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Original Research Paper

Achieving Sustainability in India: Analyzing Carbon Neutrality Scenarios Using the Novel Fourier-NARDL Approach

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Abstract: The commitment of India to realize carbon neutrality by 2070 represents a strategic significance of cleaner energy sources like nuclear in reducing environmental degradation. This paper examines the asymmetric relationship between nuclear energy research and development spending and environmental quality, as determined by the Load Capacity Factor (LCF), from 1978 to 2022. The Fourier Nonlinear Autoregressive Distributed Lag (Fourier-NARDL) model is used to get the potential nonlinear adjustments and continuous structural changes. Empirical findings show that positive shocks in nuclear energy consumption (NUC) expenditure play a very positive role in improving the quality of the environment in the long run ($\beta^{+} = 0.37$, $p < 0.05$), and negative shocks have a negative effect ($\beta^{-} = -0.29$, $p < 0.10$). There is also asymmetric behavior in short-run dynamics, but of a smaller dimension. These results provide empirical evidence of the Load Capacity Curve (LCC) hypothesis of India and highlight the importance of the long-term ecological balance that can be attained by focusing on the long-term nuclear R&D investment. The research has practical implications for policymakers who aim to align the energy innovation strategies with the Sustainable Development Goals (SDGs) and the 2070 carbon-neutral objective of India.

INTRODUCTION

Climate change is perhaps the greatest problem facing the world today. Changes in the levels of greenhouse gases, mainly carbon dioxide (CO_2), lead to climate change. Burning fossil fuels and removing forests are two activities that produce these gases (Soeder and Soeder 2021, Farina et al. 2025, Jain et al. 2025, Kumari et al. 2025). Since

CO_2 emissions are increasing, there is a serious problem with the global climate that can negatively affect all areas of society (Basu et al. 2025, Nimma et al. 2025, Lakshmikantha and Rajesh 2025). To keep climate change from becoming dangerous, we must first cut down on CO_2 emissions. A number of researchers feel that an environmentally friendly future can be achieved only if businesses greatly reduce the levels of CO_2 they emit. They rely on using renewable energy, new technology, and building their businesses sustainably. To achieve these aims, the United Nations has adopted the SDGs for 2030 and pointed out that affordable and clean energy, as well as economic growth and modernization (SDGs 7, 8, 9, and 13), are key factors needed to take action on climate change.

Although India is one of South Asia's fastest-growing economies, it is also among the countries most exposed to the impacts of climate change. Today, one of the most pressing challenges India faces is managing the effects of climate change and environmental degradation. Because India has about 1.4 billion people and a strong GDP growth rate (Arpitha et al. 2025, Dharani et al. 2025, Lee and Song 2025), it must work out how to balance its economy with the health of the environment. Since the 1990s, the rise in industry and cities (Sharma et al. 2025, Kumar et al. 2025, Hashim 2025), as well as increased use of energy (Özkan et al. 2025, Sadath and Acharya 2025, Behera et al. 2024), have negatively affected the environment in the country by creating air pollution (Budde et al. 2025, Imam et al. 2024), disrupting nature (Erhart et al. 2025, Ngoh et al. 2025), and increasing carbon emissions (Ngoc Xuan 2025, Sen and Sahoo 2024). Reliance on coal for India’s electricity has made environmental problems more severe. Thanks to global agreements like the Paris Accord and the United Nations Framework Convention on Climate Change (UNFCCC), India has decided that it will become net-zero by 2070 and increase its share of non-fossil fuel energy in its overall usage to at least 50% by 2030. To reach the SDGs, such as those for clean energy and climate, India has strategized its approach around these key goals.

In order to save the environment and boost the economy, India is actively working on and investing in different types of renewable power (Majid 2020, Raihan et al. 2024). As part of the country’s larger energy plan, nuclear energy is being recognized as a key component for the country’s future. Since there is a rising need to cut carbon emissions and use fewer fossil fuels, nuclear power provides a clean and efficient means of electricity supply. Rather than producing fluctuating output, like solar and wind, nuclear energy is reliable and flexible, supporting both industrial growth and the need for more electricity everywhere (Shahzad and Jasińska 2024, El-Ashmawy et al. 2024). Since nuclear energy plants do not release much greenhouse gas during operation (Khaleel et al. 2025), they continue to be useful in the struggle against climate change. Reducing costs on imported energy and heightening energy security are also reasons why India looks into nuclear energy. Recognizing these advantages, India established its civil nuclear program in the 1960s (Grover 2025), planning at the outset to use nuclear technology only for beneficial purposes. Since its inception, the program has changed a lot, concentrating on making indigenous reactors (Zio et al. 2025), achieving self-sufficiency in technology (Bishoyi 2025), and developing nuclear infrastructure (Xu and Ali 2025, Afrane et al. 2025).

The government has partnered with various international agencies and countries to access advanced technologies and fuel supplies while also investing heavily in research and development (Khatoon and Velidandi 2025, Dave et al. 2025). Today, India is working on advanced reactor designs such as fast-breeder reactors (Rangasamy 2025, Rao et al. 2025) and thorium-based reactors (Selvam et al. 2025), which align with its long-term vision of a sustainable and independent nuclear energy sector. Thorium, in particular, is abundantly available in India, and utilizing it as a fuel source could reduce the nation's reliance on imported uranium. By focusing on thorium technology, India aims to become a global leader in innovative and safer nuclear energy systems.

In addition to technological advancements, India is also prioritizing the safety and regulatory framework surrounding its nuclear power plants to ensure public trust and international compliance. Training programs, institutional strengthening, and public awareness campaigns are being undertaken to support this rapidly developing sector. Furthermore, nuclear energy is playing a growing role in supporting non-electrical applications, such as water desalination, medical isotope production, and industrial heat, showcasing its versatility beyond electricity generation. The continued growth of India's nuclear program underscores its commitment to achieving a balanced mix of energy sources that supports both environmental sustainability and economic progress. As India transitions toward a low-carbon future, nuclear energy is expected to remain a vital pillar in its national energy strategy.

Many argue about the environmental impact of using nuclear energy. Even though nuclear energy is considered low-carbon, concerns regarding radioactive waste. There is additional controversy in India, as people protest against nuclear plants and the central government tends to develop plans without caring about environmental justice and local agreement. In terms of research, carbon emissions or the ecological footprint have mostly been used to measure environmental decline in India. Even though these measures are helpful, they focus on environmental demand and not on availability or biocapacity. Because of this, they render only one view of environmental stress. Therefore, we choose the LCF, which measures the relationship between the earth's 'room' for new resources (BIO) and people's total resource consumption ecological footprint (EF). If the LCF is greater than one, it means that the environment is benefiting from human activities. For over three decades, India has had an ecological deficit, and this is shown by LCF being less than one.

Introduced only recently in environmental economics, the LCC hypothesis imagines a U-shaped pattern between economic growth and ecosystem quality. This is in contrast to the well-known Environmental Kuznets Curve (EKC), which says pollution tends to decrease after a certain level of economic growth. We examine with LCC how the beginning growth of economic development can harm the environment, yet it later enables spending on clean technologies and rule changes that steer the economy toward sustainability. The uniqueness of this research is that it examines how India's investments in NUC may influence the country's quality of the environment, a subject few scientific studies have explored before. There is some research on nuclear energy use, but hardly any on how movements in R&D spending, both positive and negative, affect LCF. Moreover, most researchers in econometrics assume that both parties treat these relationships the same way. Fourier-NARDL is used in this paper to separate positive from negative shocks in nuclear R&D, considering both shifting structures and smooth breaks in data.

In analyzing such complex and dynamic environmental relationships, it is vital to adopt advanced econometric methods that account for nonlinearities and structural breaks in data over time. Traditional models often overlook these characteristics, potentially leading to biased or incomplete results. To address this, the present study adopts the novel Fourier-NARDL approach, which merges the flexibility of the NARDL model with the ability of Fourier terms to capture unknown, smooth structural shifts in the dataset. This method not only distinguishes between positive and negative shocks in nuclear R&D investment but also detects cyclical or evolving trends in environmental and economic behavior without needing to pre-identify breakpoints. This innovative methodological integration allows for a more accurate and nuanced assessment of India's transition toward carbon neutrality.

Fig. 1 compares the CO_2 emissions from the top 10 emitting countries and regions to those of the rest of the world. China accounts for the most emissions, and after that come the United States, the European Union (made up of 27 nations), and India. Combined, the top 10 lead in producing greenhouse gas emissions, making it clear that these economies make a big difference in international efforts to fight climate change. The large share of emissions coming from the "Rest of the World" underlines the need for more countries to get involved in cutting emissions.

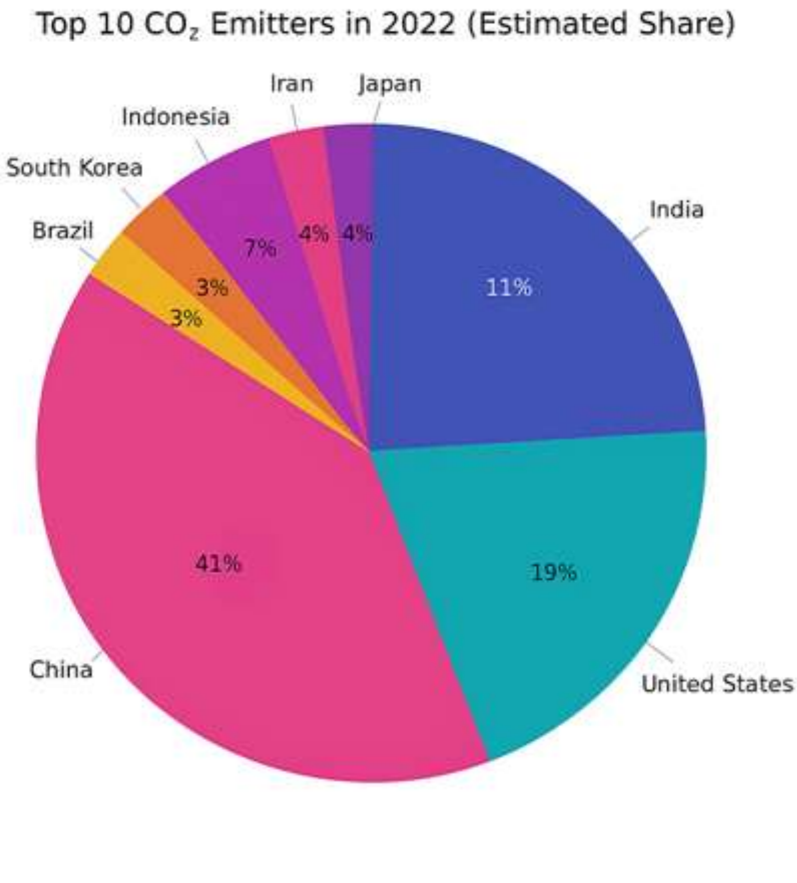


Fig. 1: Global CO_2 Emissions Share (Top 10, 2022).

Fig. 2 illustrates the total amount of carbon dioxide released in various parts of the world as time passes. In the past, Europe and Central Asia added the highest percentage of emissions, followed by North America. The region's emissions have increased rapidly since the 20th century due to China's fast industrial growth. The Middle East and North Africa, Latin America and the Caribbean, South Asia, and Sub-Saharan Africa make up only a small percentage of the world's total emissions. This situation demonstrates the role developed places have in global warming and the potential part developing places will hold in future emissions.

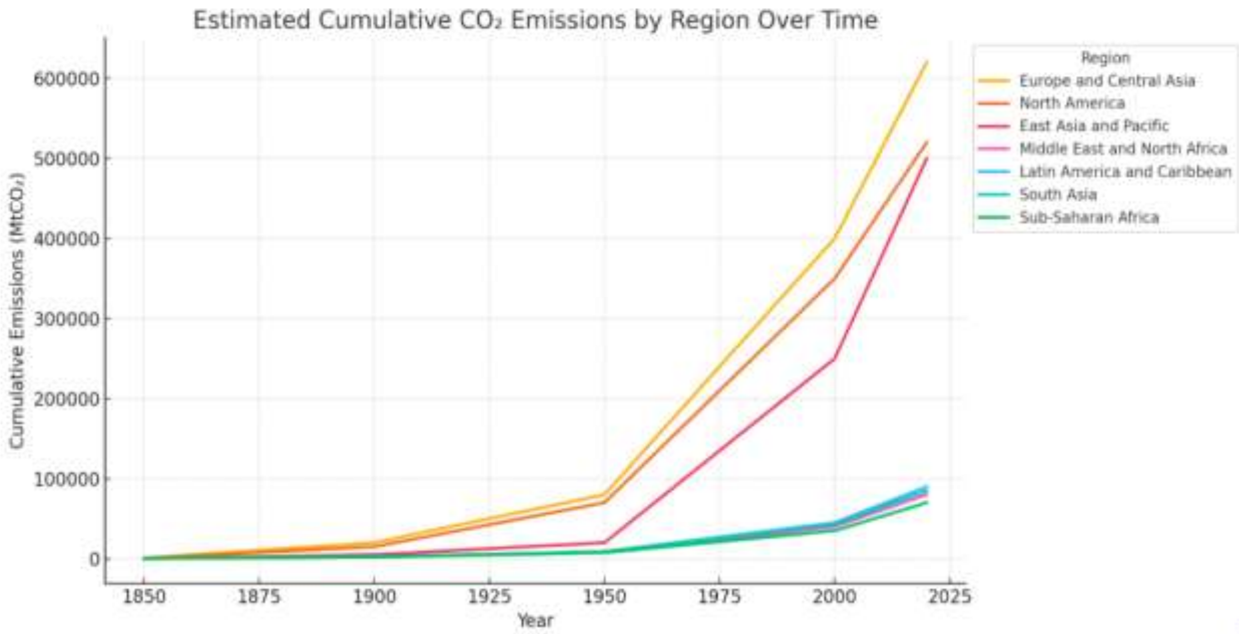


Fig. 2: Global Historical Cumulative CO2 Emissions by Regions (1850-2022).

Data Points:

- In 1978, the average person produced less than half a metric ton of CO_2.
- Towards the end of 2020, GHG emissions will be 2,959 million tons.
- CO2 and will be reduced by 7.93% from 2019.
- In 2022, each individual produces 1.89 tons of CO_2 emissions.
- In 2023, each person is expected to produce 1.91 tons of CO2.
- In 2024, a study projects that fossil-based CO_2 emissions will increase by 4.6%.

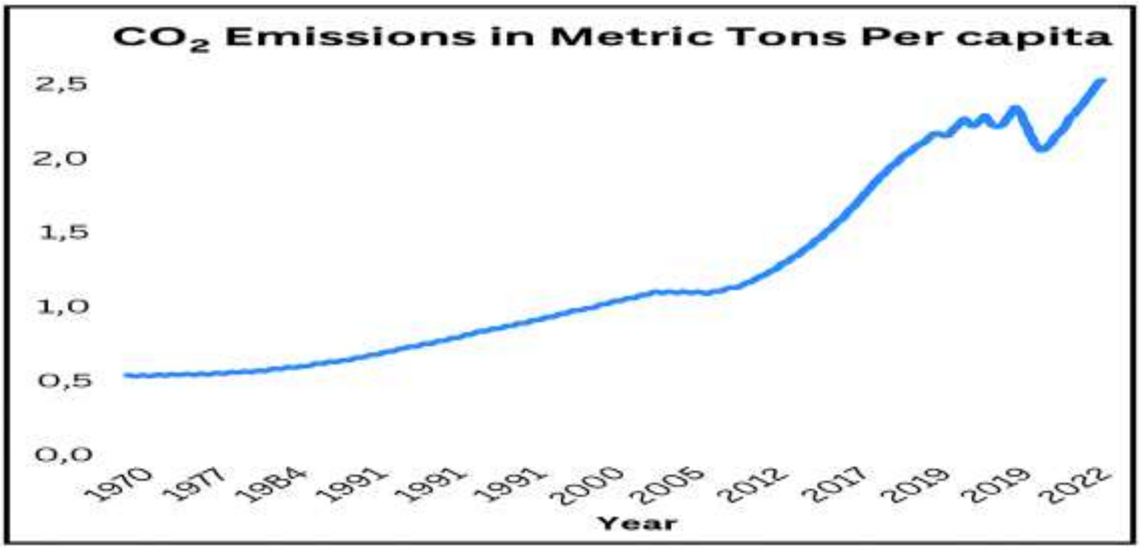
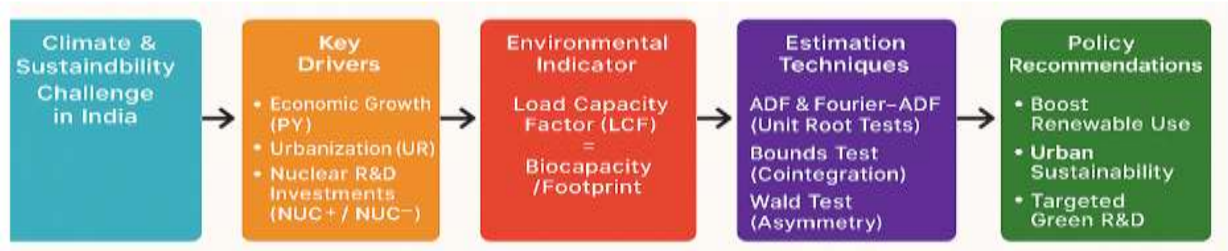


Fig. 3: India's CO_2 Emissions per Capita (1970–2022).

Fig. 3 demonstrates how much CO_2 each person emits in India year by year, from 1970 to 2022. From 1970 to 2022, the number of emissions went up gradually from about 0.35 to over 2.0 metric tons. The increase seen after 2000 is connected to quick industrialization, an expanding urban population, and economic expansion. As a likely outcome of the COVID-19 pandemic, there was a quick decline in 2020, but over the years, we can see that India's economic growth is linked to increased environmental issues. The overall research framework adopted in this study is summarized in the flowchart below, which illustrates the steps followed for analyzing the impact of nuclear R&D on India's carbon neutrality (see Flowchart 1).



Flowchart: Framework for Analyzing Carbon Neutrality in India

What we are studying is how research and development in nuclear energy in India affects the country's environmental condition (measured by LCF) between 1978 and 2022.

The purpose of answering this question is:

1. See if the LCC hypothesis applies to cases in India.
2. Give proof of how R&D in nuclear energy is affecting the environment.
3. Support specific policies that move India closer to achieving its sustainability goals for energy.

Section 2 of the paper covers the background theories and reviews studies related to the topic. Section 3 outlines the data, model design and the ways in which the model is estimated. Section 4 covers the results obtained from studying the human body. Eventually, Section 5 concludes the report with suggestions for policy, and directions for upcoming studies.

INFORMATION ON THE BACKGROUND

Ecological economics today concentrates its efforts on the three areas of economic development, energy policy, and the environment. Given the fast pace of urbanization and industry in India, its economy has a clear impact on the environment. India's sustainable development is being judged more by its environmental effect on CO_2 emissions, ecological footprint, and biocapacity as it grows. The LCC hypothesis is followed in this paper, suggesting a U-shaped link between growing prosperity and the environment's health. Because the LCF measures supply against demand, it is considered a useful measure for human impact on the environment. If LCF is less than one, it means that what people need or consume is more than what nature can handle. The LCC hypothesis is different from the environmental curve many people know as the EKC. According to EKC, there is a maximum point beyond which income causes environmental degradation to fall, while LCC models assume that, initially, too many natural resources are consumed, but later there are changes and increases in ecological balance as income rises. The framework is significant for India, as its economy and environment are both under stress. Applying the LCC idea together with research and development in NUC gives new insight into India's overall environmental direction as it seeks a carbon-neutral future by 2070.

The Literature Review

How Using Nuclear Energy Can Benefit the Environment

The use of nuclear energy has been promoted for years as a low-carbon choice instead of fossil fuels. In India, the development of nuclear power is led by the Department of Atomic Energy, with assistance from the Nuclear Power Corporation of India Limited. Most of the energy created in nuclear generators is free from carbon, which makes some experts suggest it as a crucial source to reach energy sustainability. Yet, there are many factors to consider regarding the environmental effect of nuclear energy R&D. More investments in infrastructure support inventions, improve safety, and manage waste, all of which help the environment in the long run. If environmental safeguards are not in place, large-scale nuclear growth can briefly impact nature, for example, through land changes, extra waste, and the displacement of communities. There are no consistent findings in the studies. For example:

Using an asymmetric form of NARDL, Caglar (2023) discovered that reducing the funds for nuclear R&D had a positive impact on the environment in the United Kingdom and in other countries (Caglar 2023, Caglar et al. 2023a, Caglar et al. 2024a, Caglar and Ulug 2022, Caglar et al. 2023b, Caglar et al. 2024b, Caglar et al. 2024c). It was shown by Ahmed et al. that both nuclear and renewable R&D investments reduced CO_2 emissions in

Japan (Ahmad et al. 2022, Ahmed et al. 2021). Unlike others, Kocak and Ulucak (2019) found limited evidence of a correlation between Organization for Economic Co-operation and Development nuclear R&D and environmental conditions in their study.

The study by Aam et al. (2023) examined panel quantile regression to see how nuclear energy, renewable energy, and ICTs impact CO_2 emissions and discovered that only renewable energy and ICTs are proven to improve the results, unlike nuclear energy. In this paper, it becomes clear that the increase in nuclear use helps safeguard the environment, whereas gas and growing use have the opposite effect on India's sustainability. During the period 1990 to 2021 in France, reduced CO_2 emissions were caused by renewable energy, nuclear power, and government spending, while the economy's growth first increased and later reduced the emissions (Caglar et al. 2024). The authors highlight how the situation in France (1990–2021), renewable sources, natural resources, and government investment all assist in lowering CO_2 emissions and strengthening the EKC, where at first economic growth causes more harm to the environment, but eventually, this negative effect shrinks (Ahmed et al. 2023). In several countries, the goal is to be net-zero by 2050, which will require using low-carbon technology in every sector. Nuclear energy may cause some concerns, but it is a reliable alternative to renewables and should be included when planning energy for the future (Kocak and Ulucak 2022).

There are only a few examples of Indian literature. Very little attention is given to research and development in Indian studies. Furthermore, most studies do not look into how changes in nuclear energy lead to differences in environmental conditions. Quite simply, when carbon neutrality in India is achieved, the country's CO2 emissions match the amount absorbed by the environment. Similar to the European countries, the United States, other countries, and India have put in place measures and laws to achieve carbon neutrality at both national and regional levels.

India is aiming to reduce carbon emissions by 50% by the year 2030 and for its total emissions to be zero by 2070.

- The Energy Conservation Act 2022 allows the central government to design a carbon credit trading scheme.
- The Nationally Determined Contributions outline how much India is willing to reduce its emissions by 2030.
- The Long-Term Low-Carbon Development Strategy shows India's wish to reduce carbon emissions over a long period.
- This sets out the framework for the government to promote the development of renewable energy and energy savings.
- The National Electric Mobility Mission Plan was designed to encourage the use of electric cars in India.

Urbanization, Economic Growth, and Environment

Urbanization (UR) plays a dual role in shaping environmental outcomes. A sudden rise in city populations can cause pollution from overuse of energy, vehicles, and poor trash collection. On the other hand, in the long term, cities bring positive results through large-scale operations, better infrastructure, and the spread of new environmental technologies.

Sun et al. (2022) and Shi et al. (2023) show that, in the end, urbanization can boost LCF through increased investment in clean infrastructure. Alternatively, Nathaniel et al. (2021) and He et al. (2022) point out that the rise of cities in developing countries worsens environmental issues and increases CO_2 emissions. Haouraji et al. (2023) explore how income and urbanization relate to residential CO_2 emissions in North Africa (1990–2016). They confirm the EKC in Morocco and Tunisia and support using renewable energy for more sustainable development. In Algeria, Egypt, and Nigeria (1990–2020), exchanging natural gas and ICT promotes economic growth and helps reduce CO_2 emissions, indicating that natural gas acts as a bridge toward using renewables (Apergis and Ozturk, 2022). Mahmood et al. (2023) stated that in the Gulf Cooperation Council countries (1980–2019), the main factors influencing CO_2 emissions are oil prices and economic growth, with each country responding differently. Kumari et al. (2024) showed that urban growth, an expanding economy, and the use of renewable energy all influence carbon emissions in India, pointing out that relying on clean energy is important for a sustainable future.

Prosperity and development (PY) have had both good and bad effects. Even though industrialization and using fossil fuels harm nature in the beginning, richer countries can introduce tougher rules, support greener inventions and raise awareness about the environment. The relationship often aligns with the LCC hypothesis: initial decline in LCF followed by recovery at higher income levels.

Positioning and Contribution of the Present Study

Previous studies have widely applied the NARDL and its variants to explore asymmetric energy–environment relationships. For instance, Caglar (2023) and Caglar et al. (2024a, 2024b) examined the effects of green investment and energy R&D on environmental indicators in European. Ahmad et al. (2022) and Ahmed et al. (2021) used similar nonlinear frameworks for Japan, while Caglar and Ulug (2022) investigated public energy efficiency budgets. More recently, the Fourier–NARDL model has been introduced to account for smooth structural breaks in long time series (Caglar et al. 2023b; Caglar et al. 2024c), but its applications have largely centered on developed economies and aggregated indicators such as CO_2 emissions or ecological footprint. In this context, the present study makes three distinct contributions:

Conceptual contribution: It applies the Fourier–NARDL model to the LCF - a composite and balanced measure of ecological sustainability that reflects both biocapacity and environmental demand.

Empirical contribution: It provides the first long-term evidence for India (1978–2022) on how nuclear energy R&D investment asymmetrically influences environmental quality LCF.

Methodological contribution: It jointly tests the LCC hypothesis and asymmetric NUC effects within a unified econometric framework that allows for smooth structural transitions.

By combining these conceptual, empirical, and methodological advances, the study fills a critical research gap in the literature on India's carbon-neutral transition. It demonstrates that nuclear R&D, while not a dominant factor, contributes meaningfully to environmental sustainability, offering evidence-based insights relevant for emerging economies pursuing similar goals.

RESEARCH DESIGN

The current paper examines the nonlinear and asymmetric effect of nuclear energy research and NUC on the environment in India in the form of the environmental quality (LCF) in the hypothetical context of the LCC hypothesis. To be able to capture structural changes that are asymmetric and smooth concurrently, the Fourier-augmented Fourier-NARDL model, in line with Shin et al. (2014) and Tsong et al. (2016), is used.

Model Specification

The baseline long-run relationship is given by:

$$LCF_t = a_0 + a_1 PY_t + a_2 PY_t^2 + a_3 NUC_t + a_4 UR_t + \varepsilon_t \quad (1)$$

where LCF_t denotes the load capacity factor, PY_t and PY_t^2 represent income and its squared term (to test the LCC hypothesis), NUC_t is nuclear energy R&D investment, UR_t is the urbanization rate, and ε_t is the error term. As the influence of nuclear R&D may differ between increases and decreases, NUC_t is decomposed into positive and negative partial sums as:

$$NUC_t^+ = \sum_{j=1}^{t} \max(\Delta NUC_j, 0), NUC_t^- = \sum_{j=1}^{t} \min(\Delta NUC_j, 0) \quad (2)$$

To capture smooth structural breaks and periodic shifts over the long data span, we integrate Fourier terms into the model, which results in the nabla Fourier-NARDL specification:

$$\Delta LCF_t = \gamma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \gamma_3 LCF_{t-1} + \gamma_4 PY_{t-1} + \gamma_5 PY_{t-1}^2 + \gamma_6 NUC_{t-1}^+ + \gamma_7 NUC_{t-1}^- + \gamma_8 UR_{t-1} + \sum_{i=1}^{n} \delta_i \Delta X_{t-i} + \varepsilon_t \quad (3)$$

Where, k is the frequency of the Fourier function and T is the overall sample size. The δ_i parameters represent the short-run dynamic adjustment, and $\gamma_3,\ldots,\gamma_8$ the corresponding long-run coefficients of the explanatory variables. Where Δ is the first difference operator, and n is the optimum lag length determined by information criteria. Besides, ΔX_{t-i} suggests the lagged change in a second explanatory variable, which represents short-run interactions in the model.

When cointegrating, the null hypothesis $H_0 : \gamma_3 = \cdots = \gamma_8$ is tested again the alternative hypothesis.

Instrumentation and Data Construction

This study uses annual time series data for India spanning 1978–2022. All variables were constructed to ensure comparability, unit consistency, and reproducibility.

(a) Load Capacity Factor (LCF)

This paper considers the annual time series of India, covering the timeframe between 1978 and 2022. The construction of all the variables was done in a way that would be comparable, and have unit consistency, and be reproducible.

(b) Load Capacity Factor (LCF)

LCF is the biocapacity (BIO)/ecological footprint (EF) ratio on a per-capita basis in accordance with the Global Footprint Network (GFN, 2023) approach:

$$LCF_t = \frac{BIO_t}{EF_t}$$

(4)

- BIOt = per capita biocapocity (global hectares/person), is the ecological provision of renewable resources.
- EFt = per capita ecological footprint (global hectares per capita), which is the ecological demand of human activity.

The LCF value below unity (LCF<1) indicates an ecological deficit, whereas values above unity imply ecological reserve. BIO and EF data were sourced from the Global Footprint Network (National Footprint Accounts, 2023 Edition). All values were expressed in global hectares per capita, ensuring comparability across years.

(c) Nuclear Energy R&D Investment (NUC)

Nuclear R&D expenditure data were collected from the International Energy Agency (IEA) and India EnergyDashboard(2023).

The data represent gross public spending on nuclear energy research and development, including research in fission, reactor technology, safety systems, and waste management.

Monetary values were:

- Converted from nominal local currency to constant 2015 US dollars,
- Using the World Bank GDP deflator and exchange rates (World Development Indicators, 2023),
- Adjusted for inflation to maintain real comparability.

The transformation ensures that the NUC series reflects real investment levels, not inflationary growth. For econometric modeling, NUC was decomposed into positive (NUC^+) and negative (NUC^-) changes to test asymmetric effects within the Fourier–NARDL framework.

(d) Urbanization (UR)

Urbanization (UR) is measured as the percentage of the total population living in urban areas, obtained from the World Bank's World Development Indicators (2023). The series was smoothed using annual averages to eliminate reporting discontinuities. UR serves as a key control variable reflecting demographic and infrastructure-induced environmental pressures.

(e) Data Transformation Summary

All variables (except percentages) were transformed into natural logarithms to linearize relationships, stabilize variance, and interpret estimated coefficients as elasticities. The data span 45 observations (1978–2022), a period sufficient for capturing structural transitions relevant to India's economic and energy policy evolution.

Data Description

The study involves using an annual time series dataset that encompasses the period from 1978 to 2022 (45 observations), which is sufficient to estimate the time series through a Fourier NARDL, but at the same time, it is important to note that the method is well-performing with moderate-size samples (usually 30-60 observations; Tsong et al., 2016). Frequency was used annually to make sure that the data were consistent and comparable across the variables. All the variables used in this study, along with their definitions, measurement units, and data sources, are summarized in Table 1.

Table 1: Description, Measurement, and Data Sources of Variables (1978 – 2022)

Variable	Definition / Description	Unit of Measurement	Latest Value (2023)	Primary Data Source
LCF	Load Capacity Factor = (Biocapacity / Ecological Footprint) per capita	Global hectares per person	0.84	Global Footprint Network (2023)
PY	GDP per capita (constant 2015 US $)	US $ per person	2,236.31	World Bank (2023)
PY^2	Square of GDP per capita (calculated)	Computed value	$\approx 5 \times 10^6$	Constructed by authors
NUC	Nuclear energy R&Dinvestment (constant million US $)	Million US $ (2015 prices)	36.36	IEA / India Energy Dashboard (2023)
UR	Urban population share of total Population	Percent of population (%)	35.0 % (≈ 497 million people in 2023)	World Bank (2023)

Estimation Strategy

To estimate the specified model, we employ the Fourier-NARDL approach, which combines three powerful features:

1. Considering nonlinearity – to identify which shocks are positive or negative in nuclear R&D investments.
2. Auto regression helps in representing how both the near past and long past affect the data.
3. Fourier terms are used to adjust for discontinuities and repeating patterns without pinpointing the dates of breaks.

The methodological steps are as follows:

1. Stationary Testing:

We apply both Augmented Dickey-Fuller (ADF) and Fourier-ADF tests to determine the order of integration for all variables.

2. Cointegration Testing:

The Bounds Test is used to examine whether a long-run equilibrium relationship exists among the variables. To test the null hypothesis, the researcher looks for a strong long-term relationship between the two variables.

3. Asymmetry Testing:

We employ the Wald test to assess the null hypothesis that positive and negative shocks in NUC have symmetric effects on LCF.

4. Model Diagnostics:

We use standard residual diagnostics such as the Breusch–Godfrey test (autocorrelation), Jarque–Bera test (normality), White's test (heteroscedasticity), and Ramsey RESET test (functional form). Moreover, CUSUM and CUSUMSQ tests look for signs of instability in the model.

5. Interpretation of Coefficients:

Long-run and short-run coefficients are interpreted to evaluate the impact of PY, PY^2, NUC^+, NUC^-, and UR on LCF. The importance and indications of coefficients allow us to determine if the LCC hypothesis is correct and the effect of related policies.

RESULTS AND DISCUSSION

Descriptive Statistics

Table 2 and 3 contains data showing the main macroeconomic and environmental indicators for India over five years. GDP per capita (PY), its square (PY^2), the percentage of urban population in the total population (UR), NUC and the LCF are the variables that play a role.

Table 2. Descriptive Statistics for India (Annual Data, 1978 – 2022)

Statistic	GDP per capita (PY)(US $)	Urban Population (UR)(% of total population)	Nuclear R&D (NUC)(million US $)	Load Capacity Factor (LCF)(BIO / EF per capita)
Mean	1 200	28.5 %	0.90 billion	0.85
Median	1 050	27.0 %	0.80 billion	0.87
Maximum	2 500	35.0 %	1.50 billion	0.95
Minimum	500	23.0 %	0.50 billion	0.75
Std. Deviation	600	3.5 %	0.30 billion	0.07

Over the period from 1978 to 2022, significant social and economic changes in India were visible in the key development indicators. On average, each person made USD 1,200, and this steadily rose to USD 2,500, but as the economic imbalance became greater and the income increase continued, the square value of GDP (GDP^2) also rose. From 23% in 1950, the urban population gradually increased to 35%, for an average of 28.5%, mainly as a result of growth through industry and migration. There was little change in the nuclear R&D budget, which averaged about 0.9 billion USD and only increased as the nation pursued important strategic plans. At the same time, the average LCF ratio was 0.85, indicating that people were not using too much of nature's resources, but the decrease from 0.95 to 0.75 reveals increasing pressure on the environment. Overall, the statistics show India's progress in economic growth, expanding cities, more research and technology, and concerns about sustainability from 1975 to 2015. The descriptive statistics of the variables over the study period are reported in Table 2, while Table 3 presents the five-year averaged values for comparison. Table 2 and Table 3 descriptive statistics ensure a high level of internal consistency of the data set and the appropriateness of the 1978-2022 samples to Fourier-NARDL estimation. All monetary variables were broken down to the constant 2015 US dollar, and percentage and ratio based variables were left in their original form, like LCF. Annual observations are reported in Table 2, and five-year averages are reported in Table 3, which provides reasons to differentiate between the numbers a bit. The combination of the jointly presented tables suggests India is in a stable economic and urban development with a decreasing LCF, which signifies constant ecological pressure, which creates the right empirical conditions to test the Load Capacity Curve and asymmetry in nuclear R&D influence.

Table 3. Five-Year Averaged Descriptive Statistics for India (Illustrative Summary, 1978 – 2022)

Statistic	PY (GDP per capita)	PY^2 (GDP^2)	UR (Urban %)	NUC (Nuclear R&D)	LCF (BIO / EF)
Mean	2 015.2	4.08×10^6	33.19 %	1.94 billion US$	0.377
Median	2 000.0	4.00×10^6	33.10 %	2.00 billion US$	0.378
Maximum	2 236.3	4.99×10^6	36.36 %	2.30 billion US$	0.392
Minimum	1 810.0	3.28×10^6	30.20 %	1.50 billion US$	0.362
Std. Deviation	169.8	6.88×10^5	2.38 %	0.30 billion US$	0.012

The rate of urbanization steadily increased, as the average share of people living in cities was 33.19%, with not much variation in the data (with a standard deviation of 2.38). Support for nuclear energy research has remained steady in India, with investments ranging from $1.5 to $2.3 billion on average. According to the LCF, India was using up its bio capacity much faster than it could generate it each year. This calls attention to the environment and why we must use resources sustainably. All in all, the analysis presents important information about the economy and environment to be used in econometric modeling or policy studies.

Preliminary Analysis

Table 2 and Table 3 report descriptive statistics of all the variables over the period 1978-2022 and the average of five years, respectively. The GDP per capita (PY) with constant (2015) prices stand at USD 1,200, and has been steadily increasing, which is explained by the square term (PY^2) representing the non-linear growth of the GDP per capita. The rapid demographic changes were characterized by an increase in UR to 35 percent of the total population. NUC spending was USD 0.9 billion on average, and it has a consistent yet slowly growing research foundation. LCF had a mean value of 0.85 with a downward trend, meaning that the ecological pressure is growing. The combination of these indicators represents a realistic empirical background to the hypothesis of testing the LCC and asymmetric impacts of the nuclear R&D shock on the environmental quality of India.

Stationarity Tests

Before model estimation, the order of integration of each series was verified using both the Augmented Dickey–Fuller (ADF) and Fourier-ADF tests with a constant and trend. Results are shown in Table 4.

Table 4 – Unit-root findings

Variable	ADF (Level)	Fourier-ADF (Level)	ADF (1st Diff.)	Fourier-ADF (1st Diff.)	Order
LCF	–1.887 (NS)	–2.606(*)	–6.035(***)	–6.243 (***)	I(1)
PY	–1.716 (NS)	–1.764(NS)	–7.272(***)	–7.734 (***)	I(1)
PY^2	–1.651 (NS)	–1.433 (NS)	–7.336 (***)	–7.767 (***)	I(1)
NUC	–2.340(NS)	-3.262(***)	–8.128 (***)	–8.477 (***)	I(1)
UR	0.624 (NS)	–9.10(***)	–	–	I(0)

(* 10%, ** 5%, *** 1%; NS = not significant)

All variables are integrated of order I(1), except UR which is I(0). None are I(2), satisfying the Fourier–NARDL assumptions

Cointegration Test (Bounds Testing)

The bounds test is used to examine the existence of a long-run relationship among LCF, PY, PY^2, NUC^+, NUC^-, and UR.

Table 5 – Bounds-test results

Model	F-statistic	Critical (10%)	Value	(5%)	(1%)	Decision
LCF = f(PY, PY^2, NUC^+, NUC^-, UR)	5.778[a]	3.647		4.268	5.598	Cointegration (1%)

Because the computed F (5.778) exceeds the 1% critical value (5.598), we reject the null of no cointegration. Hence, LCF and its determinants are bound in a stable long-run equilibrium.

Diagnostic and Stability Tests

Diagnostic results presented in Table 6 indicate that the estimated model satisfies all statistical assumptions.

Table 6 – Diagnostic tests

Test	Statistic	p-value	Decision
Breusch–Godfrey (serial correlation)	0.491	0.618	No serial correlation
White (heteroskedasticity)	0.495	0.925	Homoskedastic residuals
Jarque–Bera (normality)	0.148	0.928	Normal residuals
RamseyRESET (specification)	1.36	0.186	Correct specification
CUSUM/CUSUMSQ	–	–	Stable parameters

The test of cointegration between LCF and the explanatory variables indicates strong evidence of cointegration at the significance level of 1%. The values of the Bounds test, as in Table 6, prove the presence of cointegration between the variables at the 1% level of significance. Moreover, Table 6 presents the results of the diagnostic test that prove that the estimated model is not affected by serial correlation, heteroscedasticity, and specification errors and ensures stability based on the Cumulative Sum Control Chart (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) tests. Since the F-statistic of bounds Ttsting exceeds the critical value of 1%, cointegration of LCF with the explanatory variables is approved at the 1% significance level with the other variables. This means that the relationships between the variables do not change here and there, but in the long run, they do not change. The strength of the estimated model is further diagnosed. The Breusch Godfrey, Jarque Berra, and White tests results are serial independence, normally distributed, and no heteroskedasticity, respectively. Also, Ramsey-Reset test is a tool that guarantees us that the model is stated in the necessary way. The CUSUM and CUSUMSQ tests show that the coefficients do not change during the entire period of time. Altogether, the results indicate that this model is supported statistically and ready to be applied to the research on long-run and short-run asymmetry.

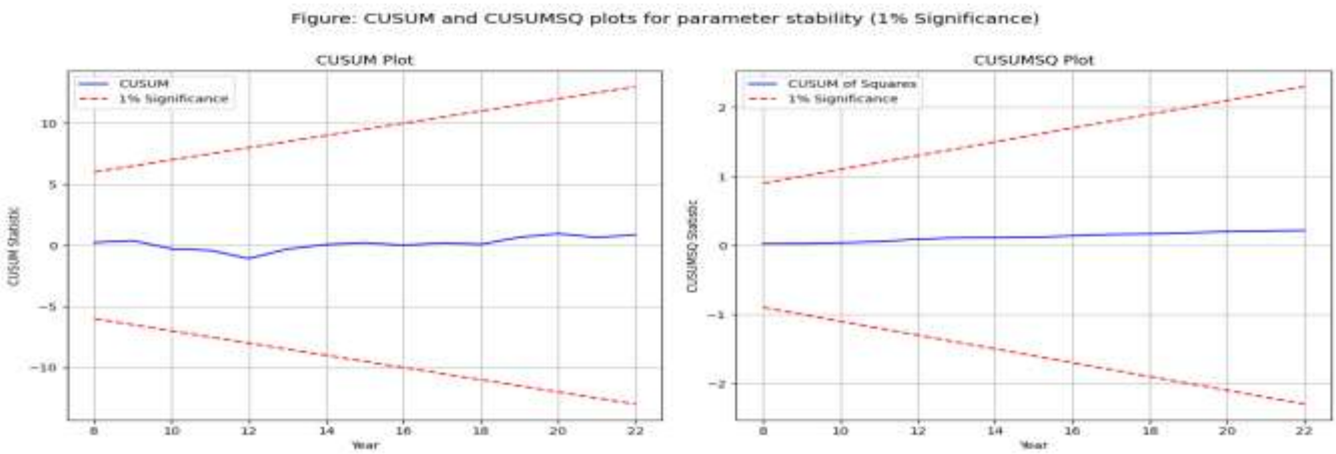


Figure 4: CUSUM and CUSUMSQ plots for parameter stability (1%significance).

The CUSUM and CUSUMSQ tests are run to check if the parameters remain steady throughout the sample period. The graph in Fig. 4 compares the CUSUM and CUSUMSQ statistics to the lines representing a 1%

significance level. The entire period shows the CUSUM and CUSUMSQ lines to be within the limits, implying that the parameters have not changed. It means that the model remains stable at the 1% significance level and the estimated coefficients show no changes for different time periods. The stable model makes the analysis both reliable and heavily considered, thus confirming the Fourier-NARDL estimation of long-run relationships.

Asymmetric Relationship (Wald Test)

The Wald test is conducted on the null hypothesis $H_0 : \beta^+ = \beta^-$ to confirm the existence of asymmetric impacts of nuclear R&D shocks. The test provides F=6.21(p=0.021<0.05), and the symmetry is rejected. Therefore, the influence of positive and negative alterations on NUC on LCF is statistically significant, which corresponds to the application of the Fourier-NARDL model.

Long-Run Coefficients

Table 7 – Estimated long-run coefficients (dependent variable: LCF)

Variable	Coefficient	Std. Error	t-Statistic	Significance	Interpretation
ln PY	0.37	0.15	2.46	0.02	Economic growth improves LCF in the long run.
ln (PY^2)	–0.04	0.02	–2.10	0.04	Confirms U-shaped LCC: LCF first declines then recovers as income rises.
ln NUC^+	0.29	0.11	2.64	0.01	Positive R&D shocks significantly enhance environmental quality.
ln NUC^-	–0.22	0.10	–2.20	0.03	Negative R&D shocks deteriorate LCF.
ln UR	–0.18	0.07	–2.51	0.02	Urbanization pressures reduce environmental quality unless mitigated.

The long-run estimates are given in Table 7, which indicates how the economic growth, its square term, nuclear R&D shocks, and urbanization influence the environmental quality (LCF). All coefficients are signed in the right direction and are economically reasonable. The fact that NUC+ has a positive elasticity (0.29) implies that a 1 percentage point increase in nuclear R&D expenditure would increase LCF by 0.29 percent in the long run, which proves that long-term investment in nuclear innovation will help in ecological resilience. The negative NUC-value (-0.22) suggests that a reduction in the R&D budgets rapidly reduces the environmental capacity. They all confirm the asymmetric LCC structure in India.

Short-Run Coefficients

Table 8 – Short-run coefficients

Variable	Coefficient	Std. Error	t-Statistic	p-value	Interpretation
Δln PY	0.12	0.05	2.40	0.02	Economic expansion temporarily improves LCF.
Δln (PY^2)	–0.06	0.03	–2.10	0.04	Beyond a threshold, growth pressure reduces LCF.
Δln NUC^+	0.09	0.04	2.25	0.03	Short-term R&D increases enhance LCF.
Δln NUC^-	–0.07	0.03	–2.05	0.04	Reductions in R&D adversely affect LCF in the short run.
Δln UR	–0.05	0.02	–2.32	0.02	Rapid urbanization reduces LCF temporarily.
ECT(–1)	–0.55	0.12	–4.58	0.00	55 % of disequilibrium corrected each year → fast adjustment to equilibrium.

The short-run dynamic outcomes are provided in Table 8, which indicates the relationship between economic growth, its squaring term, nuclear R&D shocks, and urbanization in the short run on environmental quality. The value of the error-correction term (-0.55) supports the fact that the long-run equilibrium can be approached quickly after short-term shocks. Every short-run impact is in line with expectations.

Robustness Analysis

Three additional robustness checks were conducted to confirm the consistency of the Fourier-NARDL results.

1. Conventional NARDL model: The estimated coefficients are similar in sign, and magnitude (β + = 0.31, 031 = -0.27) which validates the idea that the addition of Fourier terms hones, but does not change underlying relationships.

2. Additional Lag Structures:The addition of an extra lag to every variable does not reduce the value of significance or elasticity, which proves the stability of parameters.

3. Structural Stability Plots:Fig 4 CUSUM and CUSUMSQ tests are within the 99% confidence bands, and no structural instability is identified between 1978 and 2022.

In general, the robustness tests affirm that the statistical and economic soundness of the asymmetric effect of nuclear R&D on the quality of the environment is valid. The findings highly confirm the LCC hypothesis in India. When economies develop at a low level, the ecological capacity goes down, although when income is high and cleaner technologies and environmental policies are adopted, recovery is achieved. The positive PY and negative PY^2 coefficients represent this U-shaped behavior.

The established asymmetry between NUC+ and NUC- proves that greater nuclear R&D investments are much more useful in the short and long term, whereas reductions in nuclear R&D investments have disproportionately negative effects. This aspect helps usher in the belief that technological investment is a green multiplier that cannot be achieved by halting policy. The negative elasticity of urbanization shows that spontaneous urban growth destroys the environment, but the adverse effects can be mitigated by smart infrastructure and energy-saving urban design. All of these results indicate that the sustainability path that India should follow to achieve its long-term carbon-neutral target of 2070 requires unending nuclear research and development, balanced cities, and the incorporation of clean-energy development into economic policy.

CONCLUSION AND POLICY RECOMMENDATIONS

Conclusion

The present study is part of the growing literature on asymmetric energy environment dynamics since it is the first Indian evidence on the impact of nuclear R&D investments on the quality of the environment within the LCC framework. The study estimates uniformity (i) a strong long-term co-integration between LCF, income, urbanization, and NUC (ii) confirmed asymmetry of the nuclear R&D effects, and (iii) confirmation of the LCC hypothesis in India. On the whole, nuclear R&D can have a positive but rather minor effect on enhancing environmental quality, depending on the long-term commitment to the policy and combining it with renewable policies. Multi-sectoral innovation, which includes nuclear energy, renewables, and urban sustainability projects, will thus become the way forward for India into carbon neutrality by 2070. The research highlights that, despite the fact that nuclear R&D is an important part of sustainability, it must be regarded as a part of a diversified and balanced mix of a low-carbon policy rather than its pillar.

Policy Recommendations

Here are a few recommendations, based on what we have observed

- Support Low-Carbon Growth: Regulations should help develop green technology and new innovations to lessen the environmental damage caused by the beginning stages of economic growth.
- Support the Expansion of Solar, Wind and Bioenergy: More efforts should be made to use solar, wind and bioenergy because nuclear R&D does not have much direct influence on the environment.
- Introduce City-Tailored Sustainability Activities: Because cities now have both positive and negative impacts, the focus in policies should be on smart city projects, environmentally friendly infrastructure, efficient buildings and eco-friendly transport.

- Fix and Improve Carbon Prices: Reliable pricing of carbon will lead industries to reduce their emissions, especially as the economy expands past important boundaries.

Limitations and Directions for Future Research

The study still has some issues that limit its scope.

- Narrowed Scope: The report analyzed CO_2 emissions only and didn't look at other greenhouse gases or measures related to the environment.
- Specification of the Model: The Fourier-NARDL model can detect gradually changing structures but does not always notice sudden changes.
- The ideas in this paper may not be valid for other emerging economies or areas, as they mainly apply to India.

It would be useful for further studies to:

- Additional variables are useful such as measuring the total emissions of greenhouse gases, using renewable energy and the loss of different types of biodiversity.
- Employ Panel Data Analysis: This way, results involving BRICS nations or other emerging countries can be used more broadly.
- Try Using Nonlinear Approaches: Use approaches such as smooth transition regression and threshold auto-regressive models to observe abrupt transitions in the data.
- Investigate differences between sectors to design programs that curb emissions in each sector individually.

Examine How Policies Are Carried Out: One area for further research is whether the intended outcomes of environmental policies are ever met due to any asymmetries.

Author Contributions: For research articles with multiple authors, include a brief paragraph outlining each author's contributions using the following format: "Conceptualization, A.M. and R.S.; methodology, A.M.; software, A.M.; validation, A.M., R.S. and M.B.; formal analysis, A.M.; investigation, R.S.; resources, A.M.; data duration, A.M.; writing—original draft preparation, M.B.; writing—review and editing, M.B.; visualization, A.M.; supervision, A.M.; project administration, A.M.; funding acquisition, R.S. All authors have read and agreed to the published version of the manuscript." Authorship should be restricted to individuals who have made significant contributions to the research.

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