results reveal a statistically significant effect, showing that a 1% increase in GDP results in a 0.072% increase in CO₂ emissions on average. Naseem et al. [36] propose that the transition of GDP's impact on CO₂ emissions from positive to negative across quantiles indicates that GDP would contribute to emissions reduction. This pattern reflects a shift in developed economies from dependence on non-renewable to renewable energy sources. Chamakhi et al. [13] look into the nexus between transportation, GDP, and CO₂ emissions in the United States. This study adds to the growing body of literature on sustainable transportation by underscoring its significance for both economic growth and environmental protection.

An expanding body of literature has examined the interaction between CO₂ emissions and GDP at global [36, 38], regional [21], and national levels. In the context of developing countries, Mikayilov et al. [32] report that GDP exerts a positive and statistically significant effect on long-run emissions in Azerbaijan, suggesting that the EKC hypothesis does not hold in this case. Namahoro et al. [35] report that while GDP generally reduces CO₂ emissions in Africa, the effect differs depending on regional and income-based distinctions. Additionally, their impulse response and variance decomposition outcomes indicate that GDP and energy intensity are primary contributors to emission fluctuations, while renewable energy adoption significantly helps reduce emissions within a 10-year period. Awan et al. [8] investigate the joint nonlinear effects of urbanization and economic growth on environmental quality in Malaysia, applying the EKC framework. Their findings support the validity of the EKC hypothesis and reveal a U-shaped relationship between urbanization and environmental outcomes in both the short and long run. Raza and Tang [41] reveal that, although GDP and merchandise trade have the smallest contributions to CO₂ emissions, 0.12% and 0.13% they still contribute positively to environmental degradation. As a solution, they propose that Pakistan leverage carbon pricing and introduce subsidies to promote environmental protection. Recently, Prakash [40] identifies a linear relationship between economic growth and CO₂ emissions across 190 countries, thereby challenging the validity of the EKC hypothesis.

2.3 GT and CO₂ emissions

The interactions between green technology and CO₂ emissions are rooted in environmental economics and innovation theory [48, 50]. GT refers to environmentally friendly innovations that aim to reduce air pollution, enhance energy efficiency, and enhance sustainable development. Theoretically, GT adoption is expected to lower CO₂ emissions by transforming production processes, energy consumption, and resource consumption [9, 15, 44]. A central foundation is also the EKC hypothesis, which suggests that environmental pollution initially increases with GDP but gradually decreases as income increases and societies demand cleaner technologies. GT plays an important role in this transition, acting as a tool that enables economies to develop while reducing their environmental footprint [27, 43, 49].

Using data from 30 provinces in China, Chen et al. [16] document that the direct effect of GT on regional carbon intensity follows an inverted-U pattern, initially contributing to higher carbon emissions at lower innovation levels, but eventually reducing emissions once innovation reaches a critical point. Zhao et al. [49] also demonstrate that

GT remarkably decreases carbon emissions and exerts positive relationship on neighboring regions. The magnitude of this influence covaries across different regions, with the eastern provinces experiencing the strongest effects, followed by the western and central regions. Similarly, according to Zhao et al. [50], environmental efficiency can be improved through industrial optimization, energy use reduction, green innovation, and stronger environmental policies. Lin and Ma [27] suggest that the influence of green technology innovations covaries across different types of cities. Their results reveal that these innovations began to play a meaningful role in reducing CO₂ emissions in Chinese cities.

Bilal et al. [9] examine the association between technological innovation, globalization, and CO₂ emissions in the One Belt One Road countries. Their findings highlight a statistically significant negative association between technological innovation and CO₂ emissions across all regions. Majekodunmi et al. [31] explore the environmental implications of green technology and export activities in Malaysia. The findings suggest that while population growth and green technology adoption contribute to reducing environmental degradation, exports and sustained economic growth exacerbate environmental pollution. Similarly, Cheah et al. [15] uncover that green organizational innovations significantly boost environmental and social outcomes, while green process innovations mainly affect social performance. Green marketing innovations enhance both outcomes indirectly by promoting other innovative efforts. In their analysis of 25 European countries, Obobisa and Ahakwa [37] document that renewable energy, environmental taxes, and human capital reduce CO₂ emissions, whereas green innovation, financial development, nonrenewable energy consumption, and GDP per capita drive emissions upward.

In the Indian context, Iqbal et al. [25] illustrate that EPU has a considerable positive influence on carbon dioxide emissions over both the short and long term. By contrast, clean energy usage and urbanization are associated with improved environmental quality, whereas GDP results in higher CO₂ emissions. The findings of Chen et al. [17] confirm that heightened EPU remarkably contributes to a reduction in per capita CO₂ emissions. Oprea et al. [39] reveal that CO₂ emissions are significantly driven by both GDP growth and population expansion, whereas increased renewable energy consumption helps mitigate CO₂ emissions. Recently, Albassam et al. [6] put forward that while GDP initially contributes to increased CO₂ emissions, it eventually results in emission reductions, thereby supporting the EKC hypothesis. Besides, urbanization is positively associated with environmental quality, and renewable energy consumption plays a significant role in mitigating CO₂ emissions. In contrast, EPU intensifies environmental degradation by driving up CO₂ emissions.

This presents a research gap our work aims to tackle by looking into the asymmetric interactions between GT, EPU, GDP and CO₂ emissions in India using WQR and QQGC tests. Through the application of WQR and QQGC analysis, the study seeks to enhance understanding of the complex linkages between economic activity, energy transitions, and environmental quality.

3 Methodology

3.1 Wavelet quantile regression (WQR)

The conventional quantile regression model for two variables is as follows:

$$\theta_{(\tau)}(Y|X) = B_{0(\tau)} + B_{1(\tau)}X \quad (1)$$

where $\theta_{(\tau)}(Y|X)$ is the conditional quantile of the dependent variable Y given the independent variable X at quantile τ , $B_{0(\tau)}$ is the intercept parameter at quantile τ , and $B_{1(\tau)}$ is the slope parameter at quantile τ .

Adebayo and Özkan [1] introduce WQR to examine the influence of an independent variable X on the conditional quantiles of a dependent variable Y across different time scales. The implementation procedures of the WQR model are as follows:

First, dependent Y and independent X are decomposed using the maximal overlapping discrete wavelet transform as below:

Let $X(i)$ a signal with a length of T , $T = 2^J$ for an integer J . As a result, consider $h_1(i)$ as the low-pass filter and $g_1(i)$ as the high-pass filter. The process of estimating coefficients of $\alpha_1(i)$ and $d_1(i)$ of length $\mathbb{N}$ is defined as follows:

$$\alpha_1(i) = h_1(i) * s(i) = \sum_k h_1(i-k) s(k) \quad (2)$$

$$d_1(i) = g_1(i) * s(i) = \sum_k g_1(i-k) s(k) \quad (3)$$

Then, the recursive process is conducted iteratively. For values of J spanning from 1 to $J_0 - 1$, we calculate coefficients of the approximate and detailed as follows:

$$\alpha_{j+1}(i) = h_{j+1}(i) * \alpha_j(i) = \sum_k h_{j+1}(i-k) \alpha_j(i) \quad (4)$$

$$d_{j+1}(i) = g_{j+1}(i) * \alpha_j(i) = \sum_k g_{j+1}(i-k) \alpha_j(i) \quad (5)$$

The WQR for the dependent variable Y and the independent variable X , at a specific decomposition level J , and for a given quantile τ can be written as follows:

$$\theta_{(\tau)}(d_j(Y)|d_j(X)) = B_{0(\tau)} + B_{1(\tau)}d_j(X) \quad (6)$$

3.2 Quantile on quantile Granger causality (QQGC)

According to the conventional Granger causality framework developed by Granger (1969), we can evaluate whether variable X provides significant information for predicting variable Y , as follows:

$$Y_t = \alpha_0 + \sum_{i=1}^p \alpha_i Y_{t-i} + \sum_{i=1}^p \gamma_i X_{t-i} + \varepsilon_t \quad (7)$$

where α_0 and p are constant term and lag order. α_i and γ_i describe coefficients of the lagged values of Y and X . ε_t is the error term.

Adebayo and Özkan [1] overcome this limitation by proposing the QQGC approach, as illustrated below.

$$QY_{\tau,t} = \alpha_{\tau,\theta,0} + \sum_{i=1}^p \alpha_i QY_{\tau,t-i} + \sum_{i=1}^p \gamma_i QX_{\theta,t-i} + \varepsilon_{\tau,\theta,t} \quad (8)$$

where the constant term at quantiles τ and θ is described by $\alpha_{\tau,\theta,0}$, α_i and β_i present the coefficients of the lagged conditional quantiles of Y and X and $\varepsilon_{\tau,\theta,t}$ is error term at time t quantiles τ and θ . Figure 1 outlines the analytical steps for the sake of brevity.

The application of WQR and QQGC in the current work is grounded in their ability to capture sophisticated, nonlinear, and frequency-dependent co-movements that traditional econometric techniques cannot adequately identify [47]. Environmental, technological, and macroeconomic indicators often exhibit time-varying relationships and asymmetric effects across different emission levels, making distribution-sensitive and scale-sensitive methods essential. WQR is particularly appropriate for this purpose because it combines quantile regression with wavelet-based multiresolution decomposition, allowing the influence of EPU, GDP, and GT on CO₂ emissions to be examined separately in the short, medium, and long run [2, 5, 42]. In a similar fashion, the QQGC model extends conventional causality tests by assessing predictive associations across pairs of quantiles of both the predictor and response variables, making it possible to detect nonlinear and tail-dependent causality patterns. Overall, these approaches provide a statistically rigorous and highly flexible methodological framework capable of

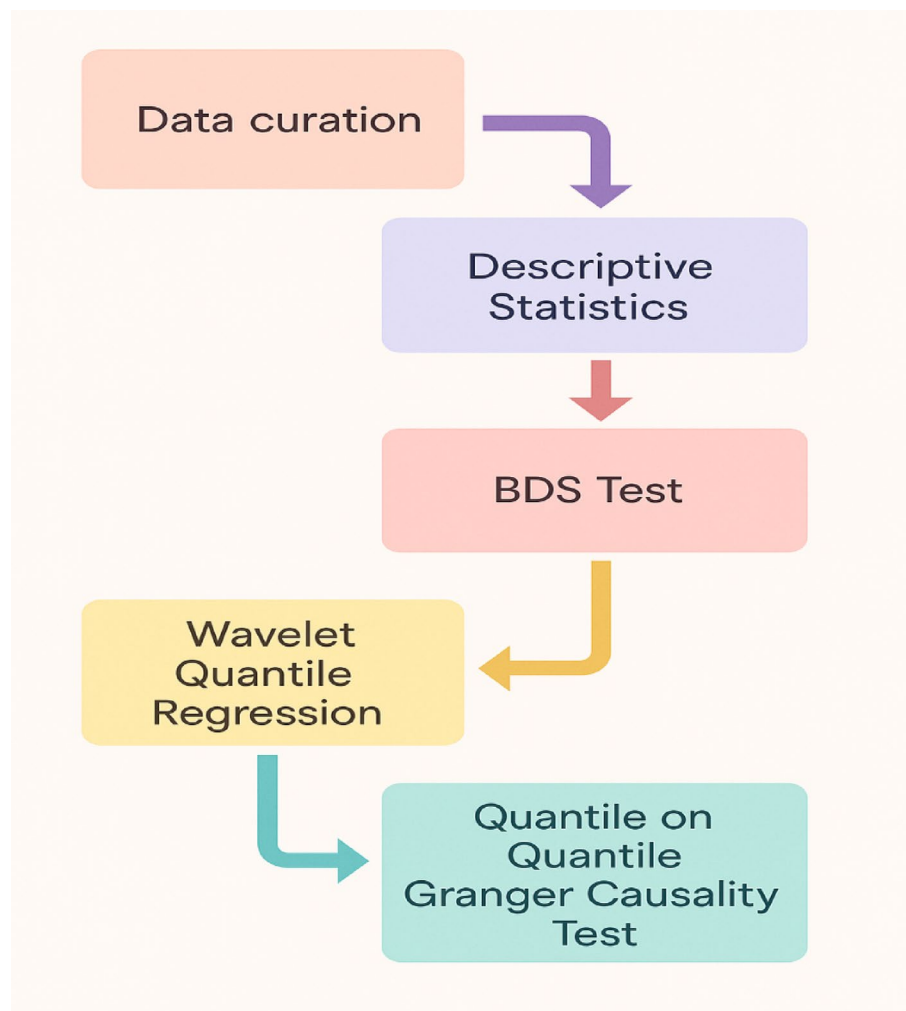


Fig. 1 Framework of the proposed methodology

Table 1 Summary of variables

Variable	Indicator	Definition	Source
GDP	GDP per capita	Constant 2010\$US	WDI
GT	Green technology	Measured as the number of patents in environmental technologies, reflecting innovation activity in green and sustainable technologies	OECD
CO2	Carbon dioxide emissions	Metric ton per capita	WDI
EPU	Economic policy uncertainty	Uncertainty related to economic and policy conditions	https://www.policyuncertainty.com/

Table 2 Descriptive statistics

	CO2	GT	GDP	EPU
Mean	0.062853	3.710726	8.086645	0.120193
Median	0.056000	3.720739	8.120075	0.109820
Max	0.123000	3.833350	9.226828	0.240525
Min	0.026000	3.530318	7.100013	0.000000
Std.Dev	0.028390	0.069556	0.634411	0.065653
Skewness	0.438669	-0.438004	0.046998	0.141526
Kurtosis	1.983964	2.852960	1.786187	1.846218
JB	2.552908	1.117765	2.099752	1.999385
Prob	0.279025	0.571848	0.349981	0.367993

uncovering asymmetric, nonlinear, and frequency-dependent dynamics that conventional econometric models cannot estimate [1].

3.3 Data

The aim of this article is to examine the influence of green technology (GT), economic growth (GDP) and economic policy uncertainty (EPU) on CO2 emissions (CO2) in India. The research sample selected for this study is from 1990 to 2023. The annual data are converted to quarterly frequencies using the quadratic match-sum technique proposed by Adebayo and Özkan [1], which accounts for seasonality and cyclical volatilities in the data. This approach produced more reliable results by minimizing short-term fluctuations and isolating the non-seasonal component, thereby enhancing confidence in the results despite data limitations. The data for each series are extracted from different sources. The indicators are represented in Table 1 with all time series expressed in natural logarithmic form.

Table 2 documents the descriptive statistics for the selected indicators in India. It is obvious that all time series experience a positive average value during the research period. GDP stands out as the most volatile in the sample, while CO2 has the lowest volatility. In addition, the skewness coefficients suggest that CO2, EPU and GDP depict positive values except for GT, revealing that the data lacks perfect symmetry. As for kurtosis, all indicators exhibit platykurtic distributions in the sample, with values less than three, indicating lighter tails compared to the normal distribution.

Figure 2 illustrates the Q-Q plot estimates. The close alignment of the data points with the diagonal line indicates a strong agreement between the sample quantiles and those of a normal distribution. Specifically, the blue points suggest no significant deviation above or below the red reference line, implying that the time series data conform to a normal distribution.

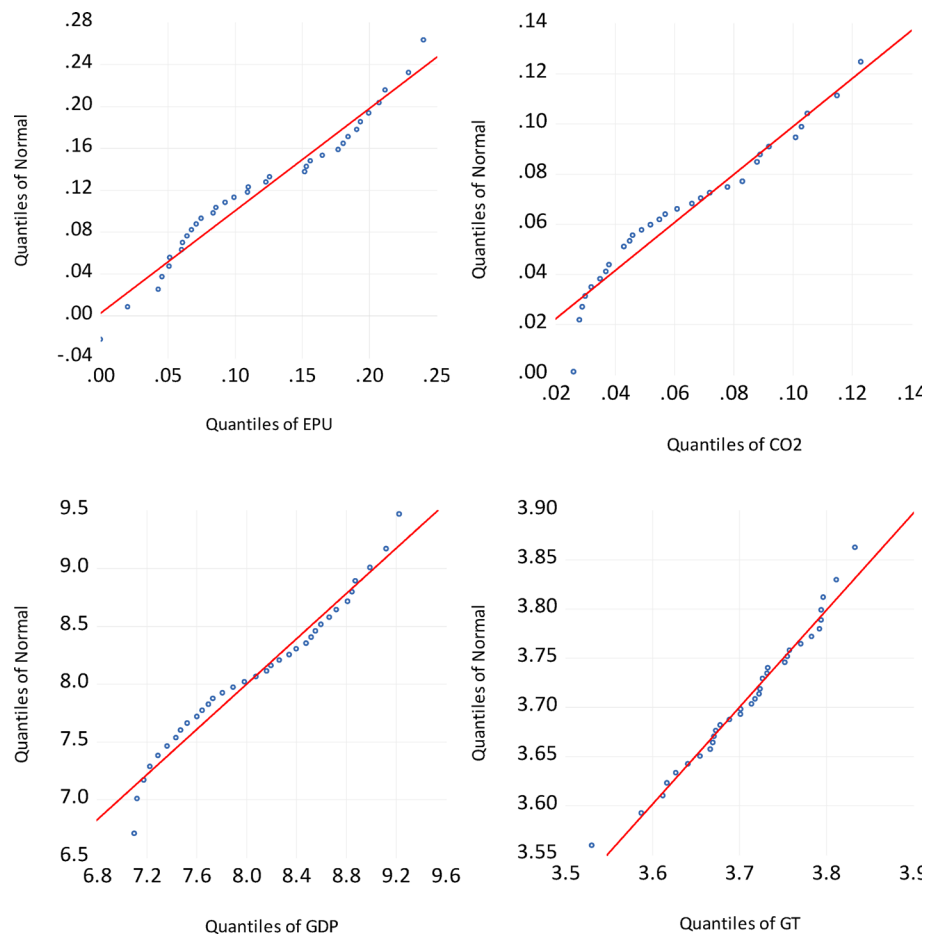


Fig. 2 Q-Q Plot

Figure 3 demonstrates the linear correlation between GDP, EPU, GT and CO₂. The results provide straightforward insights into the intercorrelations between indicators under consideration. Importantly, all indicators experience a positive correlation with CO₂ emission in India.

It is important to choose a suitable methodology that is in line with the property of the data, as results derived from an ill-suited model might result in misinterpretation. As a result, we apply the BDS test developed by Broock et al. [10] to detect the existence of non-linearity in this study. Table 3 shows findings of the BDS test to assess the linearity characteristics of the indicators under investigation. The null hypothesis is rejected for each variable across different embedded dimensions, which highlights the persistence of non-linear for all selected indicators. The affirmation of non-linearity reveals the appropriateness of using non-linear approaches like wavelet quantile regression and quantile Granger causality in the present study.

Before implementing further analysis, we first evaluate the stationarity properties of the variables. Table 4 reports the results of the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests under the null hypothesis that each series contains a unit root. At levels, the ADF statistics for EPU, GT, GDP, and CO₂ are all insignificant at the 5% level, indicating failure to reject the null of a unit root for any series. The PP test also has a similar conclusion for GT, GDP, and CO₂, while EPU is marginally stationary



Fig. 3 Heatmap correlation matrix

Table 3 Nonlinearity BDS test

Variables	Dimensions					Result
	m = 2	m = 3	m = 4	m = 5	m = 6	
EPU	0.144014***	0.228532***	0.272382***	0.291905***	0.301085***	Nonlinear
GT	0.165422***	0.270366***	0.332242***	0.362880***	0.374885***	Nonlinear
GDP	0.204508***	0.346446***	0.446108***	0.517263***	0.569260***	Nonlinear
CO2	0.193212***	0.324171***	0.414990***	0.478540***	0.525406***	Nonlinear

at the 5% level. Nevertheless, once the series are first-differenced, both tests reject the null hypothesis for all variables: the ADF test indicates stationarity of Δ EPU and Δ GT at the 1% level and of Δ GDP and Δ CO₂ at the 10% level, whereas the PP test rejects the null for all differenced series at the 1% level. Generally, these findings suggest that the variables are integrated of order one, I(1), with some borderline evidence of level stationarity for EPU, and thus justify modeling them as I(1) processes in the subsequent WQR and QQGC analyses.

3.4 Empirical findings

3.4.1 Wavelet quantile regression results

In this paper, we use the WQR model to investigate the influence of EPU, GDP and GT on CO₂ emissions in India. This method determines the quantile impact of these regressors on the independent variables across different frequencies.

Table 4 Stationarity tests results

	EPU	GT	GDP	CO2
<i>Unit Root Test Results (ADF test)</i>				
Null Hypothesis: Variable has a unit root				
At level				
t-statistics	-2.171839	-1.630429	0.981181	2.572340
Prob	0.2176	0.4641	0.9963	1.0000
At first difference				
	d(EPU)	d(GT)	d(GDP)	d(CO2)
t-statistics	-4.147662	-7.985190	-2.823580	-2.775783
Prob	0.0012	0.0000	0.0579	0.0647
<i>Unit Root Test Results (PP test)</i>				
Null Hypothesis: Variable has a unit root				
At level				
t-statistics	-3.013671	-2.347520	1.609778	1.118867
Prob	0.0361	0.1588	0.9995	0.9975
At first difference				
	d(EPU)	d(GT)	d(GDP)	d(CO2)
t-statistics	-11.97589	-5.432218	-5.351455	-5.779708
Prob	0.0000	0.0000	0.0000	0.0000

*** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.1$

Figure 4 shows the estimates of the WQR analysis, which demonstrates the asymmetric influence of EPU, GDP and GT on CO₂ emissions in India across multiple frequencies and quantiles. The results highlight significant asymmetries in these interactions, reflecting the heterogeneous nature of environmental responses to economic and technological conditions in India.

Regarding the effect of EPU, the WQR heatmap reveals a mixed pattern across frequencies. In the long run, EPU has a positive but somewhat weak influence on CO₂ emissions at both the lower and upper quantiles, suggesting that persistent policy uncertainty slightly increases emissions when the economy is operating at very low or very high emission levels. Nevertheless, in the short and medium term, the nexus becomes considerably negative across all quantiles. This indicates that increasing EPU often leads to a contraction in industrial and investment activities, especially in energy-intensive sectors, resulting in lower demand for fossil fuels and consequently reduced CO₂ emissions. In the Indian context, where coal and petroleum products remain dominant, any slowdown in production or investment due to uncertainty directly suppresses carbon emissions. These findings correspond with those reported by Wang et al. [46] and Aslan et al. [7], who observe that EPU tends to mitigate environmental pressure in the short run.

In case of GDP-CO₂ pair, we find that there is significant relationship across multiple quantiles and frequencies. At different quantiles, corresponding to the multiple frequencies, GDP consistently exerts a positive influence on CO₂ emissions, and the magnitude of this impact remains relatively strong. This implies that GDP might enhance the level of CO₂ emission in India. The reasonable explanation for this issue is that economic development is associated with increased energy consumption, industrial activity and transportation, which are primary sources of CO₂ emissions. Additionally, as India's economy expands, driven by construction, manufacturing and infrastructure growth, there is a higher demand for energy. While economic development brings improvement in living standards, without adequate investments in renewable energy and green

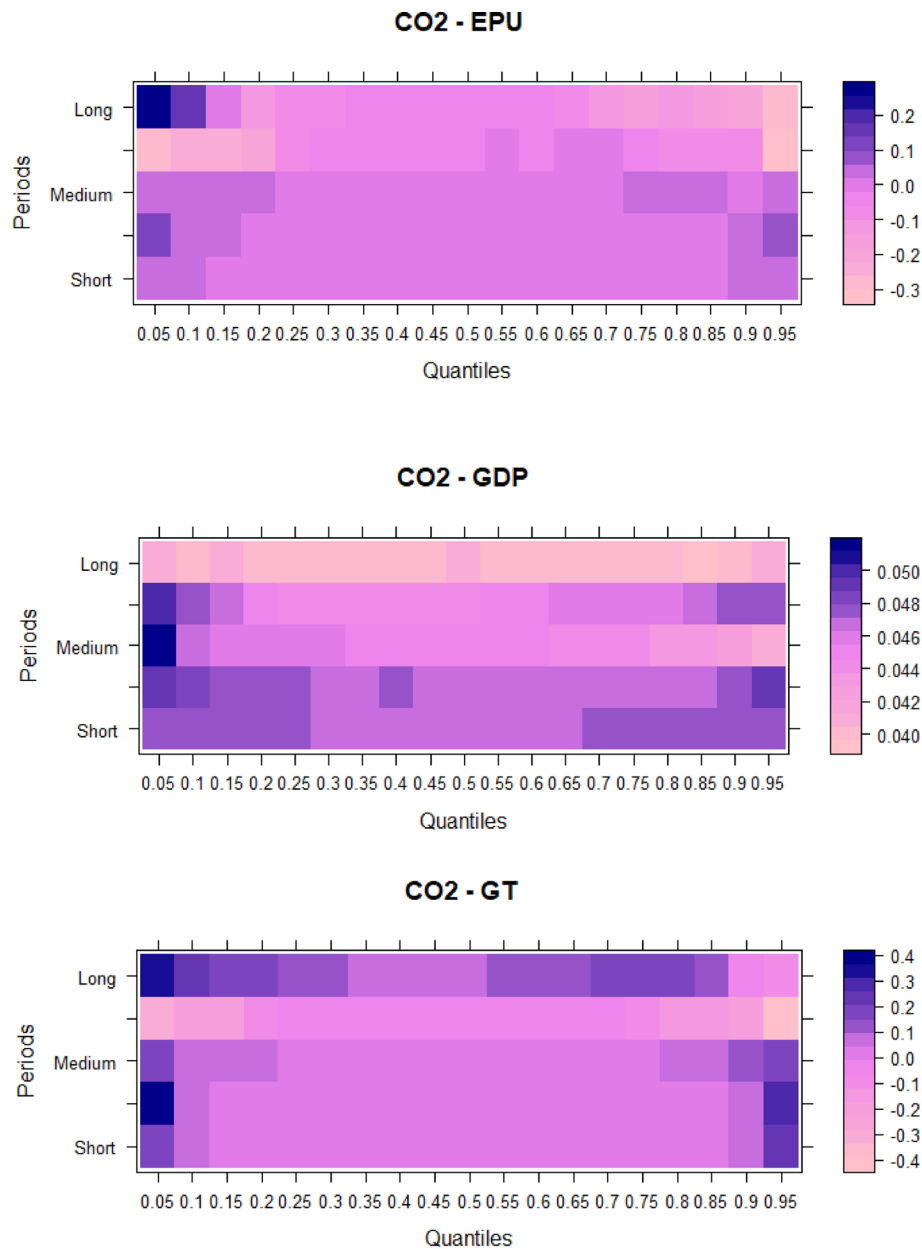


Fig. 4 Wavelet quantile regression results. The heatmaps show the estimated slope coefficients with values spanning from light pink to dark blue

technologies, it tends to exacerbate environmental pollution. These outcomes are in line with studies such as Namahoro et al. [35] and Awan et al. [8], who document that periods of heightened GDP might increase environmental degradation.

Figure 4 shows the impact of GT on CO2 emissions in India, highlighting a consistent negative impact across all frequencies and quantiles. However, we also observe some areas that have dark blue colors, suggesting that there is a positive association between GT and CO2 at lower and higher quantile across different frequencies. Overall, the findings reveal that the negative influence of GT on CO2 is stronger at middle quantiles, compared with lower and higher quantiles across different timescales. This means that although GT initially boosts renewable energy demand to some extent, its broader

impact emerges over the long term, as continued economic development supports the growth of renewable energy infrastructure and encourages wider adoption. Actually, GT has a negative effect on CO₂ emissions in India because it enhances cleaner, more efficient alternatives to traditional, carbon-intensive practices. GT declines the reliance on conventional energy sources like coal and oil by employing advanced technologies like solar and wind power, electric vehicles, energy efficient appliances and sustainable industrial processes, which are the core sources of CO₂ emissions in this country. The results are consistent with the arguments by Chen et al. [16], Zhao et al. [50] and Lin and Ma [27], that GT plays a prominent role in reducing ED.

3.4.2 Quantile on quantile Granger causality tests

In the QQGC test, each cell in the heatmap presents a t -statistic that tests whether the lagged conditional quantiles of the predictor variable X Granger-cause the corresponding conditional quantiles of CO_2 . Formally, the null hypothesis for each cell is:

$$H_0 : \gamma_{\tau,\theta,i} = 0$$

which states that the quantile θ of X does not Granger-cause the quantile τ of CO_2 .

The alternative hypothesis is:

$$H_1 : \gamma_{\tau,\theta,i} \neq 0$$

implying that past values of the θ -quantile of X contain statistically significant predictive information for the τ -quantile of CO_2 .

The heatmaps in Fig. 5 display the corresponding t -statistics for these tests across all combinations of (τ, θ) . Cells marked with *, ** and *** indicate rejection of H_0 at the 10%, 5%, and 1% significance levels, respectively, signaling quantile-specific and direction-dependent causal associations.

The study further employs the QQGC to capture causality between indicators. Figure 5 demonstrates the findings of QQGC running from EPU, GDP and GT to CO₂ emissions in India. For example, GDP depicts strong causality in over different quantiles of CO₂. This indicates that past values of economic growth can predict the future values of carbon emissions in this economy, highlighting a directional impact from economic growth to environmental degradation. Put differently, changes in GDP contain significant information that can be applied to predict environmental quality, but not necessarily the other way around in India. This suggests that as India's economy grows, through increased industrial activity, energy consumption, transportation, and consumption, CO₂ emissions tend to rise as a consequence.

For the pair of EPU-CO₂, the QQGC estimates are statistically significant across quantiles of EPU to CO₂, particularly middle and high quantiles of CO₂. This implies that an increase in EPU in India, likely connected to economic policy, would strongly impact CO₂ emissions. In other words, EPU help predict future changes in CO₂ emissions, which suggests a time-dependent impact of policy uncertainty on environmental outcomes. Importantly, when there is high uncertainty about economic policies like unclear regulations, fiscal instability, or unpredictable government decisions, businesses and investors could delay or reduce investments in clean energy projects and environmentally friendly technologies. This hesitation would result in continued reliance on conventional, carbon-intensive energy sources, thereby increasing CO₂ emissions.

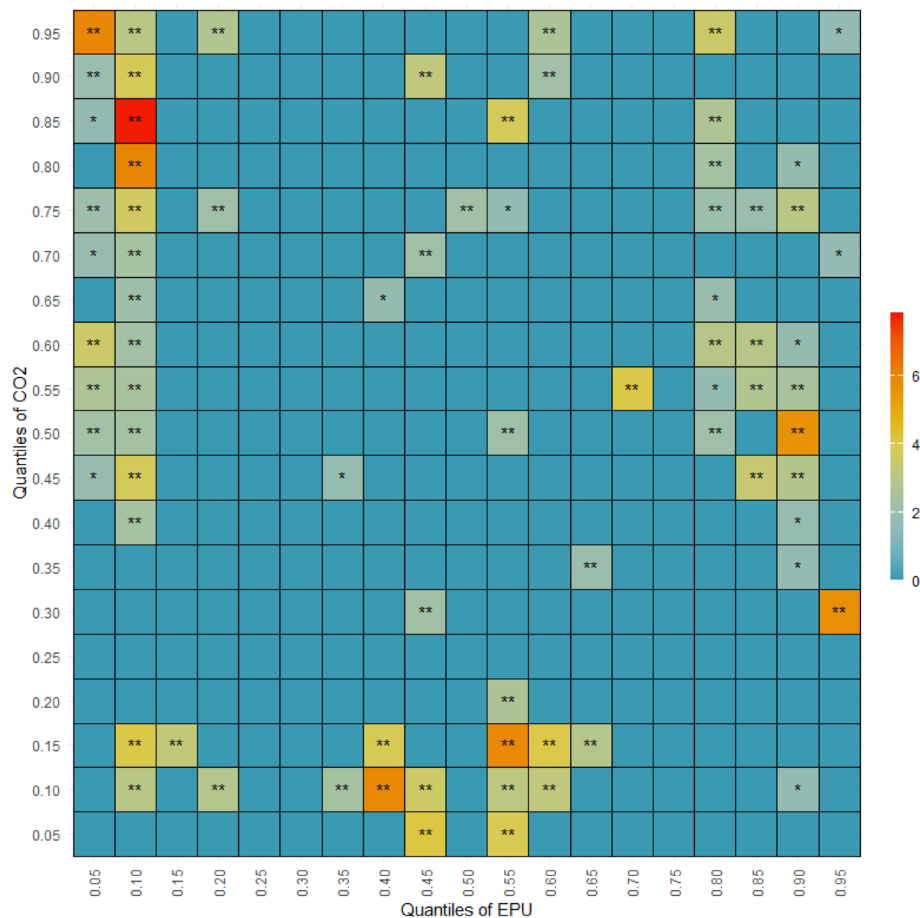


Fig. 5 QQGC between GT, GDP, EPU and CO₂ emissions in India. Notes: These figures show the Granger causality running from the quantiles of EPU, GDP and GT on the quantiles of CO₂ emissions. * $p < 0.1$, ** $p < 0.05$ and *** $p < 0.01$

Similarly, the QQGC findings show relatively causality in both low and high quantiles of GT to CO₂, especially in middle quantiles of both distributions, but more scattered causality across quantiles from GT to CO₂. This implies a significant predictive power of GT over CO₂. It is observed that there is a directional and time-dependent nexus in which increased adoption and improvement of GT precedes reductions in CO₂ emissions. In practical perspective, as India invests more in GT like renewable energy, energy-efficient systems, and clean transportation, these innovations gradually result in a decline in the country's reliance on fossil fuels. The Granger causality does not imply a direct cause in a strict sense, but it indicates that improvements in GT plays a leading role in shaping the path of environmental outcomes. Therefore, GT Granger-causing CO₂ emissions supports the idea that enhancing sustainable technology is an effective strategy for reducing India's environmental footprint.

The current study offers straightforward insights into how green technologies, economic development and economic policy uncertainty impact CO₂ emissions in India, albeit in different directions and magnitudes. Firstly, GDP remarkably impacts environmental degradation, which is consistent with the EKC hypothesis, where economic growth initially results in higher emissions because of increased energy consumption, industrial activity and transportation demands. Nevertheless, economies frequently

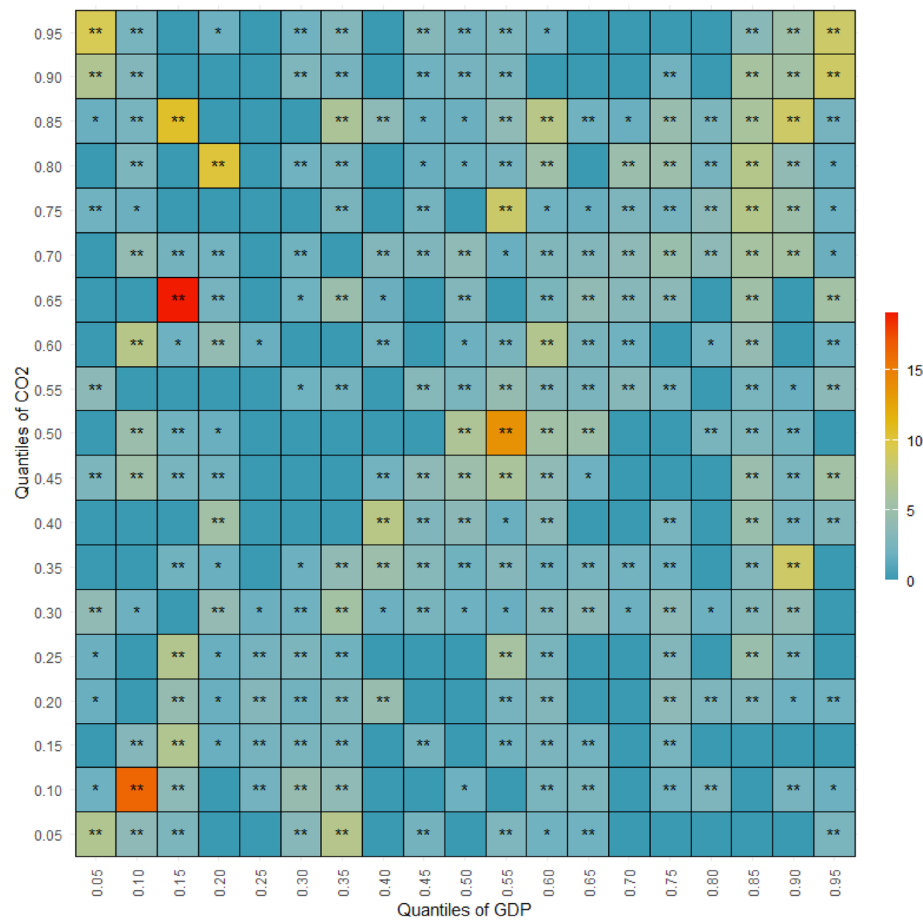


Fig. 5 (continued)

start to invest in cleaner technologies and conduct stricter environmental regulations when income levels increase, and environmental awareness enhances. The considerable positive association between GDP and CO2 emissions would suggest that India remains in the earlier stages of this curve, where economic development is still closely tied to carbon-intensive activities. This outcome supports the findings of Mohanty et al. [33], Chamakhi et al. [13], Bilal et al. [9] and Majekodunmi et al. [31].

However, EPU plays a significant role in shaping environmental quality. This remarkable nexus between EPU and carbon emissions points out that periods of heightened policy uncertainty would deter investment in green projects and delay the implementation of environmental regulations. Uncertainty can cause firms to prioritize short-term cost savings over long-term sustainability, resulting in increased reliance on traditional, polluting technologies. On the other hand, a reduction in EPU might enhance investor confidence, encourage long-term planning, and support the adoption of clean energy solutions. India known as an emerging economy, ensuring stable and transparent policy environments is therefore vital for facilitating effective environmental governance. The study of Wang et al. [46] and Aslan et al. [7] document similar results.

Lastly, there is a remarkable interaction between GT and ED reflecting the dual role it plays in transition toward sustainable development in this country. In the short run, the deployment of GT could be connected with increased emissions because of the energy and resource intensity of building green infrastructure and the continued reliance on

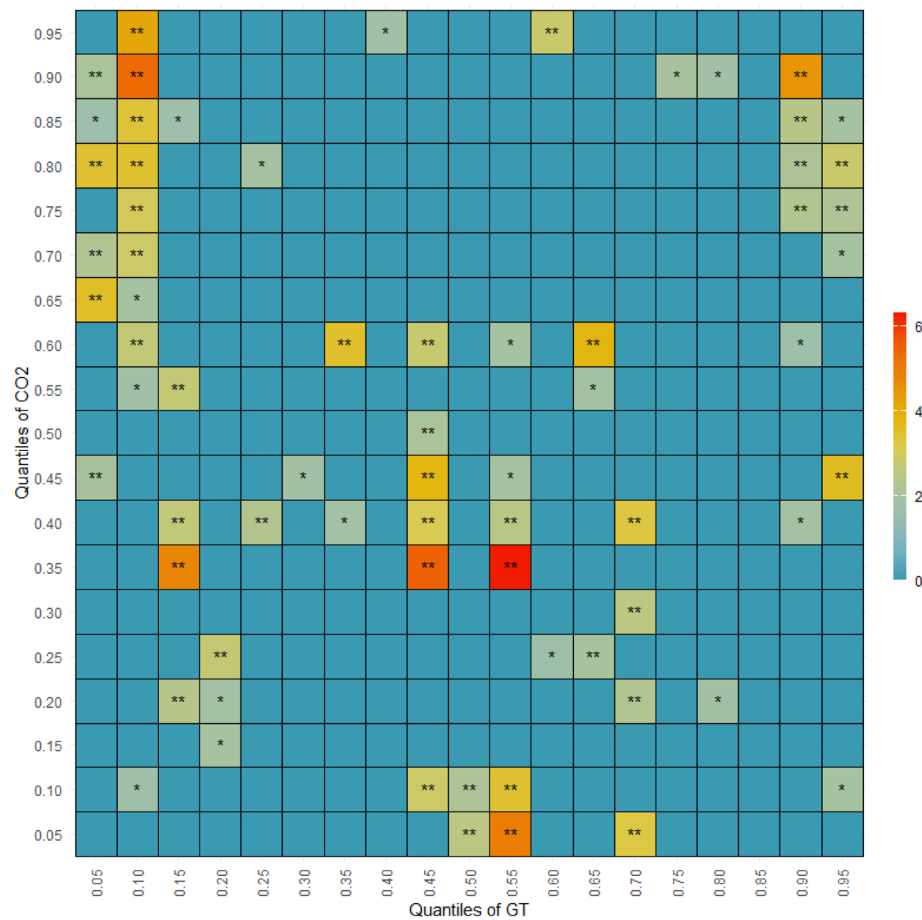


Fig. 5 (continued)

fossil fuels during the transition phase. Nevertheless, in the long term, GT adoption tends to decrease air pollution by improving energy efficiency, enhancing the usage of renewable energy, and enabling cleaner industrial processes. As a result, the negative interplay highlights the need for sustained investment in green innovation and supportive policy frameworks to maximize the long-term environmental benefits of GT. The conclusions of Chen et al. [16] and Zhao et al. [49] corroborate our outcomes.

The current study suggests several important and asymmetric interplays between GT, GDP, EPU, and CO₂ emissions in India. First, GDP experiences a strong positive impact on CO₂ emissions across all quantiles and frequencies, indicating that economic development in India remains heavily dependent on energy-intensive, fossil-fuel-based activities; this pattern places the country in the rising phase of the Environmental Kuznets Curve, where growth continues to aggravate environmental pressures. On the other hand, GT illustrates a significantly negative association with CO₂, suggesting its role in reducing pollution through improved energy efficiency, expanded renewable energy consumption. In addition, EPU shows a nonlinear influence: while long-run uncertainty occasionally raises emissions by discouraging investment in clean technologies, the short- and medium-run effects are largely negative, reflecting reduced industrial activity and energy consumption. Overall, our work emphasizes the interrelationship of economic growth, technological progress, and policy stability in addressing environmental challenges. Policymakers should adopt a comprehensive approach that enhances green

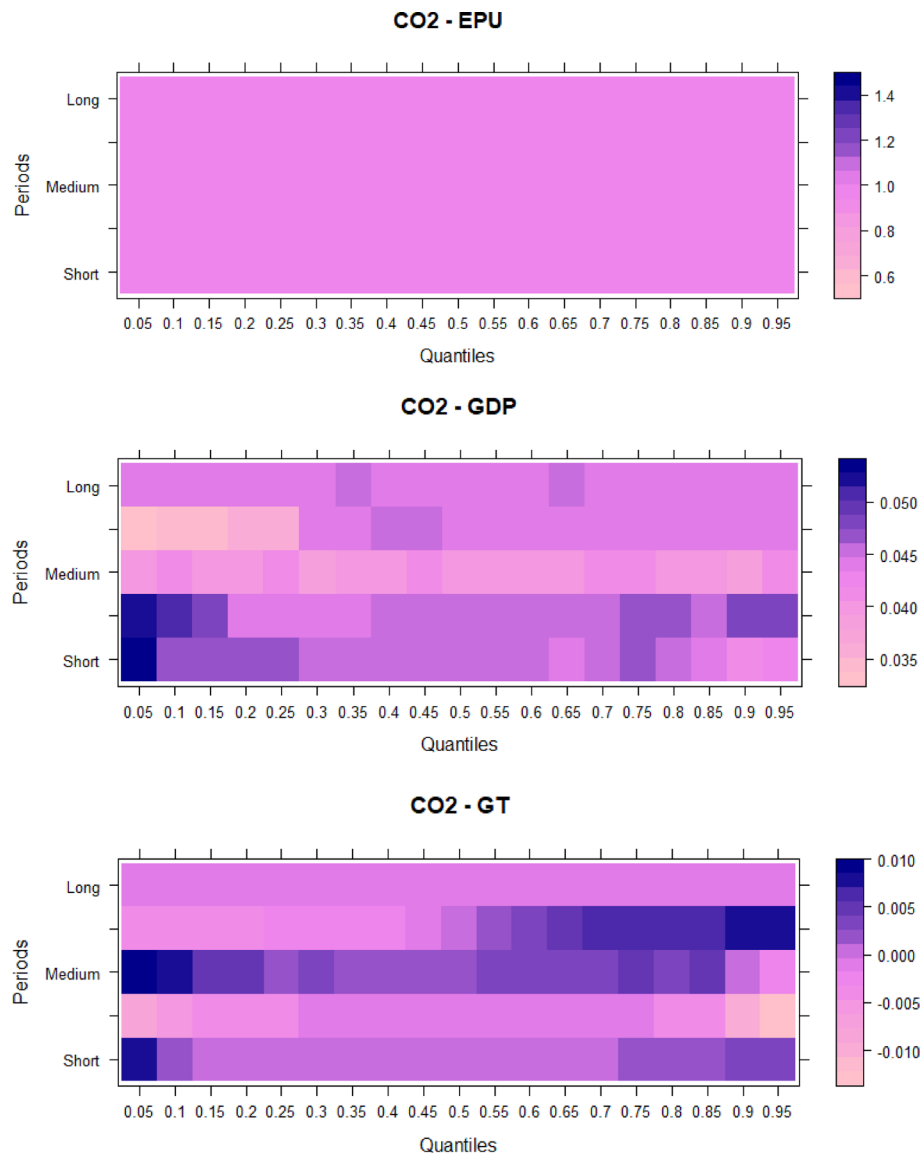


Fig. 6 Wavelet quantile regression between CO₂ and the selected variables (original annual data)

technology, supports sustainable economic development, and reduces policy uncertainty to achieve carbon reduction goals and climate commitments in India.

3.5 Robustness check

To address concerns that the empirical findings may be influenced by the conversion of annual data into quarterly frequency, this study conducts an additional robustness analysis using the original annual series. Specifically, we employ WQC approach to reassess the relationship between green technology, economic growth, economic policy uncertainty, and CO₂ emissions without relying on artificial frequency expansion.

Figure 6 reports WQC estimates based on the original annual data, serving as a robustness check against the WQC results obtained from interpolated quarterly series. Overall, the dependence patterns are highly consistent across the two approaches. GDP exhibits a strong and persistent positive association with CO₂ emissions across most quantiles and time scales, confirming that India's economic development remains closely

linked to carbon-intensive activities. However, GT suggests a negative interplay with CO₂ emissions, particularly at medium- and long-term horizons, reinforcing its emission-mitigating role identified in the main analysis. The relationship between EPU and CO₂ emissions appears relatively stable and moderate across quantiles and frequencies, in line with the earlier findings that its effects are nonlinear and frequency dependent. In general, the close alignment between the WQC estimates using annual data and the WQR results indicates that the main empirical conclusions are robust and not driven by artificial frequency conversion or interpolation procedures.

4 Conclusion

This study makes significant contributions to the under-explored area of research on the asymmetric interactions between GT, GDP, EPU, and CO₂ emissions in the Indian context. To date, limited attention has been given to the asymmetric effects of GT, GDP, and EPU on ED in India. This study addresses that gap by analyzing data from 1990 to 2023. The analysis employs advanced quantile-based methods, including WQR and QQGC. The findings provide valuable insights that inform both theoretical understanding and practical policy implications.

The results highlight that GT and EPU consistently reduce CO₂ emissions across major quantiles and all frequencies, suggesting its effectiveness in declining environmental pollution. By contrast, increases in economic development are connected to increases in CO₂ emissions, indicating that higher economic expansion encourages cleaner energy consumption. In addition, the causality estimates point out that all predictors, namely GT, GDP and EPU, remarkably predict CO₂ emissions across the distribution. These findings emphasize the importance of integrating GT into economic development and carrying out strategic economic policies to support carbon reduction and long-term environmental sustainability in India.

These findings have several significant implications for India. The results reveal a negative relationship between EPU and CO₂ emissions. This highlights that periods of uncertainty could, under certain conditions, result in reducing emissions, possibly due to slowed industrial activity or changes in investment behavior. Hence, policymakers should aim to harness the potential positive effects of uncertainty while minimizing its negative impacts. This can be achieved through stronger governmental support for environmental initiatives and the enactment of regulations that favor clean energy development. Put differently, the meaningful influence of EPU reveals that unstable regulatory environments can hinder long-term green investment, emphasizing the importance of predictable environmental rules, transparent policy frameworks, and stable renewable energy tariffs. To improve a low-carbon economy and tackle climate change, the Indian government should conduct policies that incentivize the adoption of green technologies, encourage sustainable practices, and prioritize environmental protection.

In light of green technology's critical role in reducing CO₂ emissions in India, increased investment in renewable energy R&D should be prioritized within the national budget. Priority areas should include energy efficiency, energy storage, cross-cutting technologies, and the advancement of both nuclear and renewable energy sources. To facilitate the rapid development and deployment of GT, establishing dedicated research institutes that foster collaboration among academia, industry, and government is essential. The results suggest that scaling up R&D incentives, patent support, and technology

transfer under programs such as the National Mission on Green India and the Production Linked Incentive for clean technologies could significantly enhance environmental outcomes.

This study provides vital insights into the roles of GDP, GT, and EPU in shaping CO₂ emissions in India. Nevertheless, like many empirical studies, it is subject to certain limitations. First, the analysis centers on three primary explanatory variables, potentially omitting other influential factors such as industrial activity, regulatory shifts, and technological progress. Future studies should include additional indicators to better capture the complexity of CO₂ emissions. Second, by focusing solely on India, the study's findings would have limited applicability beyond the national context. Expanding the geographic scope to include both advanced and developing countries might improve the generalizability of the results. Third, while advanced quantile-frequency econometric methods were employed, the analysis does not account for the varying time horizons. Finally, the use of environmental patents as a proxy for green technology reflects innovation activity rather than the actual adoption or diffusion of green technologies. While this measure provides meaningful insights into long-term technological progress, it may not fully capture on-the-ground implementation in the Indian context. Future research could therefore complement patent-based indicators with adoption-oriented measures such as renewable energy capacity, clean technology investment, or firm-level deployment data to provide a more comprehensive assessment of the environmental impacts of green technology.

Author contributions

Tran Van Hung was responsible for the conception, design, writing of the draft of the article, conceptualization, software, writing—original draft.

Funding

This research is supported by Hung Vuong University, Ho Chi Minh City, Viet Nam.

Data availability

The datasets used and/or analyzed during the current study are available from the author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable. This study follows all ethical practices during writing. We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

Consent for publication

Not applicable.

Clinical trial registration

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 28 September 2025 / Accepted: 9 February 2026

Published online: 24 February 2026

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