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RESEARCH ARTICLE

Re-examining the environmental Kuznets curve (EKC) for India via the multiple threshold NARDL procedure

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Abstract
Irrespective of the vast array of empirical evaluations pertaining to the environmental Kuznets curve (EKC) hypothesis, both for India and other countries, previous studies, amid divergent submissions, inadvertently failed to highlight the relevant threshold that ensures significant reductions in environmental decay. Additionally, the implications of environmental-control technology on environmental quality are also lacking mostly in the context of Indian economy. Thus, this study enlists environmental-control technology and other relevant factors over the period 1980–2018 and employs the novel multiple threshold nonlinear ARDL technique, a model rarely applied in previous studies for updated empirical narratives. Accordingly, the empirical evidence rectifies that the variables converged to long-run equilibrium. Furthermore, from the tercile partial deviations, it is established that at the middle threshold ($GDP^2{}_{W2}$), pollution shrinks more significantly amid rising income, thereby validating the EKC hypothesis for India. Likewise, environmental-control technologies provided only a short-term insignificant carbon neutrality pathway, whereas they provided long-term insignificant emission increasing effects. This implies that the depth of such technology in India is inadequate to invoke cleaner environments at all times. Likewise, energy consumption and urbanization processes are significant environmental polluters, while trade openness provides insignificant long- and short-term carbon emission effects. Against this background, economic growth within the middle threshold promises a more sustainable environment amid rising national income at all times. Moreover, given its short-term outcomes, strengthening the depth of environmental-control technology is imperative to ensure a long-lasting clean environment in India.

Keywords Environmental Kuznets curve · Environmental sustainability · Environmental-related technological innovations · Multiple threshold nonlinear ARDL · India

Introduction

In the present economic advancement patterns, the issue of increasing rates of environmental decay and climate change has turned into an incredible challenge for all countries, both developed and developing. In addition, it is generally difficult to ensure the total abatement of greenhouse emissions and other related environmental pollutants. Given the surge in CO_2 emissions and the underlying environmental decay, the commitment to clean climate and sustainable development eludes world economies, especially developing/emerging economies. Meanwhile, it has been proven that unregulated human activities in all ramifications contribute over 70% to climate change (Adebayo and Rjoub 2021). In reference to the enormous challenges of environmental decay and changing climatic conditions, the United Nations (UN) has initiated several international conventions, including the

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Kyoto protocol in 1997, the Paris Agreement in 2015, and the Intergovernmental Panel on Climate Change (IPCC) in 2018, which are all geared toward pushing the trajectory of sustainable ecosystems for all inhabitants of the earth. Additionally, the epoch making conference of Paris (COPI21) has its overall objective to ensure that the global temperature level is kept within 2 °C above the preindustrial levels with possible further declines to at least 1.5 °C (Bilgili et al. 2019; UNFCCC 2016; Umar et al. 2020). Likewise, environmental scholars are also at the forefront of identifying the core determinants of environmental decay as well as providing sustainable and workable policy strategies to ensure that environmental decay is mitigated.

Commenting on the voluminous body of empirical narratives related to environmental sustainability, Anwar et al. (2022) and Bashir et al. (2021) delineated, among other factors, the prominent place vested the relationship between economic growth and environmental pollution. That is, the popular environmental Kuznets curve (EKC) hypothesis extended by Grossman and Krueger (1995). Accordingly, the EKC hypothesis remarks a unique relationship between economic growth and emissions, whereby environmental pollution increases alongside economic growth at the initial stage; then, over time, higher economic growth invokes significant reductions in environmental pollution (Bilgili et al. 2021a, b, c; Bilgili et al. 2021a, b, c). This suggests a short-run positive and long-run inverse relationship between economic growth and environmental quality. Empirical studies have also highlighted that the shape of the EKC could be a U-shaped, inverted U-shaped, N-shaped, or inverted N-shaped relationship between national income and environmental pollution (see Danish and Ulucak, 2022; Doğan et al. 2022; Gormus and Aydin 2020; Sun et al. 2020; Tiba and Frikha 2020; Ulucak and Bilgili 2018). The highlighted relationship within the economic growth–environmental quality nexus is further buttressed by three effects (Grossman and Krueger 1995): the scale, technique, and composition effects cited in extant studies, including Emre et al. (2022) and Bilgili et al. (2019). Accordingly, the scale effect considers an early-stage positive relationship, the composition effect suggests a likely U-shaped relationship, while the technique effect indicates an inverse relationship between economic growth and pollution mainly due to improved technologies (Bashir et al. 2021; Güngör et al. 2021).

Sequel to the inference of the EKC hypothesis, including the theoretical postulations of the highlighted effects, researchers have found themselves in a web of seemingly unending debate about the veracity or otherwise of the hypothesis cutting across several countries and continents. Accordingly, Kanjilal and Ghosh (2013) relied on a threshold cointegration procedure to validate the EKC hypothesis for India, which was also confirmed by a related study (Adebola Solarin et al. 2017). However, Villanthenkodath et al. (2021), based on the linear autoregressive distributed lag (ARDL) model, suggest that it is rather an unconventional U-shaped EKC that prevails in India. Furthermore, in a study of 19 African countries through the ARDL technique, Shahbaz et al. (2016) explain that the EKC hypothesis holds for most African countries but for Sudan and Tanzania, where a U-shaped EKC prevails. For Ben Nasr et al. (2015), Adzawla et al. (2019), Shoaib et al. (2020), and Zafar et al. (2019), the EKC is invalid in South Africa, sub-Saharan Africa, G8 countries, and the USA, respectively. Conversely, Bello et al. (2018), Katircioğlu and Katircioğlu (2018), and Zhu et al. (2019) canvassed an inverted U-shaped EKC in the context of Malaysia during the 1971–2016 period, Turkey during the 1960–2013 period, and 76 Chinese cities during the 2013–2017 period, respectively. Extant studies such as Hao et al. (2018) and Shujah-ur-Rahman et al. (2019), based on the outcomes of spatial and VECM models, contend that it is a rather N-shaped EKC that prevails in China and Central and Eastern European (CEE) countries during the 2006–2015 and 1991–2014 periods, respectively. However, Javid and Sharif (2016) and Adebola Solarin et al. (2017) further emphasized the conventional EKC in the context of Pakistan, China, and India, respectively.

Recent investigations have also extended the polarized opinions in terms of the pollution-economic growth nexus and the probable validation of the EKC in many countries and over several periods. Notably, Ansari et al. (2020) relied on the outcomes of dynamic OLS and fully modified OLS to contend with the vagueness of the EKC in Gulf Corporation countries during the 1991–2017 period. Similar inferences, in terms of the vagueness of the EKC, were extended by Asiedu et al. (2021) and Chien et al. (2021) in the context of Belgium, the USA, Canada, and ASEAN countries, respectively. Likewise, on the outcome of the MG-CCE technique, Danish and Wang (2019) rectified that growth did not exacerbate pollution in Next-11 countries during 1971–2014. Erdoğan et al. (2020) also report that the EKC is invalid in the case of G20 countries based on the outcomes of the CCE and AMG models during the 1991–2017 period. Similar evidence buttressing the invalidity of the EKC in the context of India was also extended by Udemba et al. (2021) based on the outcomes of the ARDL and modified Toda-Yamamoto causality tests. In addition, Bilgili et al. (2021a, b, c) document that there are no unique dynamics of the EKC, as reported by prior studies. Their position arose from a study of thirteen developed nations based on a panel quantile regression process. As against these opinions, several other empirical expositions extended the polarized opinions by upholding the validity of the EKC in several economies. These include Chishti and Sinha (2022), Danish and Ulucak (2022), Eregha et al. (2021), and Godil et al. (2021), who validate the EKC hypothesis in BRICS, China, sub-Saharan Africa, and Pakistan, respectively. However, for others, including Gyamfi et al. (2021), Jiang et al. (2022), Salari et al. (2021), and Villanthenkodath and Arakkal (2020), it is a U-shaped EKC that holds for E7 countries, China, USA, and New Zealand, respectively. However, for Sheikhzeinoddin et al. (2022), based on the outcomes of the panel NARDL technique and dataset from 2000 to 2015, it is rather an N-shaped EKC that prevails between growth and emissions in MENA countries.

Based on the above overview of empirical inquiries suggesting open debate in terms of the pollution-economic growth nexus, a notable fact is that an emerging country and top 10 emitters, such as India, was understudied. Meanwhile, the few that considered India failed to establish convergent policy options, therefore incentivising further inquiries. In addition, their inferences were derived through not too robust econometric algorithms, such as ARDL and panel NARDL. Buttressing the point that India was understudied is the survey of literature related to the EKC hypothesis by Bashir et al. (2021), which confirmed that China and the USA were the countries considered by the majority of scholars, followed by Turkey and Pakistan. Notably, India is among the top 10 CO_2 emitters and a prominent emerging economy and the second largest CO_2 emitter (coming behind China) in the comity of emerging economies (Neog and Yadava 2020). Specifically, Yang et al. (2021) remarked that India is among the top four most polluted economies of the world. It is also documented that on estimate, approximately 40% of worldwide greenhouse emissions emanate from the BRICS countries (Li et al. 2022), among which India is prominent. Furthermore, the IMF remarks that India is also noted as one of the fastest growing economies in the world and the country's commitment to sustainable growth. Therefore, it is expected that policymakers in India strike a balance between economic growth and the ecosystem leading to sustainable economic growth, thereby ensuring total commitment to UN SDGs 7, 12, 8, and 13. Graphical illustrations, Figs. 1 and 2, have been provided to illustrate the interactions of economic growth and pollution, as well as environmental-control technological innovativeness in India over the period 1980–2018. Accordingly, Fig. 1 reveals a simultaneous surge in both economic growth and carbon emissions over time. This outcome seems to invalidate the EKC phenomenon for India. However, detailed outcomes based on empirical evaluation are expected to either accept or reject the validity of EKC for India. Similarly, Fig. 2 portrays the relationship between environmental-control technology and emissions in India. The graph (Fig. 2) signifies a continuous surge in the level of CO_2 emissions, while environmental-control technologies lag behind. This presupposes some levels of inefficiencies on the part of environmental-control technologies that have left the country among the top emitters in the world.

From the foregoing, this study is a firm commitment to bear, through enhanced econometric algorithms, inclusions of key variables, and updated datasets, how the Indian ecosystem performs amid rising economic growth and the impasse of environmental-control-related technological innovativeness on environmental quality in India. Based on these undergirding objectives, the following empirical questions are critical: how does the Indian ecosystem respond to the dynamics of economic growth? To what extent has environmental-control related technologies affected environmental pollution in India? The study will also critique the relative influence of trade openness, energy consumption,

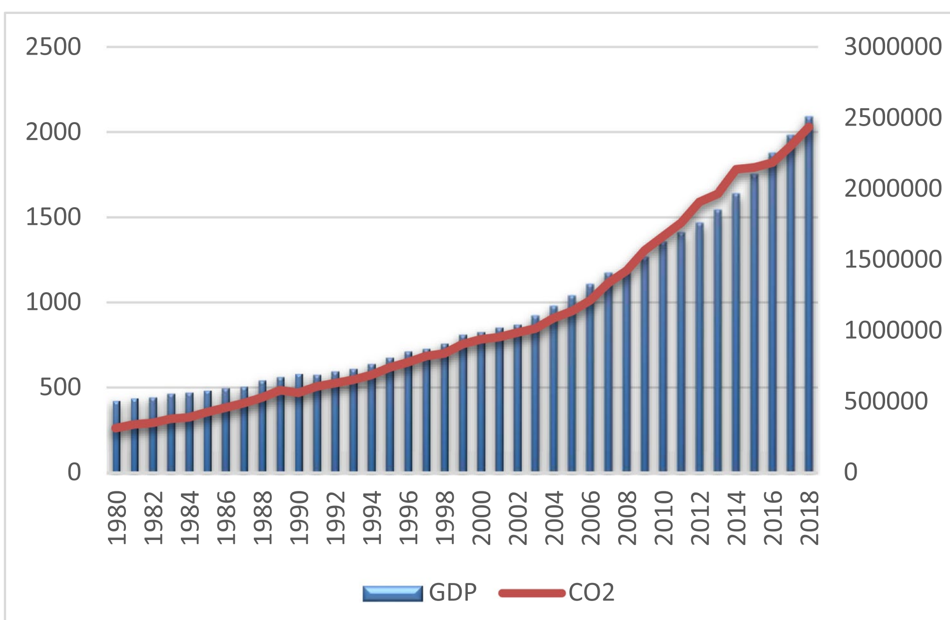

Fig. 1 Trend of carbon emission (CO_2) and economic growth (GDP)

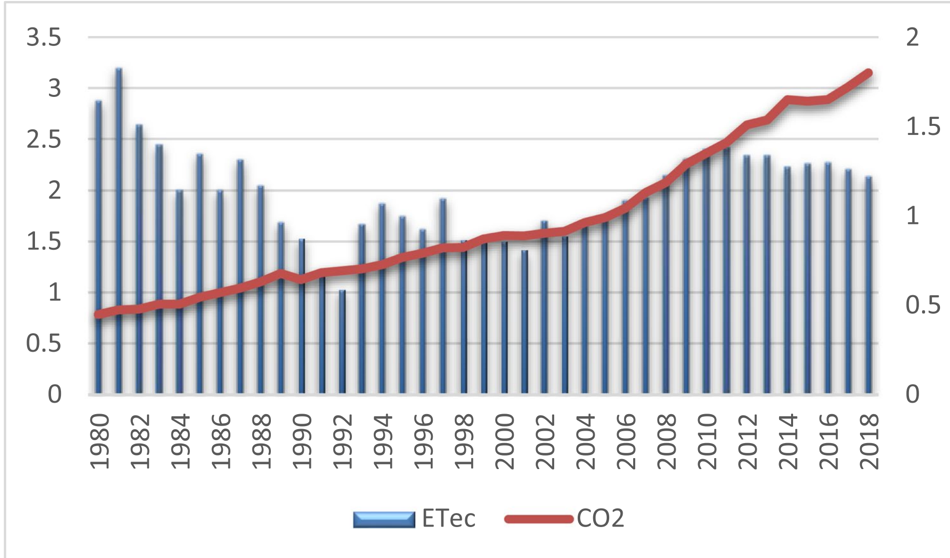

Fig. 2 The trend of carbon emissions (CO_2) and environmental-control technology (ETec)

and urbanization processes on environmental quality in the country. All these efforts are conscientiously geared toward providing a formidable environmentally friendly blueprint for India. Additionally, to ensure the attainment of relevant SDGs and other environmental treaties, the country sworn to uphold. Moreover, the expected robust inferences could also be extended to other emerging economies with similar economic outlooks.

In specific terms, the current empirical evaluation is an updated/novel contribution to and extension of the trajectories of existing studies given the unique steps that have been taken in the study. Such steps include its reliance on updated rigorous datasets sourced from reliable data repositories. The study also considered the effects of GDP and GDP squared (GDP^2) on environmental quality, which most studies related to India may not have considered. The enlistment of critical variables such as environmental-control-related technological innovativeness, trade openness, energy consumption, and urbanization processes into the EKC framework for India further separates this sturdy from others given that, to the best of our knowledge, most previous empirical evaluations, particularly for India, failed to consider. Another significant contribution of the present empirical inquiry is the adoption of a very recent and enhanced econometric technique—the multiple threshold nonlinear ARDL (MTNARDL) technique akin to Pal and Mitra (2015, 2016). This enhanced econometric algorithm that has remained attractive to several studies, including Chang (2020), Hashmi et al. (2020), Uche and Effiom (2021), and Uche et al. (2022), provides empirical narratives over a range of times against the zero-threshold effects of most existing econometric algorithms. Specifically, the MTNARDL technique identifies the reactions of an explained variable to both major, minor, and moderate changes in the explanatory variable(s). Thus, according to Verheyen (2013), these thresholds highlight when it is relevant to take action or when not to (moments of action or inaction). Thus, such specific time-varying outcomes make the act of policy making less hectic and more realistic. Therefore, within the context of the present investigation, streamlined policy guidelines to curtail environmental decay and ensure green growth in India and perhaps for other developing economies will emerge. Unarguably, the above steps mark a significant contribution and extension of the literature related to the EKC, particularly in the context of India's economy and elsewhere.

Following the introductory viewpoints is the next section, where we describe the relevant datasets, estimation techniques and model specifications. The third section presents a detailed analysis of the data and subsequent discussions. The study is summarized with critical policy prescriptions in the fourth section.

Data, estimation techniques, model specification

Data

It is imperative at this stage to highlight the properties and characteristics of the relevant datasets upon which the current study and the consequential inferences emanate. Accordingly, the study relies on annual frequency datasets spanning the 1980–2018 period. It is imperative to highlight that due to data availability constraints, the identified period of study could not be extended. Meanwhile, the datasets were extracted from very reliable public data repositories such that the inferences thereof are reproducible.

Accordingly, we have provided more technical details of the relevant datasets in Table 1.

Model specification

Based on the stated objectives of this study and insights from related previous investigations (Eregha et al. 2021; Gyamfi et al. 2021; Jóźwik et al. 2021; Udemba et al. 2021), we present herein the empirical model to explain the EKC hypothesis for India when embellished with environmental control-related technological innovativeness.

$$CO_{2t} = f(GDP_t,\ GDP^2,\ ETec_t,\ HCD_t,\ Eng_t,\ Urbn_t,\ Topn_t) \quad (1)$$

where CO_2, GDP, GDPsq/GDP^2, ETec, HCD, Eng, Urbn, and Topn denote carbon dioxide emissions, economic growth, the squared value of economic growth, environmental control-related technological innovativeness, human capital development, energy consumption, the urbanization process, and trade openness, respectively, in India over time t, while f is a functional notation. Meanwhile, GDPsq and GDP^2 are used interchangeably in this study to denote the square root of GDP. Equation (1) is further decomposed into an econometric specification with the addition of the stochastic error term and the logarithmic notation (ln) displayed in Eq. (2).

$$\ln CO_{2t} = b_0 + b_1 \ln GDP_t + b_2 \ln GDP^2{}_t + b_3 \ln ETec_t + b_4 \ln HCD_t + b_5 \ln Eng_t + b_6 Urbn_t + b_7 Topn_t + \varepsilon_t \quad (2)$$

It is imperative to highlight that all the series have been defined earlier, and such definitions are retained in Eq. (2) and subsequent equations. Accordingly, $\ln CO_2$ (environmental quality indicator) is the dependent variable, lnGDP is the principal regressor used to explore the possible validation of the EKC hypothesis, and lnETec is the moderating variable used to critique its influence on environmental quality in India based on insights from Khan et al. (2020), Jin et al. (2021), and Umar et al. (2020). The other control variables, including energy consumption (lnENG), human capital development (lnHCD), urbanization process (lnUrbn), and trade openness (lnTopn), have been enlisted given their peculiar influences on environmental quality. Meanwhile, several extant investigations, including Jiang et al. (2022), Obiakor et al. (2022), Opuala et al. (2022), Salari et al. (2021), and Uche and Effiom (2021), have also explored the potential influence of these enlisted control variables and described them as viable stimuli of environmental quality in several countries and over time.

Estimation techniques

As earlier revealed, the current study adopts a recent and enhanced econometric technique for its analysis. Accordingly, the multiple threshold nonlinear autoregressive distributed lag (MTNARDL) model proposed by Pal and Mitra (2015, 2016) was relied upon for empirical narratives. Undoubtedly, the MTNARDL is an extended version of the conventional linear ARDL and the zero threshold nonlinear ARDL techniques of Pesaran and Shin (1999) and Shin et al. (2014), respectively. Thus, the model adopts all relevant procedures and prerequisites of the conventional ARDL model. Meanwhile, the MTNARDL, which has been applied extensively in several studies (Chang 2020; Hashmi et al. 2020; Uche and Effiom 2021; Uche et al. 2022), has several advantages over other models. Such advantages include the ability to account for varying (major, minor, and moderate) effects of the explanatory variables on the explained variable. The model also unveils the possible hidden cointegration that zero-threshold models, such as the NARDL, cannot reveal. According to Verheyen (2013), there are moments of action and inaction at which the influence of the regressor on the regressand could be substantial or otherwise. MTNARDL is also very sensitive and robust to response outliers. Therefore, the ability to capture such unique varying effects and remain very robust to outliers separates the MTNARDL technique from other econometric techniques. However, it is worth mentioning that the model does not consider series that are integrated of order-two. Suffice it to highlight that the analysis of the MTNARDL model is preceded by several tests including the descriptive statistic, correlation analysis, stationarity tests, and test of cointegration. Meanwhile, the outcomes of the model are

Table 1 Data description

Series	Notation	Unit of measurement	Source
Greenhouse emission	CO_2	CO_2 emission per capita	WDI
Economic growth	GDP	GDP per-capita (Constant 2010 US$)	WDI
Environmental technology	ETec	Patent on environmental control technology	OECD
Human capital	HCD	Human development index	PENN World table
Urbanization	Urbn	Urban population (% of total population)	WDI
Trade openness	Topn	Trade % of GDP	WDI
Energy consumption	Eng	Per-capita energy consumption (KWH)	WDI
GDP square	GDPsq/GDP^2	The squared value of GDP	Authors' computation

WDI and OECD connote the World Development Indicators and Organization for Economic Co-operation and Development, respectively subjected to rigorous post-estimation diagnostic evaluations to ensure its overall reliability. Thus, we present the typical MTNARDL framework vis-a-vis the enlisted variables within the tercile threshold accordingly. Accordingly, the economic growth variable (GDP^2) is decomposed into three (3) tercile partial series following Pal and Mitra (2019).

$$CO_{2t}^{i} = GDPsq_0^i + GDPsq_t^i(\varphi_1) + GDPsq_t^i(\varphi_2) + GDPsq_t^i(\varphi_3) \quad (3)$$

In Eq. (3) above, $GDPsq_t^i(\varphi_1)$, $GDPsq_t^i(\varphi_2)$, and $GDPsq_t^i(\varphi_3)$ signify the partial sum series at the 30th and 70th quintiles of national income changes as thresholds represented by τ_{30} and τ_{70}, respectively. Furthermore, the thresholds are calculated with the formulas given below:

$$GDPsq_t^i(\varphi_1) = \sum_{j=1}^{t} \Delta GDPsq_t^i(\varphi_1) = \sum_{j=1}^{t} \Delta GDPsq_j^i I\{\Delta GDP_{sqj}^i \le T_{30}\}, \quad (4a)$$

$$GDPsq_t^i(\varphi_2) = \sum_{j=1}^{t} \Delta GDPsq_t^i(\varphi_2) = \sum_{j=1}^{t} \Delta GDPsq_j^i I\{T_{30} < \Delta GDPsq_j^i \le T_{70}\}, \quad (4b)$$

$$GDPsq_t^i(\varphi_3) = \sum_{j=1}^{t} \Delta GDPsq_t^i(\varphi_3) = \sum_{j=1}^{t} \Delta GDPsq_j^i I\{\Delta GDPsq_j^i > T_{70}\}, \quad (4c)$$

where $I\{T\}$ is an indicator function that assumes the value of 1 if the stipulated conditions, within the bracket { } in Eqs. (4a)– 4c), are achieved, and 0 otherwise. The MTNARDL tercile series decomposition is provided in Eq. (5) below:

$$\begin{aligned} \Delta \ln CO_{2t} &= \beta_0 + \beta_1 \ln CO_{2t-1} + \beta_2 \ln ETec_{t-1} + \beta_3 \ln HCD_{t-1} + \\ &+\beta_4 \ln Eng_{t-1} + \beta_5 \ln Urbn_{t-1} + \beta_6 \ln Topn_{t-1} + \sum_{j=1}^{3} \beta_7 \ln GDPsq_{t-1}^{i}(\varphi_1) \\ &+ \sum_{i=1}^{n1} \Delta \ln CO_{2t-j} + \sum_{i=1}^{n2} \theta_2 \Delta \ln ETec_{t-j} + \sum_{i=1}^{n3} \theta_3 \Delta \ln HCD_{t-j} \\ &+ \sum_{i=1}^{n4} \theta_4 \Delta \ln Eng_{t-j} + \sum_{i=1}^{n5} \theta_5 \Delta \ln Urbn_{t-j} + \sum_{i=1}^{n6} \theta_6 \Delta \ln Topn_{t-j} + \\ &+ \sum_{j=1}^{3} \sum_{i=0}^{n7} \theta_7 \ln GDPsq_{t-j}^{i}(\varphi_1) + \varepsilon_t \end{aligned} \quad (5)$$

where $k = j + 2$.

The cointegration relationship of the long-run variable in Eq. (5) can be estimated through the underlying null hypothesis: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = \beta_7 = 0$. The bounds tests can be calculated through the critical values provided by Pesaran and Shin (1999) and applied by Verheyen (2013), Pal and Mitra (2019), and Hashmi et al. (2020). The null hypotheses of no short- and long-run asymmetries are estimated following the procedures stated herein: H_O: $\theta_3 = \theta_4 = \theta_5 = \theta_6 = \theta_7 = 0$ and H_O: $\beta_3 = \beta_4 = \beta_5 = \beta_6 = \beta_7 = 0$.

Data analysis and discussions

The empirical outcomes of this study emanate from several rigorous analyses, including very relevant pre- and post-estimation diagnostic investigations. Principally among them are the descriptive and correlation tests provided in Table 2, the unit-root tests based on the traditional augmented Dickey-Fuller (ADF), and the nonlinear versions based on Perron and Lee-Strazicich procedures that have been illustrated in Table 3. Further evaluations include the long-run convergence tests based on Pesaran et al. (2001) bounds test and Bayer and Hanck (2013) cointegration procedures. Accordingly, the outcomes of the bounds and Bayer-Hanck cointegration tests are illustrated in Table 4. Following the outcomes of the MTNARDL (Table 5) are the critical post estimation tests, including serial correlation test (Bresuch-Godfrey), heteroscedasticity test (Breusch-Pegan-Godfrey), specification error test (Ramsey-RESET), and the stability test based on the Cumulative Sum and Cumulative Sum of Square (CUSUM and CUSUMSQ) charts. Accordingly, the relevant post-estimation diagnoses are summarized under the lower panel of Table 5, whereas the stability graphs (CUSUM and CUSUMSQ) are represented in Figs. 3 and 4, respectively.

The summarized outcomes of the descriptive statistics and correlation matrix (Table 2) provide the following piece of empirical evidence. Accordingly, the standard deviations of all the variables lie between the maximum and minimum values, suggesting that, to a large extent, the series converged to the mean. Furthermore, the series of national income (lnGDPSq) is more dispersed than other series, followed by trade openness (lnTopn) and environmental control technology (lnETec). In terms of the various moments, all the series have positive tails, are mesokurtic, and are normally distributed. The correlation matrix shows that all the series, except environmental control technology (lnETec), provide a substantial positive influence on environmental pollution in India within the period under investigation. This outcome largely signals the likely environmental quality-enhancing attributes of environmental control-related technologies. Notably, there are notable cases of multicollinearity among some of the explanatory variables; however, the study, following Naili and Lahrichi (2022), adopts the variance inflation factor (VIF) to crosscheck the severity of multicollinearity. On the basis of the outcomes of the VIF test (Table 6 in Appendix A), the variable human capital development (*HCD*) was subsequently dropped from the model because of its high degree of correlation (6.859), which crosses the permissible range of approximately 3 (Everitt and Skrondal 2010).

Table 3 provides a concise summary of the outcomes of unit-root tests conducted based on several unit-root procedures highlighted earlier. The outcomes of all the procedures provide overwhelming evidence that all the enlisted datasets are first-difference stationary variables. That is, the enlisted series only became stationary after they were differenced once—integrated at order-one [$I(1)$]. Accordingly, none of the series failed stationarity tests beyond order-one, which is

Table 2 Descriptive statistics and correlation matrix

Coefficients	*lnCO$_2$*	*lnGDPSq*	*lnETec*	*lnHCD*	*lnEng*	*lnUrbn*	*lnTopn*
PANEL A							
Mean	0.959	45.594	1.993	0.495	8.132	3.324	3.264
Maximum	1.799	58.442	3.196	0.647	8.830	3.527	4.021
Minimum	0.449	36.567	1.029	0.362	7.455	3.139	2.503
Std. dev	0.402	6.559	0.451	0.086	0.405	0.112	0.516
Skewness	0.680	0.394	0.263	0.214	0.028	0.159	0.026
Kurtorsis	2.224	1.943	3.097	1.818	1.919	1.904	1.519
Jarque–Bera	3.990	2.825	0.467	2.564	1.901	2.117	3.566
PANEL B							
	lnCO$_2$	*lnGDPSq*	*lnETec*	*lnHCD*	*lnEng*	*lnUrbn*	*lnTopn*
lnCO$_2$	1.000						
lnGDPSq	0.988***	1.000					
lnETec	0.145	0.081	1.000				
lnHCD	0.980***	0.997***	0.035	1.000			
lnEng	0.970***	0.987***	-0.032	0.994***	1.000		
lnUrbn	0.977***	0.995***	0.003	0.999***	0.996***	1.000	
lnTopn	0.883***	0.923***	0.059	0.938***	0.933***	0.932***	1.000

*** denotes a statistically significant correlation at the 1% significance level

Table 3 Stationarity tests

Variables	ADF		Perron				Lee-Strazicich			
	Level	Δ ADF	Level	Break year	Δ Perron	Break year	Level	Break year	Δ L-S	Break year
lnCO$_2$	3.109	−4.858[a]	−2.574	2008	−7.571[a]	2006	−1.250	2013	−4.462[a]	2005
lnGDPSq	4.688	−4.057[a]	−1.885	1990	−6.650[a]	1991	−1.260	1989	−6.203[a]	1999
lnETec	−2.366	−7.087[a]	−2.615	2002	−6.846[a]	2002	−1.892	1983	−3.343[c]	2000
lnHCD	2.343	−4.540[a]	−3.294	1998	−7.190[a]	2003	−1.468	2003	−4.735[a]	1983
lnEng	0.113	−6.665[a]	−3.450	1988	−9.282[a]	1993	−2.373	2000	−5.344[a]	1983
lnUrbn	3.801	−1.958	−3.364	2012	−6.072[a]	2008	−1.556	2007	−3.959[b]	2005
lnTopn	−0.511	−4.946[a]	−1.241	1991	−7.012[a]	2001	−3.367[c]	2002	-	-

a, b, and c signify the rejection of the null hypothesis of the unit-root problem at the 1%, 5%, and 10% levels of significance, respectively.Δ is the difference operator indicating the first difference effects of each variable

Table 4 PSS bounds and Bayer-Hanck cointegration results

PSS bounds test		
Coefficient	Value	*p* value
F-statistics	57.183***	0.000
Chi-square	514.648***	0.000
Bayer-Hanck cointegration test		
Model	EG-JOH	EG-JOH-BO-BDM
$LNCO_{2T}=B_0+B_1LNGDPSQ_T+B_2LNETEC_T+B_3LNHCD_T+B_4LNENG_T+B_5URBN_T+B_6TOPN_T$	21.769***	27.481**
1% Bayer-Hanck critical value	15.348	29.544
5% Bayer-Hanck critical value	10.352	19.761
10% Bayer-Hanck critical value	8.2	15.746

*** and ** signify the rejection of the null hypothesis of no long-run equilibrium at the 1% and 5% levels of significance, respectively. EG-JOH is the combination of the Engel and Granger and Johansen cointegration procedures, while EG-JOH-BO-BDM is the combination of the Engel and Granger, Johansen, Boswijk, and Banerjee-Dolado-Mestre cointegration procedures

Table 5 MTNARDL (tercile-partial series) estimates

Series	Coefficients	t-stat		*p* value
Long run effects				
lnGDP	0.230**	2.609		0.040
$lnGDPSq_{(W1)}$	− 0.001*	− 1.872		0.078
$lnGDPSq_{(W2)}$	− 0.003***	− 3.012		0.007
$lnGDPSq_{(W3)}$	− 0.001*	− 2.045		0.056
lnETec	0.020	0.555		0.586
LnEng	0.508**	3.919		0.030
lnTopn	0.004	0.095		0.925
LnUrbn	5.624*	1.838		0.083
Constant	19.813**	2.707		0.014
Short run effects				
Δ*ln GDP*	− 0.348	− 1.117		0.279
Δ *lnGDP(-1)*	− 0.209	− 0.704		0.490
Δ$ln\ GDPSq_{(W1)}$	− 0.001	− 0.722		0.479
Δ $lnGDPSq_{(W3}$*-1)*	− 0.002**	− 2.421		0.027
Δ *lnETec(-1)*	− 0.029	− 1.091		0.290
Δ *lnEng*	0.936**	2.206		0.041
Δ *lnTopn*	0.059	0.920		0.370
Δ *lnUrbn*	− 8.621	− 1.062		0.302
ECT	− 0.62***	− 12.318		0.000
Post-estimation/diagnostic tests				
Breusch-Godfrey serial Correlation LM test	1.781{0.169}	Breusch–Pagan-Godfrey Heteroskedasticity Test		1.347{0.271}
Ramsey RESET test	0.868(0.398)	Adjusted R-Square		0.60
Wald long-run asymmetric test	3.128*	Wald short-run asymmetric test		2.209

***, **, and * imply the rejection of the null hypothesis of no significant relationship at the 1%, 5%, and 10% levels of significance, respectively. Values in { } are probability values of relevant post-estimation criteria, while Δ is the difference operator indicating short-run implications of various explanatory variables. ECT denotes the error correction term showing the speed of adjustment to equilibrium

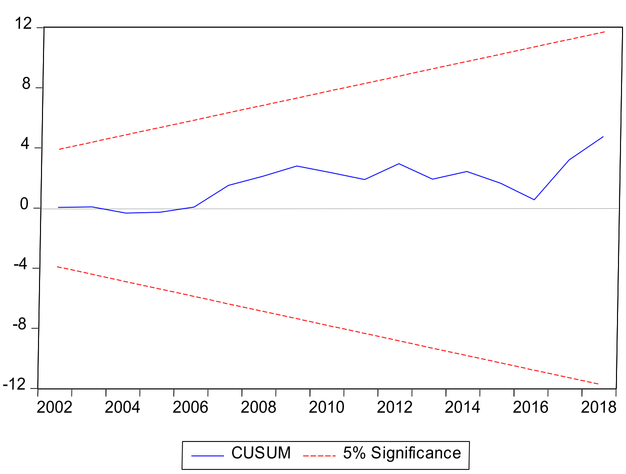

Fig. 3 CUSUM graph

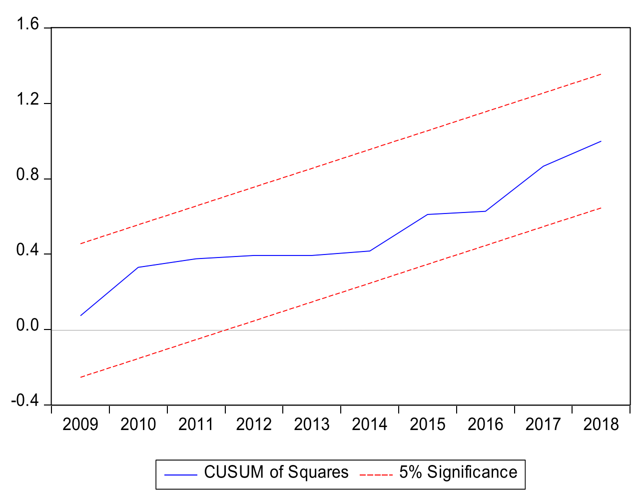

Fig. 4 CUSUM of squares graph

a critical prerequisite for the application of the ARDL technique or its extended versions, including the MTNARDL technique. Meanwhile, it is pertinent to highlight that the series of urbanization processes (lnUrbn) had an inconsistent integration order. From the linear ADF, the series failed the stationarity test even after the first difference, but from the nonlinear and more enhanced procedures (Perron and Lee-Strazicich), it became stationary after the first difference and at levels. Furthermore, the nonlinear stationarity tests that consider the effects of breaks denote the need to apply a nonlinear (time-varying) technique such as the MTNARDL that could circumvent the challenges imposed by the structural breaks and ultimately provide more dependable estimates that will ensure the attainment of the relevant SDGs. It is also imperative to highlight that the enlisted variables were affected by shocks across different years, including 1983, 1999, 2000, 2002, 2005, and 2012. Given the above, the outcome of the nonlinear unit-root procedures (Perron and Lee-Strazicich) provides the background to retain the series of urbanization processes within the framework of this study. Having achieved stationarity, the study proceeds to test the eventual long-run convergence of the enlisted series. The outcomes of the cointegration tests are projected in Table 4.

Based on insights from previous studies (Nwani et al. 2021; Omoke and Uche 2021; Uche et al. 2022), we conducted the test for the long-run convergence among the enlisted series within two robust cointegration procedures—the Pesaran et al. (2001) bounds test cointegration and the Bayer and Hanck (2013) specifications. The summarized outputs (Table 4) identify that all the series enlisted within the model converged to equilibrium in the long run. The outcomes are consistent both within the bounds tests based on Wald test evaluations and the recently introduced Bayer-Hanck procedure. Given the outcomes of the cointegration tests and the rectifications of all the relevant prerequisites of the MTNARDL technique, the study, therefore, proceeds with the next step and evaluates the eventual shape of the EKC in India amid environmental-control-related technological innovativeness and other enlisted environmental quality determinants. The estimate of the MTNARDL (tercile-series) specification is illustrated in Table 5.

Based on the background laid beforehand, the empirical analysis of this study is based on a tercile partial series of the MTNARDL econometric algorithm. Notably, both the traditional ARDL and NARDL techniques were also considered, but for brevity, we reported only the MTNARDL, which provides the most reliable estimates among the other models considered. The outcomes of the various models excluded from this report, mainly due to brevity, are available in the supplementary pages.

Accordingly, the MTNARDL estimate reveals interesting outcomes, which, with due diligence, the carbon neutrality commitment and the achievements of relevant SDGs in India become realizable; hence, economic growth (GDP) exerts significant long-term positive impacts on CO_2 emissions, while GDP^2 at various partial deviations, upper (GDP^2_{W1}), middle (GDP^2_{W2}), and lower (GDP^2_{W3}), exert significant long-term negative impacts on carbon emissions. Specifically, among the various outcomes, the MTNARDL results clearly indicate that the EKC hypothesis is substantiated for the Indian economy. From the estimates, it is shown that at the middle thresholds of economic growth (GDP^2_{W2}), economic growth possesses more environmental quality enhancing effects (0.03%) than the 1% effects recorded at both the upper (GDP^2_{W1}) and lower (GDP^2_{W3}) thresholds. Specifically, at the middle threshold (GDP^2_{W2}), a 1% change in GDP^2 results in an approximately 3% significant decline in the levels of environmental degradation in India during the long run. However, at both the upper and lower thresholds, a 1% change in GDP^2 leads to an approximately 0.01% reduction in carbon emissions. Based on these outcomes and in alignment with some prior studies (Chishti and Sinha 2022; Danish and Ulucak 2022: Eregha et al. 2021), it is obvious that the EKC hypothesis is validated in India; hence, there was a significant turn of events leading to substantial declines in pollution. On this note, it is imperative to highlight that the middle threshold (GDP^2w_2) is the most critical threshold that ensures a cleaner environment such that India stands to reap the benefits of sustainable prosperities. The short-term impacts of economic growth on environmental quality are largely inconsistent, as they vary between significant positive and negative outcomes within some time lags.

On the effects of environmental-control technology (lnETec) on India's ecosystem, our investigation rectifies that against its expected effects, the variable was only able to mitigate environmental pollution insignificantly in the short run. Surprisingly, it accelerates environmental decay insignificantly in the long run. This suggests momentary improvements in environmental quality occasioned by innovations in environmental-control technology. However, it is worrisome that such effects were not sustained over a long time, but rather, the lack of commitment to improving such technologies resulted in significant long-term environmental decay. Suggestively, policies should be geared toward ensuring an all-time improvement in environmental-control technologies such that the economy will reap its expected benefits (cleaner environment) even in the long run. Among other enlisted control variables, trade openness (lntopn) exerts insignificant long-term positive effects, while energy consumption (lnEng) and urbanization (lnUrbn) also exert significant positive effects on environmental quality. These outcomes, consistent with the studies of (Danish and Ulucak 2022; Eregha et al. 2021), suggest that these variables, especially nonrenewable energy consumption and urbanization processes, are highly unfriendly to the environment. Similarly, the short-term influences of the enlisted control variables on India's ecosystem were largely inconsistent. Given the above, policies should be committed to ensuring that all the enlisted control variables are responsive to cleaner ecosystems at all times. The adoption and implementation of more environmentally friendly approaches, such as renewable energy, could provide a more conducive environment in India. As such, the country stands on the part of attaining all the specified SDGs 11, 12, and 13 accordingly.

Another notable outcome of this investigation is the revelation of a long-term asymmetric relationship between changes in economic growth (GDP^2) and environmental quality in India. As remarked within the lower panel (post-estimation/diagnostic tests) in Table 5, the evidence indicates significant long-run (*Wald long-run asymmetric test*) asymmetric effects between economic growth and environmental quality. Suggestively, such effects require varied policy strategies at all times to ensure a cleaner environment given that a one-policy-fits-all strategy may be counterproductive to attaining the expected SDGs. Overall, the outcomes of the present study are robust and plausible for reliable policy prescriptions given that all the post-estimation diagnostic evaluation criteria conform to expected signs. Specifically, the results are free from serial correlation, heteroscedasticity, misspecifications, and instability. The relevant evaluation yardsticks have been provided within the lower part of Table 5. Meanwhile, the CUSUM and CUSUM of squares graphs (Figs. 3 and 4) also highlight the stability of the plausibility of the estimates. Likewise, the outcome of the variance inflation factors (VIF) reported in Appendix B (Table 7) denote that the estimates are free from the problems of multicollinearity.

Conclusion and policy prescriptions

This study is a further step toward understanding the workings and veracity of the environmental Kuznets curve (EKC) hypothesis, especially in the case of India. Notably, the EKC suggests varying relationships between economic growth and environmental quality. Given the intrigues about such varying interactions, several empirical enquiries have been committed to critically explaining the actual shape of the EKC both for India and other countries. However, it is imperative to highlight that, given their divergent opinions, previous studies have not confirmed the exact threshold where rising prosperity could ensure a cleaner environment. Moreover, based on an in-depth empirical survey, it is disappointing that a notable emerging economy such as India has been understudied. Beyond the above identified lacunas in extant studies, it is also identified that most existing studies relied on linear econometric algorithms that lack the capacity to critically unravel the particular threshold at which rising prosperity does not hurt environmental health. Furthermore, several extant studies have failed to consider how environmental-control technologies moderate the nexus of economic growth and environmental quality, particularly for India.

To provide updated insights and extend the trajectory of knowledge, this study engaged relevant annual datasets from 1980 to 2018 for empirical narratives. Furthermore, in addition to the enlistments of relevant series, we adopted the MTNARDL econometric technique that vigorously accounts for varying (minor, major, and moderate) effects of the explanatory variable(s) on the explained variable both in the long and short runs. Arising from the estimates, it is ascertained that the enlisted variables coevolve in the long run. Overall, the study validates the EKC hypothesis for India given that GDP significantly promotes environmental pollution in the long run, whereas GDP^2 significantly dampens pollution mostly at the middle threshold and within the long run. This invariably implies that a sustainable environment is achievable when growth reaches and remains at the middle threshold. Suggestively, policymakers are implored to ensure unwavering commitment to maintain growth within the middle threshold that simultaneously ensures rising prosperity and cleaner environments. Meanwhile, it is imperative to always consider the asymmetric effects between GDP^2 and carbon emissions, especially in the long run. Unarguably, a commitment to the subsisting threshold that ensures sustainable development and the conscious consideration of asymmetric dynamics is sacrosanct to achieve ecological balance in India.

In terms of the impact of environmental-control technology on environmental quality in India, it was ascertained that such innovations only warranted short-term insignificant ameliorative effects and insignificant unpleasant long-term effects on the environment. This outcome indicates that environmental-control technology in India is at best, at its lowest ebb. Therefore, to reap the full benefits of such technology and vigorously push the carbon neutrality agenda, every effort must be committed to ensuring that such technology is fully developed and adequately deployed in such a way that the entire ecosystem could become healthier. Additionally, energy consumption and urbanization processes wreaked havoc on environmental quality in India mostly in the long run, with notable inconsistencies in the short run. Given the above scenarios, it is more profitable to clean energy sources rather than crude energies. In the same vein, efforts should be extended to balance urbanization processes given their negative consequences on environmental health. Similarly, policies to promote environmentally friendly patterns are required to invoke cleaner environments in India given the insignificant positive influence of trade on the ecosystem. Expectedly, other emerging and developing economies could find the inferences therein amenable to their ecosystems. However, country-specific characteristics must be taken into account. Therefore, such dimensions could be explored in future studies to ensure a cleaner/healthier environment for all humankind. Moreover, it is also imperative to explore the noble advantages of the robust estimation technique (MTNARDL) and its extension, the multiple asymmetric threshold nonlinear ARDL (MATNARDL), in future evaluations.

Appendix A

Table 6 Variance inflation factor (VIF) result

Variable	VIF
LNGDP	0.862
$LNGDP^2$	0.003
LNTEC	0.000
LNENG	0.030
LNTPN	0.002
LNHDI	6.859
LNUB	3.301

Source: Authors' computation

Appendix B

Table 7 Variance inflation factor (VIF) result

Variable	VIF
LNGDP	0.640
$LNGDP^2$	0.002
LNTEC	0.000
LNENG	0.033
LNTPN	0.001
LNUB	1.434

Source: Authors' computation

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Author contribution EU and ND conceptualized the idea. DN provided the initial draft. EU conducted the analysis and provided some editing. PB provided the literature section and proofread the manuscript.

Data availability The data can be made available on reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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