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IMPACT OF FINANCIAL DEVELOPMENT, TRADE, AND ENERGY CONSUMPTION ON ENVIRONMENTAL FOOTPRINT IN INDIA: EVIDENCE FROM QARDL AND WAVELET COHERENCE APPROACH

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Highlights:

- quantile autoregressive distributed lag (QARDL) and wavelet coherence model are applied;
- the impact of financial development, trade openness, renewable and non-renewable energy on environmental footprint is examined;
- renewable energy consumption reducing CO_2 emissions;
- financial development, energy consumption, and trade openness have a positive impact on CO_2 emissions;
- wavelet coherence analysis found causal relationship between the CO_2 emissions and independent variables.

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Abstract. The aim of this study is to analyze the impact of financial development, trade openness, renewable energy, and nonrenewable energy consumption on CO_2 emissions in India by analyzing the quarterly data from 1980 to 2020. Quantile ARDL and Wavelet Coherence methods are employed to examine the nexus. In the long and short run, nonrenewable energy consumption, financial development, and trade openness have a positive impact on CO_2 emissions. When emissions are already high, it suggests that financial development may also lead to increased CO_2 emissions. Moreover, Renewable energy consumption has a negative impact on CO_2 emissions irrespective of the emission level that whether it is high or low in the nations, which shows that if financial enhancement increases, carbon emissions decrease. Finally, we test the EKC hypothesis, and the QARDL findings support the EKC in India. Additionally, the wavelet coherence study found a causal relationship between the CO_2 emissions and independent variables, and the findings under the Wald test reject the parameter constancy for all variables. To create effective policies for environmental deterioration, the empirical findings of the current analysis can be used as guidelines for policy implications.

Keywords: financial development, renewable and nonrenewable energy consumption, EKC, India, QARDL.

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1. Introduction

Environmental pollutions are recognized as a threat to humanity and sustainable development worldwide. Human activities have resulted in an excess of CO_2 emissions, contributing to the phenomenon of global warming and subsequent climate change (Alam et al., 2025). Climate change contributes to the increased frequency and intensity of extreme weather events, including severe droughts, floods, and other natural disasters, posing significant risks to public health and environmental stability. To ensure sustainable development, it is essential to utilize fossil fuel resources efficiently, thereby preventing their premature depletion and preserving them for future generations. The Sustainable Development Goals (SDGs) emphasize the protection of the Earth's atmosphere while striving to meet the needs and aspirations of both present and future populations (Ganda, 2019; Pata et al., 2023; Qin et al., 2023). The 1987 World Commission on Environment and Development (WCED) identified population growth, excessive energy use, and unsustainable exploitation of fossil fuels as major challenges to realizing Sustainable Development Goals (SDGs) (Saqib et al., 2023; Shabbir Alam et al., 2023). The Commission also argues that sustainability requires economic growth, as well as a decrease in resource and energy intensity. Especially, since India is recognized as one of the highly polluted and severely climate change-vulnerable global economies (Ahmed et al., 2019; Das et al., 2020), the relevance of promoting sustainable growth (or green growth) in this country is remarkably high.

Moreover, achieving low-carbon, sustainable economic performances can enable India to meet the Paris goals as well (Van Soest et al., 2021). Furthermore, by achieving economic growth sustainably, India can be expected to achieve its domestic target of becoming carbon-neutral by 2070, as well (Das et al., 2023; Hossain et al., 2023; Murshed et al., 2023). As India was ranked 7th among countries most vulnerable to climate change in 2021 (Mohanty & Wadhawan, 2021), controlling the increase in carbon emissions at the national level has become a critical policy challenge for the country. Despite these commitments, India has struggled to implement effective carbon reduction policies. As a result, the country faces significant challenges in meeting both its national and international environmental obligations, which are increasingly putting pressure on its ecological indicators.

Nonrenewable energy sources have played a key role in India's financial development. NREC is a main contributor to GHG emissions, mainly carbon dioxide (CO_2), which exacerbates climate change and environmental degradation. As a response, India has been increasingly investing in resources of RE like wind, solar, and hydroelectric energy, aiming to decrease its carbon footprint and promote sustainable development (Paramati et al., 2017; Zhong et al., 2024). These energy sources have driven economic activities, generated employment, and contributed significantly to the nation's GDP. However, this dependency comes with substantial environmental and financial challenges. The natural resources and nonrenewable energy linked to ecological degradation, such as GHG emissions and air pollution, pose risks to sustainable growth. Consequently, India faces the critical task of balancing its energy needs with environmental sustainability to ensure long-term financial stability and development (Alam et al., 2011; Salifu et al., 2024; Murshed & Alam, 2021; Nibedita & Irfan, 2022). Policy interventions continue to play a significant role in mitigating climate change and promoting sustainable economic growth (Apergis & Payne, 2011; Danish et al., 2017). In order to ensure sustainable development, nations are attempting to encourage the use of more renewable energy. Moreover, financial development, characterized by the growth of markets and financial institutions, plays a vital role in shaping energy consumption patterns and environmental outcomes. A well-developed financial sector can facilitate investments in cleaner technologies and renewable energy projects, potentially reducing the environmental footprint. On the other hand, trade openness, by enhancing economic activities and industrial output, can have mixed impacts on the environment depending on the energy mix and regulatory framework in place (Shahbaz et al., 2024).

A key contribution of this study lies in examining the impact of renewable energy consumption, nonrenewable energy consumption, financial development, and trade openness on environmental sustainability. These factors are particularly critical as India strives to advance its financial sector without exacerbating environmental degradation. Promoting the adoption of renewable energy sources (RES) within the financial system can serve as a strategic avenue for supporting the green economy and mitigating environmental pollution. Given India's substantial reliance on coal, a fossil fuel widely recognized as causing environmental damage, the role of nonrenewable energy (NREC) remains pivotal. A rapid transition away from coal is essential for achieving long-term environmental sustainability. However, the continued industrial demand for nonrenewable energy resources necessitates a balanced approach to ensure industrial competitiveness is not compromised. This study offers insights that can inform governmental policy formulation regarding renewable energy consumption (REC), nonrenewable energy consumption (NREC), financial development (FD), and trade openness (TO), while also serving as a valuable reference for private sector stakeholders aiming to improve their environmental performance. The Quantile Autoregressive Distributed Lag (QARDL) model will be utilized to empirically assess these relationships and validate the study's findings.

The remaining sections of this study are arranged as follows: Section 2, it discusses the literature. The methodology and results presentation are in Sections 3 and 4, respectively. The conclusions and policy sections are in Section 5.

2. Review of literature

Recent literature well explains the determinants of environmental quality and carbon emissions. It is documented that financial development, trade openness, and renewable and non-renewable energy consumption are all important factors affecting environmental quality (Khan et al., 2023). The literature about the financial development relationship for several nations around the global, attained from these studies (Dagar et al., 2024; Jiang et al., 2022; Mngumi et al., 2022), supports the positive impact of financial development on ecological quality. For 27 years, from 1965 to 2016, Kang et al. (2019) examined an intriguing connection between nonrenewable and renewable energies and economic development in Turkey. The findings suggest that the QARDL techniques support nonrenewable energy resources, and financial development positively impacts long and short-run periods at all quantiles. The empirical evidence also indicates that bidirectional causal association exists among financial development, NREC, and REC with ecological footprint in the Turkish economy. The EKC-curve existence in Turkey is also established in empirical studies. A study by Bloch et al. (2015) and Chen et al. (2019) investigated the connection among REC, NREC, financial development, and foreign trade for China from 1980 to 2014, by applying VECM and ARDL methods. The significant findings show that China does not have an EKC of pollution under the impact of nonrenewable sources, foreign trade, and financial development. Nevertheless, after the addition of renewable sources is found that the EKC-curve of an inverted U-shaped is supported in the long run.

Moreover, long-term results suggest that increasing nonrenewable energies and economic development rises carbon emissions, whereas green energy and foreign trade have a negative influence on ecological pollution. Zhong et al. (2024) investigated the link among natural resources, renewable electricity, and economic growth in China from 1983 to 2021. The outcomes suggest that the Bayer-Hanck method should be used for each forecasted variable to ensure the long-term equilibriums of explanatory variables with the forecasted one. Furthermore, CCR and FMOLS are used for primary estimations, while the robust least-squares technique is utilized for robustness checks. Furthermore, government spending on education has a negative impact that is limited to the financial markets index, whereas renewable electricity significantly and positively affects the multidimensional and market indices of financial development. Additionally, both temporarily and permanently, the financial markets index is lowered by renewable electricity. Furthermore, robustness check analysis yields valid and comparable results. Policies that are pertinent to the connection between economic expansion indices and natural resources are recommended. Ahmad et al. (2016), Qamruzzaman and Karim (2023) scrutinized the association between environmental pollution, energy use (coal, gas, oil, and electricity), and financial development for India from 1970 to 2015. Their findings support the long-term co-integration of the variables and the validity of the EKC hypothesis. Additionally, they discovered that there is a feedback connection between environmental pollution and financial development and that energy use and environmental pollution have a positive association.

Sebri and Ben-Salha (2014) explore the link between trade, economic growth, renewable energy, and carbon emissions in the long run, over the period 1971 to 2010, in BRICS countries. Using the ARDL model, the authors find that renewable energy use enhances economic growth in India and South Africa. Moreover, reduced carbon emission is observed with enhanced use of renewable energy sources. Shahbaz et al. (2018) investigate the GDP-climate phenomenon in EU economies over the period 1985 to 2016, including natural resource rent, electrical energy consumption, and innovation in the model, and show that renewable energy, natural resource rents, and innovation improve climate quality.

In MENA countries, Zouine et al. (2024) control for trade openness, energy use, and urbanization while investigating the impact of political stability on climate degradation. The authors employ econometric models to explore the relationship and find that more stable political systems help provide better and more sustainable environmental quality. Dagar et al. (2024) investigate the impact of institutional quality on forest degradation and find that strong institutions have smooth operating strategies and enforce regulations for climate mitigation. Moreover, strong and established institutions reduce transaction costs and hence improve economic performance. Therefore, institutional quality is crucial for economic growth, as it ensures fair procedures and that the rule of law is followed in devising and implementing strategies. Institutions that operate within proper legal frameworks promote climate security mechanisms and mitigate environmental damage.

Furthermore, climate-related financing plays an essential role in supporting multiple Sustainable Development Goals (SDGs) and is crucial for attaining the 1.5 °C global temperature target (Iacobuţă et al., 2022). For producers of renewable energy (RE) resources, access to both private and public capital—particularly during the early stages of investment—is often more feasible (Przychodzen & Przychodzen, 2020). This indicates that the expansion of green energy generation is contingent upon a certain level of industrial development and economic growth. Nevertheless, energy producers and large-scale consumers operate within an environment of heightened uncertainty, facing risks associated with market deregulation, rapid technological advancements, and geopolitical or economic instabilities (Paraschiv et al., 2015). Specifically, renewable energy investment is frequently associated with substantial financial risks due to the high upfront costs of technology and uncertainties about long-term returns (Kim & Park, 2016; Neog & Yadava, 2020). At the same time, robust economic growth facilitates efficient information dissemination among key stakeholders and expands financing opportunities, potentially lowering the cost of capital for renewable energy investments and accelerating the energy transition (Shahbaz et al., 2021). The complexity of this topic arises from the interdependence of methodological, cultural, geopolitical, and economic variables, making empirical assessments of financial development's role in environmental outcomes often inconclusive (Magazzino et al., 2021) consequently, the literature presents divergent findings, with one strand suggesting that financial development can contribute to emission reductions.

According to Dogan and Seker (2016), green energy consumption helps to decrease pollutions in developed nations but not in developing ones, while nonrenewable energy raises emissions in all of them. The energy-led growth theory is supported by Shahbaz et al. (2024) assessment of India's economic growth, NREC, and green-energy use connection using an NARDL approach. They opine that the policy of deterring NREC might have a deflationary influence on the financial expansion of India. In the case of these countries, Paramati et al. (2017) discovered that the EKC hypothesis is valid. According to their findings, growth and energy use both raise emissions, but using clean energy lowers greenhouse gas emissions. There is no causal association between economic growth and REC, but there is unidirectional causality from energy consumption to financial development.

According to the literature, the majority of studies have two main characteristics: first, they use financial development to estimate environmental quality; second, there isn't much talk about the impact of NREC, FD, TO, and REC on environmental quality in India. Therefore, by disaggregate data analysis, we aim to close the research gap in this work by examining the influence of financial development, renewable energy, and nonrenewable energy sources on environmental quality, which serves as a proxy for CO_2 emissions in India.

3. Methodology and data

3.1. Data

The study investigates how renewable energy consumption, financial development, trade openness, nonrenewable energy consumption impact on CO_2 emissions in India. We collected data regarding the concerned parameters from the Development of World Bank Indicators. The data spans from 1980Q1–2020Q4. Additionally, we converted the annual dataset into quarterly dataset utilizing the quadratic match sum technique as outlined by Hussain et al. (2020) and Sharif et al. (2020). This procedure efficiently transforms a lower-frequency dataset into a higher-frequency dataset by accounting for seasonal variations and eliminating end-to-end data discrepancies. Table 1 provides the measurement scales and the associated data sources for the concerned variables. Figure 1 provides graphical representations of all variables.

Table 1. Variable description and units of measurement

Variable description	Symbol	Unit	Sources
CO_2 emissions per capita	CO_2E	CO_2 emissions (metric tons per capita)	WDI
Financial development	FD	Percentage of GDP	WDI
Renewable energy consumption	REC	Percentage of total final energy consumption	WDI
Nonrenewable energy consumption	NREC	Percentage of total Nonrenewable energy consumption	WDI
Trade openness	TO	Percentage of GDP	WDI

3.2. Model specification

Financial development (FD), renewable energy consumption (REC), nonrenewable energy (NREC), and trade openness (TO) are taken as independent variables, while CO_2 emissions are taken as the dependent variable to investigate the environmental quality in India. We utilize the traditional method introduced by Cho et al. (2015) i.e., QARDL. This new method is an improved variant of the ARDL method. The investigation of potential asymmetries and nonlinearities between *REC*, *NREC*, *FD*, *Trade*, and CO_2E is aided by quantile-ARDL. It can be expressed as follows in Equation (1):

$$CO_2E_t = \mu + \sum_{i=1}^{p} \sigma_{CO_2E_i} CO_2E_{t-i} + \sum_{i=0}^{q} \sigma_{REC_i} REC_{t-i} + \sum_{i=0}^{r} \sigma_{NREC_i} NREC_{t-i} + \sum_{i=0}^{s} \sigma_{FD_i} FD_{t-i} + \sum_{i=0}^{u} \sigma_{TO_i} TO_{t-i} + \varepsilon_t \upsilon. \quad (1)$$

In the above equation ε_t is the sign of error term indicated that $CO_2E_t - E[CO_2E_t / \omega_{t-1}]$ with ω_{t-1} being the smallest v – field generated by {*REC*, *NREC*, *FD*, *TO*, CO_2E, CO_2E_{t-i}, REC_{t-i}, $NREC_{t-i}$, FD_{t-i}, TO_{t-i}} and *p*, *q*, *r*, *s*, *u*, and *v* are long-order's detected by the AIC Information Criterion.

In Equation (1), CO_2E_t, REC_t, $NREC_t$, FD_t, and TO_t, are carbon emissions, nonrenewable and renewable energy consumption, financial development, and trade openness.

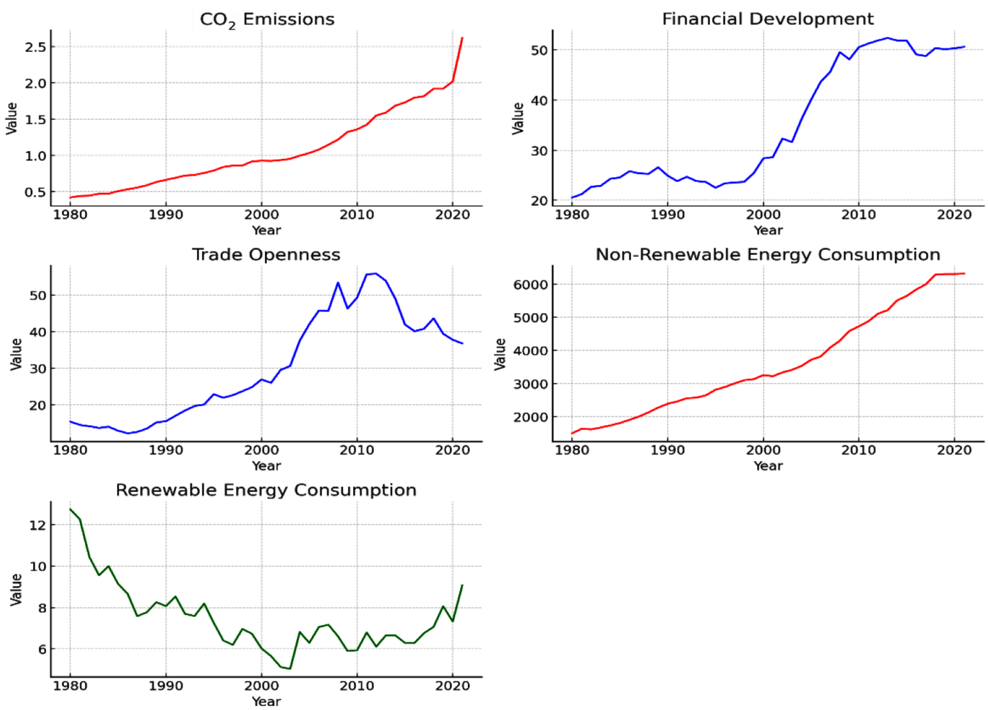

Figure 1. Graphical representations of all variables

Cho et al. (2015) used a more general version of Equation (2) to talk about quantiles and gave a thorough explanation of quantile ARDL (p, q, r, s, u, v) with the following models under Equation (2).

$$Q_{CO_2E_t} = \alpha(\tau) + \sum_{i=1}^{p} \beta_1(\tau)CO_2E_{t-i} + \sum_{i=0}^{q} \beta_2(\tau)REC_{t-i} + \sum_{i=0}^{r} \beta_3(\tau)NREC_{t-i} + \sum_{i=0}^{s} \beta_4(\tau)FD_{t-i} + \sum_{i=0}^{u} \beta_5(\tau)TO_{t-i} + \varepsilon_t(\tau), \quad (2)$$

where $\varepsilon_t(\tau) = CO_2E_t - Q_{CO_2E}(\tau / \delta_{t-1})$. Considering δ_{t-1} represents the small $\sigma-$ field generated by the explanatory variables in the model and $Q_{CO_2E}(\tau / \delta_{t-1})$ is the π-th quantile of CO_2E_t conditional on F_{t-1}. The short-run dynamics are represented as follows:

$$Q_{CO_2E_t} = \alpha(\tau) + \rho(\tau)(CO_2E_{t-1} - \omega_1(\tau)REC_{t-i} - \omega_2(\tau)NREC_{t-i} - \omega_3(\tau)FD_{t-i} - \omega_4(\tau)TO_{t-i}) + \sum_{i=1}^{p-1} \beta_1(\tau)CO_2E_{t-i} + \sum_{i=0}^{q} \beta_2(\tau)REC_{t-i} + \sum_{i=0}^{r} \beta_3(\tau)NREC_{t-i} + \sum_{i=0}^{s} \beta_4(\tau)FD_{t-i} + \sum_{i=0}^{u} \beta_5(\tau)TO_{t-i} + \varepsilon_t(\tau), \quad (3)$$

where in the above equation, the title of

$$\gamma_{REC}(\tau) = \sum_{i=0}^{p} \omega_i(\tau), \quad \delta REC_j(\tau) = -\sum_{j=i+1=0}^{q} \omega_i(\tau),$$
$$\gamma NREC(\tau) = \sum_{i=0}^{r} \lambda_i(\tau), \quad \delta NREC_j(\tau) = -\sum_{j=i+1}^{r} \lambda_i(\tau),$$
$$\gamma FD(\tau) = \sum_{i=0}^{w} \theta_i(\tau), \quad \delta FD_j(\delta) = -\sum_{i=i+0}^{q} \theta_i(\tau),$$
$$\gamma TO(\tau) = \sum_{i=0}^{r} \lambda_i(\tau), \text{ and } \delta TO_j(\tau) = -\sum_{j=i+0}^{s} \lambda_i(\tau).$$

The short-term dynamics are shown by Equation (3) above. The long-term relationship between the *NREC*, *REC*, *FD*, and *TO*. The modified form is expressed as follows:

$$Q_{CO_2E_t} = \alpha(\tau) + \rho(\tau)(CO_2E_{t-1} - \omega_1(\tau)REC_{t-i} - \omega_2(\tau)NREC_{t-i} - \omega_3(\tau)FD_{t-i} - \omega_4(\tau)TO_{t-i}) + \sum_{i=1}^{p-1} \beta_1(\tau)\Delta CO_2E_{t-i} + \sum_{i=0}^{q-1} \beta_2(\tau)\Delta REC_{t-i} + \sum_{i=0}^{r-1} \beta_3(\tau)\Delta NREC_{t-i} + \sum_{i=0}^{s-1} \beta_4(\tau)\Delta FD_{t-i} + \sum_{i=0}^{u-1} \beta_5(\tau)\Delta TO_{t-i} + \varepsilon_t(\tau). \quad (4)$$

The impact of cumulative short-run the lag of carbon emissions on current emanation is measured by $\phi = \sum_{j=1}^{p-1} \phi_j$, while the cumulative shorter-run impact of previous and present values of *REC*, *NREC*, *FD*, and *TO* on the present values of CO_2E are estimated by $w = \sum_{j=1}^{p-1} w_j$, $\lambda^* = \sum_{j=1}^{q-1} \lambda_j$ and $\theta^* = \sum_{j=1}^{r-1} \theta_j$, respectively. Moreover, the long-run cointegration coefficients for the *REC*, *NREC*, *FD*, and *TO* are calculated with the help of $\beta^* = \frac{\phi REC}{P}$, $\beta_{NREC} = \frac{\phi NREC}{P}$, $\beta_{FD^*} = \frac{\phi FD}{P}$, $\beta_{TO^*} = \frac{\phi TO}{P}$, accordingly. The delta method was applied to calculate both the short and long-run co-integration coefficients.

The error correction model suggests that the coefficient should exhibit negative and significant. As evident from the expression above, all coefficients are negative, thereby satisfying this condition. Furthermore, to investigate the short and long-run non-linear and asymmetric impacts of REC, NREC, FD, and TO on CO_2 emissions, the study employed the Wald test. This test is utilized to evaluate the null and alternative hypotheses for both short and long-run coefficients, denoted as β^*, ρ^*, ω^* and ϕ_*, by utilizing the χ^2-distribution.

$$H_1^{\phi} : F\phi_*(\tau) = F \text{ vs } H_2^{\phi} : F\phi_*(\tau) \neq F;$$
$$H_1^{\phi} : S\omega^*(\tau) = s \text{ vs } H_2^{\phi} : S\omega^*(\tau) \neq s;$$
$$H_1^{\phi} : S\beta^*(\tau) = s \text{ vs } H_2^{\phi} : S\beta^*(\tau) \neq s;$$
$$H_1^{\phi} : S\rho^*(\tau) = s \text{ vs } H_2^{\phi} : S\rho^*(\tau) \neq s.$$

3.3. Analysis of wavelet coherence

The term wavelet coherence technique was proposed by Aguiar-Conraria et al. (2008) and defined as the ratio of the cross-spectrum to the sum of the spectra of all the series. Taking into account both the frequency and temporal components, this concept specifies the exact association between two time series. Normally, the WTC range is between one and zero; a higher wavelet coherence fraction denotes a significant correlation. On the other hand, a low percentage suggests that there is a lower correlation between the variables. The wavelet transform is incredibly effective at decreasing noise and compressing data. According to Adamowski and Chan (2011), wavelet transformations primary benefit is their capacity to compute a signal's time, position, and frequency all at once. This is because other time series estimators are limited in their ability to account for frequencies and temporal causation. Using the wavelet transform results in inefficient computing of geometrical features. The wavelet coherence (WTC), a tool that explores the links between time series data, is essential to this methodology. This WTC is mathematically defined as follows:

$$R_{xy}^2(a,b) = \frac{\left|S(b^{-1}W_{xy}(a,b))\right|^2}{\left|S(b^{-1}W_x(a,b))\right|^2 \left|S(b^{-1}W_y(a,b))\right|^2}.$$

In Equation (2). $W_{xy}(a,b)$ and $W_x(a,b)$ are indicated as the wavelet transforms, and S stands for the smoothing operators.

4. Results and discussions

This study aims to investigate the relationship between renewable and nonrenewable energy consumption, trade openness, financial development, and carbon emissions in India. Table 2 provides the descriptive statistics used for this research. i.e., REC, NREC, TO, FD, and CO_2E concerning

India. The average values of CO_2E, REC, NREC, TO, and FD exceed their corresponding standard deviations, indicating an uneven distribution in India. Skewness statistics suggest that the sample data are a right-skewed distribution. Jarque Bera (JB) test results indicate that CO_2E, REC, NREC, TO, and FD are not normally distributed.

Table 2. Summary of descriptive statistics (source: authors' calculations)

Variables	CO_2E	REC	NREC	TO	FD
Mean	1.005	7.452	3464.203	28.114	34.277
Std. Dev	0.458	1.698	1449.502	3.282	12.079
Skewness	0.627	1.403	0.504	0.317	0.454
Kurtosis	2.221	2.977	2.089	1.969	1.419
JB-test	3.635	4.651	3.075	2.439	5.539
JB-test probability	0.162	0.451	0.214	0.295	0.062
Observations	40	40	40	40	40

Thus, the nonlinearity tests are also summarized in Table 3. The outcomes of the two preliminary tests have the following peculiar insights. The variables are nonlinear and deviate from normal distributions, as evidenced by the outcomes of the linearity tests and summary statistics.

Table 3. Results of nonlinearity BDS test (source: authors' calculations)

Variables	Dimensions					
	2	3	4	5	6	Remakes
CO_2E	0.1764	0.3465	0.3465	0.3790	0.3832	Nonlinearity
REC	0.1679	0.2793	0.3552	0.3983	0.4182	Nonlinearity
NREC	0.1810	0.2924	0.3590	0.3985	0.4136	Nonlinearity
FD	0.1665	0.2823	0.3521	0.4023	0.4274	Nonlinearity
Trade	0.1712	0.2949	0.3699	0.4146	0.4390	Nonlinearity

In particular, the BDS test verified that the entire series is nonlinear, while the Jarque-Bera test highlighted a deviation from normal distribution. Furthermore, all of the stated variables' non-normal distributions are depicted in the density plots (Figure 2). In light of this, using time-variant econometric methods is the most appropriate and justified choice for generating objective estimates.

After estimating the descriptive statistics and BDS tests, the traditional guidelines related to the econometrics methodology and statistical techniques, several tests were applied to estimate the validity of the data before implementing the final test, which is the QARDL approach. Hence, at the initial stage, the Augmented Dickey and Fuller (1979) (ADF) and Zivot and Andrews (1992) ZA unit

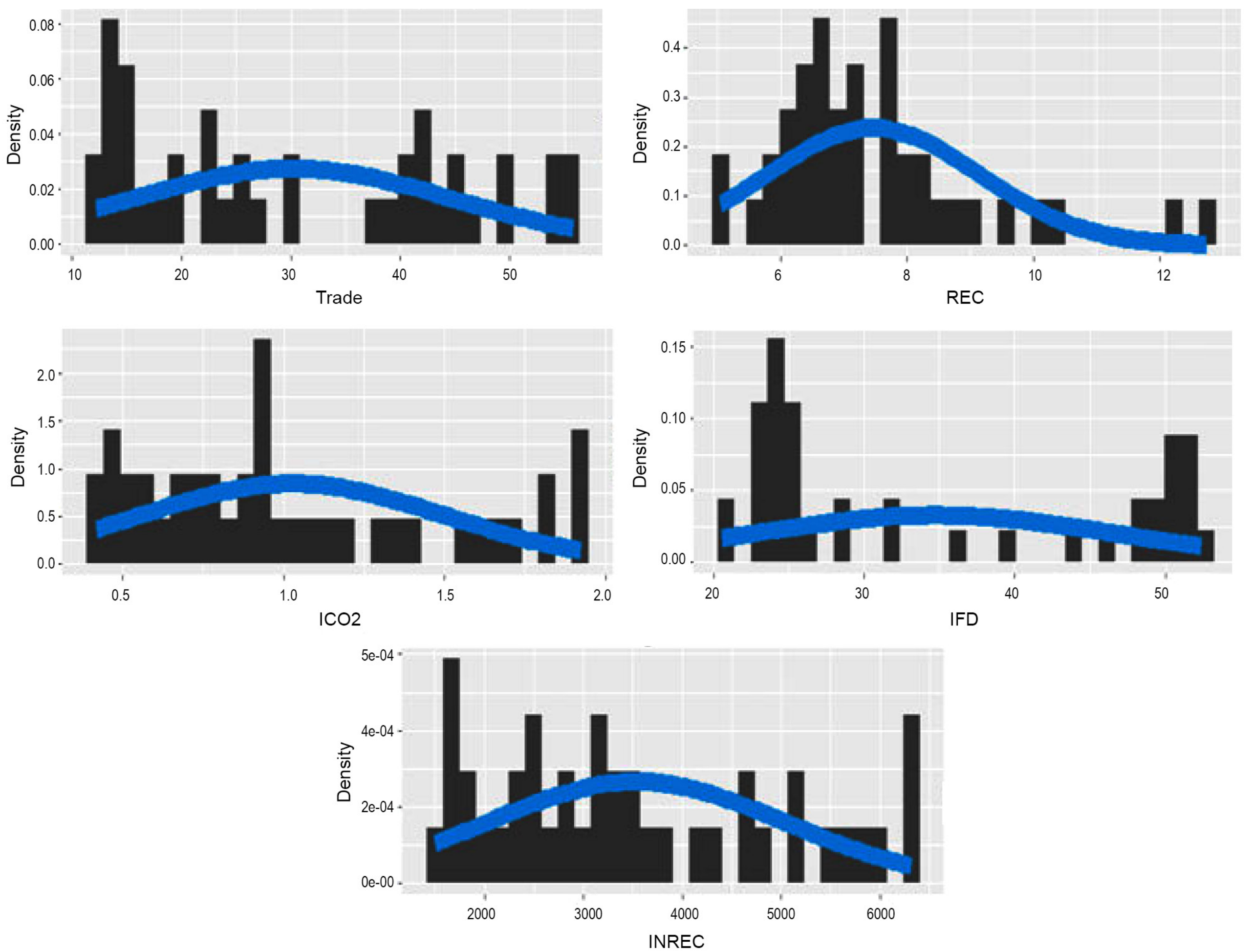

Figure 2. Non-normal distributions density plots

root test results are displayed in Table 4. The results show that FD, TO, REC, NREC, and carbon emissions are nonstationary at the level. However, all variables are stationarity after first differencing using the ADF and ZA approach. In general, the results provide evidence that all variables are stable and that the variables are integrated at I(1). The structural break unit root test results hint that the variables are stationary with different years of structural break. Especially, all the variables are stationary at the first difference, I(1). The findings thus demonstrate that each variable has a unique integration order.

Table 4. Summary of unit roots test

Tests	CO_2E	NREC	REC	TO	FD
ADF	–3.739	–6.437	–5.014	–0.986	–1.017
ZA Break Year	–0.573 2001Q02	–3.731 2006Q04	–2.973 2005Q02	–1.382 2011Q01	–1.367 2007Q04
Panel B: (Δln) 1st difference					
ADF	–7.970**	–9.320***	–11.064***	–5.171***	–7.892***
ZA Break Year	–6.704*** 2012Q01	–8.086*** 2009Q03	–7.284*** 2008Q04	–5.048*** 2011Q02	–9.107*** 2005Q03

Notes: *** and ** are levels of significance at 1% and 5%, respectively.

4.1. Results of quantile ARDL model

Table 5 provides the findings of the asymmetric QARDL model. The findings indicate that a positive shock in NREC has a significant and positive impact on CO_2 emissions in India in the long run, specifically at quantiles 0.05 to 0.95. That is, in the long run, when CO_2 emissions are already very high. Furthermore, the data show that the influence of NREC on environmental footprint is larger than that of REC. The results align with the research conducted by (Du & Wang, 2023; Feng et al., 2024; Huang, 2024; Kai et al., 2024; Shastri et al., 2020). According to earlier studies, exploiting natural resources for non-renewable energy increases efficiency and affects the environment, resulting in carbon dioxide emissions. Emerging countries are the main users of these energy-intensive resources for economic endeavors that pollute the environment by emitting CO_2. Additionally, this necessitates governments implementing various plans to shift their energy supply to meet increased energy demands in the long run while also attracting international investors who can bring green technology innovation and capital. Furthermore, efficient use of power due to innovation improvement assists in lowering CO_2 emissions.

Furthermore, the results of the long-run coefficient portray that there is an extensive role of financial development (FD) in enriching CO_2 emissions at all quantiles. It reveals that when carbon dioxide emissions are already high in the country, they become much more intense as FD increases. The findings support those of Sharif et al. (2020) and Zhong et al. (2024). The findings imply that emerging countries must begin to provide significant debt for environmental initiatives at a low interest rate. Moreover, FD creates prospects for financial capital by increasing investor trust and assisting them in adopting energy-efficient products. Furthermore, the observed results indicate that the coefficient of trade openness has a positive impact on accelerating CO_2 emissions. The results also support the hypothesis that growing trade with a certain level of openness will raise CO_2 emissions significantly and that a large volume of international trade-possibly brought on by an increase in production capacity-will greatly worsen the negative externality in the import sector and raise carbon emissions. This finding contributes to the body of literature by expanding on earlier research in this field (Adams & Nsiah, 2019; Alam et al., 2011; Bloch et al., 2015).

Similarly, the long-run relationship between REC and ecological quality demonstrates that REC has an important and valuable effect on ecological quality and decreases the likelihood of carbon dioxide emissions, and has a significant positive impact on environmental quality. Numerous studies have demonstrated that economies that switch from nonrenewable to renewable energy sources help both the environment and the economy (Govindarajan & Ganesh, 2021). Firstly, generating energy through renewable energy projects avoids the likelihood of fossil fuels

Table 5. Results of QARDL

Quantile's (τ)	Short-run				Long-run			
	NREC	REC	Trade	FD	NREC	REC	Trade	FD
τ = 0.05	0.891** (0.264)	–0.844*** (0.123)	0.260*** (0.061)	0.942*** (0.126)	3.096*** (0.338)	–2.764** (0.928)	0.903** (0.348)	2.378** (1.043)
τ = 0.25	1.170 (0.311)	–0.475*** (0.180)	0.282*** (0.072)	0.9567** (0.274)	3.816** (2.425)	–1.550 (6.647)	0.921 (2.496)	6.236** (2.796)
τ = 0.50	0.790 (0.418)	–0.1530 (0.243)	0.264 (0.096)	0.835*** (0.163)	2.618* (4.418)	–0.506 (12.107)	0.877* (4.547)	2.311 (1.819)
τ = 0.75	1.080 (0.284)	–0.272 (0.165)	0.1340 (0.065)	0.810*** (0.102)	2.451*** (1.688)	–0.618** (4.626)	0.304** (1.737)	2.156* (5.498)
τ = 0.95	1.354*** (0.158)	–0.355** (0.092)	0.0491 (0.036)	0.671*** (0.096)	3.209* (0.227)	–0.841** (0.622)	0.116 (0.233)	4.586*** (2.814)

Notes: The table denotes the consistent element check for quantile ARDL, NREC, REC, Trade, and FD. The Std. Errors are in brackets. ***, **, and * signify the 1%, 5%, and 10% level of significant, respectively.

and greenhouse gases, and also decreases the chances of air pollution. Secondly, their economy benefits from diversifying its energy sources and moving away from imported fuels. Over the past few years, India, a developing country, has faced numerous challenges related to air pollution and climate change. Its economy is also negatively impacted by severe energy problems (Shabbir Alam et al., 2023). For the previous five years, India has taken some steps and initiated numerous coal-energies projects to increase the resources of renewable energy and reduce nonrenewable resources that are the main sources of the CO_2 emissions in the nation. Although India has implemented various steps and plans to address these concerns, the energy industry is poorly managed, and the proportion of power consumed from green energy resources is low; as a result, meeting the target will take time. Figure 3 reflects the long-run pictorial findings from the quantile ARDL.

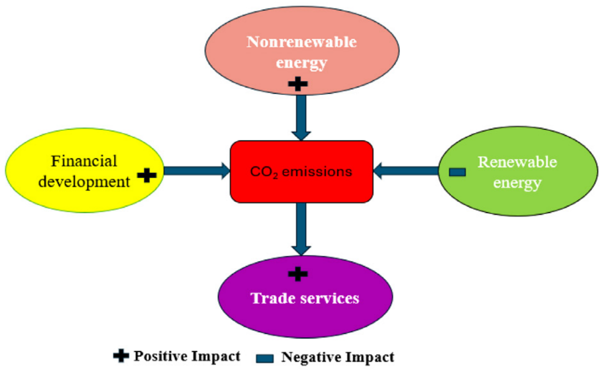

Figure 3. Long-run estimation results

Regarding the short-run dynamics, the results from the quantile ARDL method are presented in Table 5. The empirical results indicate that the current nonrenewable energies had a positive impact on carbon emissions at all quantiles. This implies that increased nonrenewable energy contributes to the ecological footprint at high pollution levels. The present and previous changes in financial development has a significant influence; whereas, trade openness has a significantly positive influence on CO_2 emissions at all quantiles. Additionally, current CO_2 emissions levels at all quantiles are significantly negatively impacted by REC changes.

Table 6. Results from Wald test (source: author estimation)

Variables	F-statistics	P-value
ρ^*	6.056	0.003
β_{NREC}	4.642	0.067
β_{REC}	0.012	0.023
β_{Trade}	3.001	0.000
β_{FD}	5.091	0.000
α_{CO_2E}	4.143	0.036
ω_{NREC}	2.614	0.046
λ_{REC}	0.243	0.087
θ_{Trade}	1.091	0.033
τ_{FD}	1.452	0.099

To estimate parameter consistency, we apply the Wald test with the overall data of economics, and the resulting estimations are given in Table 6. The results disclose that the null hypothesis of a linear relationship between variables is significantly rejected for ECT at the 5% level of significance. Moreover, the consistency of long-run parameters for REC, Trade, and FD is confirmed, while the null hypothesis is rejected. Conversely, the long-run parameters for NREC accept the null hypothesis of linear linkage. Regarding short-run parameters, there is evidence of a non-linear relationship between the past and lagged value of CO_2 emissions with current CO_2 emissions, as the null hypothesis is rejected. Additionally, short-run parameters for NREC and trade also reject the null hypothesis, while parameters for REC and FD accept the null hypothesis of linear linkage.

4.2. Wavelet coherence analysis results

The after-effect wavelet coherence (WC) analysis is carried out to determine the causal relationship amongst the CO_2 emissions and NREC, FD, TO, and REC. The outcomes are indicated in Figures 4, 5, 6, and 7. The cold (blue) color specifies no causal relationship, while the warmer (reddish) color and thick-black contours indicate significant causality or correlation among the factors. In the analysis of wavelet, the significant direction causal relationship is shown by the darts surrounded by the thick black contours. Pointing arrows north, northeast, or southwest suggests that the first factor granger-causality between the second factor. In contrast, pointing arrows south, southeast, or northwest imply that the second variable Granger causality exists between the first factors. In this investigation, the first factor denotes the several exogenous factors (NREC, FD, REC, and TO), and the second factor indicates the endogenous factor (CO_2 emissions), as represented in the title above each figure. Concerning the nonrenewable energy consumption and CO_2 emissions in Figure 4, the pointing arrows south and northeast (within the thick black contours) indicate a high causal relationship among them (from 1990 to 2020). Concerning REC and CO_2 emissions in Figure 5, the pointing arrows southeast and northeast show a lower causal relationship between REC to CO_2 emissions (from 1992 to 2002). With respect to trade openness and CO_2 emissions in Figure 6, the pointing arrows southeast and northeast indicate a lower causal link among TO and CO_2 emissions (from 1994 to 1999, and 2015 to 2019). Regarding the FD to CO_2 emissions in Figure 7, the pointing arrows southeast to northeast indicate a higher Granger causal relationship between FD to CO_2 emissions (from 1990 to 2020).

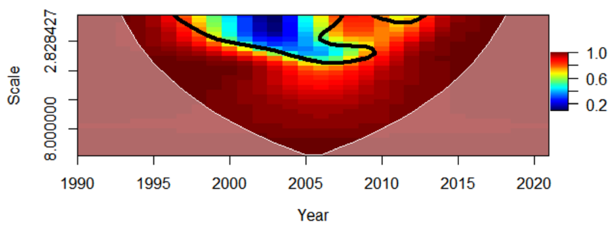

Figure 4. Wavelet coherence among NREC to EF

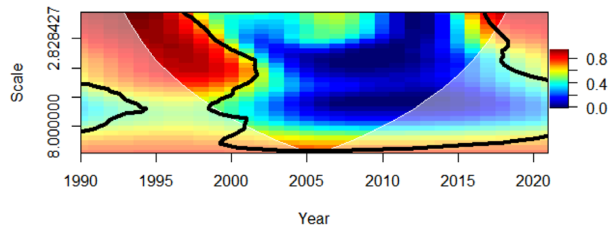

Figure 5. Wavelet coherence among REC to EF

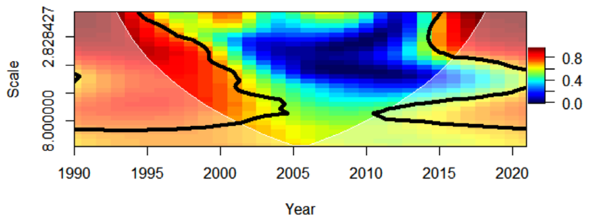

Figure 6. Wavelet coherence among Trade Openness to EF

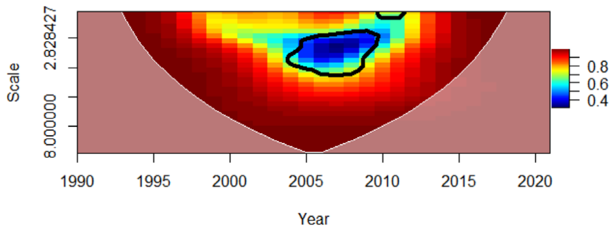

Figure 7. Wavelet coherence among FD to EF

5. Conclusions and policy recommended

This study provides new insights into exploring the relationship between REC, NRE, TO, and FD to promote environmental sustainability in India, utilizing time-series data from 1980 to 2022. We examined the impacts of REC, NREC, FD, and TO on ecological degradation with a primary focus on the environmental footprint. We utilized the adopted QARDL model and Wavelet Coherence techniques to achieve our research goals. Before advancing to the final modeling phase, we validated the stationary characteristics of our chosen variables by employing the conventional ADF test. We additionally applied the Zivot-Andrews unit-root test to account for the structural breaks. The Nonlinearity BDS test confirms the nonlinearity of the variables and the method of wavelet coherence (WC) to observe the causal relationship between carbon emissions and independent variables.

The empirical findings showed a positive and significant association between financial development and carbon emissions from the low to higher quantiles. Thus, we conclude that, in the case of India, financial development rises carbon dioxide emissions. This implies that in the long run, economies at different levels of development carry maximum damage to the atmosphere. At higher quantiles, the empirical research revealed substantial and negative associations between environmental pollution and trade openness. The empirical analysis indicates that the nonrenewable energy consumption is significantly positively correlated with CO_2 emissions at the higher quantiles. Finally, in the case of India, renewable energy consumption is also substantially and negatively correlated with carbon emissions. Moreover, it is essential to concentrate on using industry-leading green construction practices to ensure energy efficiency.

The empirical suggestion has very important policy recommendations for India. This study's findings show that the effect of FD and TO is ultimately transferred to carbon emissions through energy consumption in the economy. India will benefit from the appropriate allocation of TO and FD towards environmentally friendly energy sources and projects without sacrificing economic development; it is crucial for the country to shift towards renewable energy sources and cleaner-fuel options. This aligns with India's strategy to enhance its generation of green electricity capabilities, aiming to progressively increase the proportion of electricity produced from renewable sources in the country's overall electricity output. India had aimed to establish a capacity of 500 gigawatts for electricity production from renewable sources by 2030. However, the remarkable increase in energy demand has compelled the government of Indian to adjust this goal, leading to a greater reliance on coal for electricity generation. Nonetheless, the choice to increase electricity production from newly constructed coal-fired power plants does not align with environmental well-being. So, India should use clean coal technologies to make it easier for CO_2 emissions from coal-based power plants to be stored. This would control the amount of CO_2 released into the air. However, completely abandoning the RE transition target should never be considered a viable energy policy, especially when taking into account the importance of environmental sustainability.

Secondly, regarding the greening of trade activities, India should formulate policies that ensure the benefits of trade-related strategies surpass the associated scale effects. International trade should facilitate the cross-border influx of green technologies into India, which can subsequently be integrated into trade-oriented Indian industries to partially mitigate trade-related carbon footprints. Moreover, restrictions should be enacted on exports that are highly pollution-intensive, while facilitating the export of commodities with lower pollution intensity. Concurrently, it is essential to reform regulations governing the importation of energy-intensive inputs for production in Indian factories to mitigate the associated growth in CO_2 emissions. Thirdly, forthcoming economic policies in India must align with the country's CO_2-neutrality objectives. Indian firms should be incentivized to adopt energy conservation practices in their production facilities to reduce energy-related CO_2 emissions.

This is crucial as India has not yet achieved self-sufficiency in eliminating its reliance on fossil fuels. Moreover, the utilization rate of RE in production processes should be improved as the limitations regarding the renewable energy transition are progressively alleviated over time. Conversely, from a consumption standpoint, Indian consumers ought to utilize energy-efficient electrical appliances to minimize energy use and thereby reduce associated carbon emissions.

References

Adams, S., & Nsiah, C. (2019). Reducing carbon dioxide emissions; Does renewable energy matter? *Science of the Total Environment*, *693*, Article 133288. https://doi.org/10.1016/j.scitotenv.2019.07.094

Ahmad, A., Zhao, Y., Shahbaz, M., Bano, S., Zhang, Z., Wang, S., & Liu, Y. (2016). Carbon emissions, energy consumption and economic growth: An aggregate and disaggregate analysis of the Indian economy. *Energy Policy*, *96*, 131–143. https://doi.org/10.1016/j.enpol.2016.05.032

Ahmed, Z., Wang, Z., Mahmood, F., Hafeez, M., & Ali, N. (2019). Does globalization increase the ecological footprint? Empirical evidence from Malaysia. *Environmental Science and Pollution Research*, *26*(18), 18565–18582. https://doi.org/10.1007/s11356-019-05224-9

Alam, M. J., Ismat Ara Begum, I. A., Buysse, J., Rahman, S., & Van Huylenbroeck, G. (2011). Dynamic modeling of causal relationship between energy consumption, CO_2 emissions and economic growth in India. *Renewable and Sustainable Energy Reviews*, *15*(6), 3243–3251. https://doi.org/10.1016/j.rser.2011.04.029

Alam, M. S., Manigandan, P., Kisswani, K. M., & Baig, I. A. (2025). Achieving goals of the 2030 sustainable development agenda through renewable energy utilization: Comparing the environmental sustainability effects of economic growth and financial development. *Sustainable Futures*, *9*, Article 100534. https://doi.org/10.1016/j.sftr.2025.100534

Adamowski, J., & Chan, H. F. (2011). A wavelet neural network conjunction model for groundwater level forecasting. *Journal of Hydrology*, *407*(1–4), 28–40. https://doi.org/10.1016/j.jhydrol.2011.06.013

Aguiar-Conraria, L., Azevedo, N., & Soares, M. J. (2008). Using wavelets to decompose the time–frequency effects of monetary policy. *Physica A*: *Statistical Mechanics and its Applications*, *387*(12), 2863–2878. https://doi.org/10.1016/j.physa.2008.01.063

Apergis, N., & Payne, J. E. (2011). Renewable and non-renewable electricity consumption–growth nexus: Evidence from emerging market economies. *Applied Energy*, *88*(12), 5226–5230. https://doi.org/10.1016/j.apenergy.2011.06.041

Bloch, H., Rafiq, S., & Salim, R. (2015). Economic growth with coal, oil and renewable energy consumption in China: Prospects for fuel substitution. *Economic Modelling*, *44*, 104–115. https://doi.org/10.1016/j.econmod.2014.09.017

Chen, Y., Wang, Z., & Zhong, Z. (2019). CO_2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renewable Energy*, *131*, 208–216. https://doi.org/10.1016/j.renene.2018.07.047

Cho, J. S., Kim, T. H., & Shin, Y. (2015). Quantile cointegration in the autoregressive distributed-lag modeling framework. *Journal of Econometrics*, *188*(1), 281–300. https://doi.org/10.1016/j.jeconom.2015.05.003

Dagar, V., Rao, A., Dagher, L., & Doytch, N. (2024). Climate change dynamics for global energy security and equity: Evidence from policy stringency drivers. *Journal of Environmental Management*, *370*, Article 122484. https://doi.org/10.1016/j.jenvman.2024.122484

Danish, B. Z., Wang, B., & Wang, Z. (2017). Role of renewable energy and non-renewable energy consumption on EKC: Evidence from Pakistan. *Journal of Cleaner Production*, *156*, 855–864. https://doi.org/10.1016/j.jclepro.2017.03.203

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association*, *74*(366a), 427–431. https://doi.org/10.1080/01621459.1979.10482531

Dogan, E., & Seker, F. (2016). Determinants of CO_2 emissions in the European Union: The role of renewable and non-renewable energy. *Renewable Energy*, *94*, 429–439. https://doi.org/10.1016/j.renene.2016.03.078

Du, Y., & Wang, W. (2023). The role of green financing, agriculture development, geopolitical risk, and natural resource on environmental pollution in China. *Resources Policy*, *82*, Article 103440. https://doi.org/10.1016/j.resourpol.2023.103440

Feng, S., Li, J., Nawi, H. M., Alhamdi, F. M., & Shamansurova, Z. (2024). Assessing the nexus between fintech, natural resources, government effectiveness, and environmental pollution in China: A QARDL study. *Resources Policy*, *88*, Article 104433. https://doi.org/10.1016/j.resourpol.2023.104433

Ganda, F. (2019). The impact of innovation and technology investments on carbon emissions in selected Organisation for Economic Co-operation and Development countries. *Journal of Cleaner Production*, *217*, 469–483. https://doi.org/10.1016/j.jclepro.2019.01.235

Govindarajan, H. K., & Ganesh, L. S. (2021). Renewable energy for electricity use in India: Evidence from India's smart cities mission. *Renewable Energy Focus*, *38*, 36–43. https://doi.org/10.1016/j.ref.2021.05.005

Huang, L. (2024). Fintech inclusion in natural resource utilization, trade openness, resource productivity, recycling and minimizing waste generation: Does technology really drive economies toward green growth? *Resources Policy*, *90*, Article 104855. https://doi.org/10.1016/j.resourpol.2024.104855

Hossain, I., Haque, A. M., & Ullah, S. A. (2023). Role of government institutions in promoting sustainable development in Bangladesh: An environmental governance perspective. *Journal of Current Social and Political Issues*, *1*(2), 42–53. https://doi.org/10.15575/jcspi.v1i2.485

Iacobuţă, G. I., Brandi, C., Dzebo, A., & Elizalde Duron, S. D. (2022). Aligning climate and sustainable development finance through an SDG lens. The role of development assistance in implementing the Paris Agreement. *Global Environmental Change*, *74*, Article 102509. https://doi.org/10.1016/j.gloenvcha.2022.102509

Jiang, Q., Rahman, Z. U., Zhang, X., Guo, Z., & Xie, Q. (2022). An assessment of the impact of natural resources, energy, institutional quality, and financial development on CO_2 emissions: Evidence from the B&R nations. *Resources Policy*, *76*, Article 102716. https://doi.org/10.1016/j.resourpol.2022.102716

Kai, Z., Sharaf, M., Wei, S. Y., Shraah, A. A., Le, L. T., Arvind Bedekar, D. A., & Bani Ahmad, A. Y. A. (2024). Exploring the asymmetric relationship between natural resources, fintech, remittance and environmental pollution for BRICS nations: New insights from MMQR approach. *Resources Policy*, *90*, Article 104693. https://doi.org/10.1016/j.resourpol.2024.104693

Kang, S. H., Islam, F., & Tiwari, A. K. (2019). The dynamic relationships among CO_2 emissions, renewable and non-renewable energy sources, and economic growth in India: Evidence from time-varying Bayesian VAR model. *Structural Change and Economic Dynamics*, *50*, 90–101. https://doi.org/10.1016/j.strueco.2019.05.006

Khan, Z., Haouas, I., Trinh, H. H., Badeeb, R. A., & Zhang, C. (2023). Financial inclusion and energy poverty nexus in the era of globalization: Role of composite risk index and energy investment in emerging economies. *Renewable Energy*, *204*, 382–399. https://doi.org/10.1016/j.renene.2022.12.122

Kim, J., & Park, K. (2016). Financial development and deployment of renewable energy technologies. *Energy Economics*, *59*, 238–250. https://doi.org/10.1016/j.eneco.2016.08.012

Magazzino, C., Mutascu, M., Sarkodie, S. A., Adedoyin, F. F., & Owusu, P. A. (2021). Heterogeneous effects of temperature and emissions on economic productivity across climate regimes. *Science of the Total Environment*, *775*, Article 145893. https://doi.org/10.1016/j.scitotenv.2021.145893

Mngumi, F., Shaorong, S., Shair, F., & Waqas, M. (2022). Does green finance mitigate the effects of climate variability: Role of renewable energy investment and infrastructure. *Environmental Science and Pollution Research*, *29*(39), 59287–59299. https://doi.org/10.1007/s11356-022-19839-y (Retraction published 2024, *Environmental Science and Pollution Research*, *31*, 46118)

Murshed, M., & Alam, M. S. (2021). Estimating the macroeconomic determinants of total, renewable, and non-renewable energy demands in Bangladesh: The role of technological innovations. *Environmental Science and Pollution Research*, *28*, 30176–30196. https://doi.org/10.1007/s11356-021-12516-6

Murshed, M., Khan, U., Khan, A. M., & Ozturk, I. (2023). Can energy productivity gains harness the carbon dioxide-inhibiting agenda of the Next 11 countries? Implications for achieving sustainable development. *Sustainable Development*, *31*(1), 307–320. https://doi.org/10.1002/sd.2393

Mohanty, A., & Wadhawan, S. (2021). *Mapping India's climate vulnerability*: *A district level assessment report*. Council on Energy, Environment and Water (CEEW), New Delhi.

Neog, Y., & Yadava, A. K. (2020). Nexus among CO_2 emissions, remittances, and financial development: A NARDL approach for India. *Environmental Science and Pollution Research*, *27*(35), 44470–44481. https://doi.org/10.1007/s11356-020-10198-0

Nibedita, B., & Irfan, M. (2022). Analyzing the asymmetric impacts of renewables on wholesale electricity price: Empirical evidence from the Indian electricity market. *Renewable Energy*, *194*, 538–551. https://doi.org/10.1016/j.renene.2022.05.116

Paramati, S. R., Apergis, N., & Ummalla, M. (2017). Financing clean energy projects through domestic and foreign capital: The role of political cooperation among the EU, the G20 and OECD countries. *Energy Economics*, *61*, 62–71. https://doi.org/10.1016/j.eneco.2016.11.001

Paraschiv, F., Fleten, S. E., & Schürle, M. (2015). A spot-forward model for electricity prices with regime shifts. *Energy Economics*, *47*, 142–153. https://doi.org/10.1016/j.eneco.2014.11.003

Pata, U. K., Kartal, M. T., Adebayo, T. S., & Ullah, S. (2023). Enhancing environmental quality in the United States by linking biomass energy consumption and load capacity factor. *Geoscience Frontiers*, *14*(3), Article 101531. https://doi.org/10.1016/j.gsf.2022.101531

Przychodzen, W., & Przychodzen, J. (2020). Determinants of renewable energy production in transition economies: A panel data approach. *Energy*, *191*, Article 116583. https://doi.org/10.1016/j.energy.2019.116583

Qamruzzaman, M., & Karim, S. (2023). Does public-private investment augment renewable energy consumption in BIMSTEC nations? Evidence from symmetric and asymmetric assessment. *Energy Strategy Reviews*, *49*, Article 101169. https://doi.org/10.1016/j.esr.2023.101169

Qin, M., Su, C. W., Umar, M., Lobonţ, O. R., & Manta, A. G. (2023). Are climate and geopolitics the challenges to sustainable development? Novel evidence from the global supply chain. *Economic Analysis and Policy*, *77*, 748–763. https://doi.org/10.1016/j.eap.2023.01.002

Saqib, N., Ozturk, I., & Usman, M. (2023). Investigating the Implications of technological innovations, financial inclusion, and renewable energy in diminishing ecological footprints levels in emerging economies. *Geoscience Frontiers*, *14*(6), Article 101667. https://doi.org/10.1016/j.gsf.2023.101667

Sebri, M., & Ben-Salha, O. (2014). On the causal dynamics between economic growth, renewable energy consumption, CO_2 emissions and trade openness: Fresh evidence from BRICS countries. *Renewable and Sustainable Energy Reviews*, *39*, 14–23. https://doi.org/10.1016/j.rser.2014.07.033

Salifu, M., Peprah, J. A., Sebu, J., & Cantah, W. G. (2024). Openness policies and financial development in Ghana: An ARDL approach. *Heliyon*, *10*(3), Article e25074. https://doi.org/10.1016/j.heliyon.2024.e25074

Shabbir Alam, M., Duraisamy, P., Bakkar Siddik, A., Murshed, M., Mahmood, H., Palanisamy, M., & Kirikkaleli, D. (2023). The impacts of globalization, renewable energy, and agriculture on CO_2 emissions in India: Contextual evidence using a novel composite carbon emission-related atmospheric quality index. *Gondwana Research*, *119*, 384–401. https://doi.org/10.1016/j.gr.2023.04.005

Shahbaz, M., Siddiqui, A., Sinha, A., & Bigerna, S. (2024). Does financial development enhance access to electricity? A rural-urban perspective in India. *Energy*, *291*, Article 130464. https://doi.org/10.1016/j.energy.2024.130464

Shahbaz, M., Topcu, B. A., Sarıgül, S. S., & Vo, X. V. (2021). The effect of financial development on renewable energy demand: The case of developing countries. *Renewable Energy*, *178*, 1370–1380. https://doi.org/10.1016/j.renene.2021.06.121

Shahbaz, M., Zakaria, M., Shahzad, S. J. H., & Mahalik, M. K. (2018). The energy consumption and economic growth nexus in top ten energy-consuming countries: Fresh evidence from using the quantile-on-quantile approach. *Energy Economics*, *71*, 282–301. https://doi.org/10.1016/j.eneco.2018.02.023

Sharif, A., Baris-Tuzemen, O., Uzuner, G., Ozturk, I., & Sinha, A. (2020). Revisiting the role of renewable and non-renewable energy consumption on Turkey's ecological footprint: Evidence from quantile ARDL approach. *Sustainable Cities and Society*, *57*, Article 102138. https://doi.org/10.1016/j.scs.2020.102138

Shastri, S., Mohapatra, G., & Giri, A. K. (2020). Economic growth, renewable and nonrenewable energy consumption nexus in India: Evidences from nonlinear ARDL approach and asymmetric causality analysis. *International Journal of Energy Sector Management*, *14*(4), 777–792. https://doi.org/10.1108/IJESM-06-2019-0016

Van Soest, H. L., den Elzen, M. G., & van Vuuren, D. P. (2021). Net-zero emission targets for major emitting countries consistent with the Paris Agreement. *Nature Communications*, *12*(1), Article 2140. https://doi.org/10.1038/s41467-021-22294-x

Zivot, E., & Andrews, D. W. K. (1992). Further evidence on the great crash, the oil price shock, and the unit root hypothesis. *Journal of Business and Economic Statistics*, *10*(3), 251–270. https://doi.org/10.1080/07350015.1992.10509904

Zhong, Y., Chen, X., Yao, X., Wang, Z., & Chang, H. L. (2024). Natural resources and the trilemma of financial development, institutions, and markets: Sustainable development pathway via natural resources for China. *Resources Policy*, *90*, Article 104759. https://doi.org/10.1016/j.resourpol.2024.104759

Zouine, M., El Adnani, M. J., & Salhi, S. E. (2024). Does higher education matter in mitigating chronic disease mortality? Evidence from MENA countries with consideration of globalization, economic growth, and environmental pollution. *Research in Globalization*, *9*, Article 100236. https://doi.org/10.1016/j.resglo.2024.100236