ENVIRONMENTAL RESEARCH
COMMUNICATIONS

INCLUSIVE PUBLISHING TRUSTED SCIENCE

Part of the ENVIRONMENTAL RESEARCH SERIES

PURPOSE-LED PUBLISHING™

PAPER • OPEN ACCESS

The capital approach to sustainability and EKC hypothesis: evidence from India

To cite this article: Priti Agarwal and Aparna Sawhney 2026 *Environ. Res. Commun.* **8** 025001

View the article online for updates and enhancements.

You may also like

- From pollution to sustainable environment: unlocking the role of energy intensity and renewable energy in highly pollutant nations
Zhi Zhen Zhou, Muhammad Shahid Hassan, Muhammad Ibrahim Saeed et al.

- Analyzing Türkiye's ecological footprint: the impact of air transportation, renewable energy, and R&D using a non-linear ARDL approach
Gökhan Konat, Veli Yilanci, Havanur Ergün Tatar et al.

- Unraveling the environmental consequences of trade openness in South Africa: a novel approach using ARDL modeling
Wang Lanhui and Abubakar Sadiq Ibrahim

This content was downloaded from IP address 103.59.198.83 on 03/02/2026 at 11:21

IOP Publishing Environ. Res. Commun. 8 (2026) 025001 https://doi.org/10.1088/2515-7620/ae3a4a

Environmental Research Communications

Check for updates

OPEN ACCESS

RECEIVED
1 June 2025

REVISED
20 December 2025

ACCEPTED FOR PUBLICATION
19 January 2026

PUBLISHED
2 February 2026

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

PAPER

The capital approach to sustainability and EKC hypothesis: evidence from India

Priti Agarwal[1,*] and Aparna Sawhney[2]

[1] Jindal School of Government and Public Policy, OP Jindal Global University, Sonipat, Haryana, India
[2] Centre for International Trade and Development, School of International Studies, Jawaharlal Nehru University, New Delhi 110067, India
[*] Author to whom any correspondence should be addressed.

E-mail: priti.agarwal@jgu.edu and aparnasawhney@yahoo.com

Keywords: India, comprehensive wealth, EKC, natural capital, environmental and resource economics, sustainability, produced capital

Abstract

The empirical evidence on the EKC hypothesis has been rather mixed, and the widely-used GDP per capita is deemed an inadequate indicator of well-being. Invoking the capital theory approach to sustainable development, namely of non-declining capital stock or wealth, we test the EKC hypothesis for carbon emissions in India for the period 1972 to 2013 through the change in comprehensive wealth (i.e. comprehensive investment) and its components of anthropogenic capital and natural capital. Employing the ARDL cointegration technique, we find N-shaped EKCs with comprehensive investment, and produced capital investment, indicating rising carbon emissions in India's current growth path. Only the increase in renewable energy resources has helped reduce carbon emissions, while the changing economic structure and foreign direct investment have had adverse environmental impact. The systematic disinvestment in natural capital through the decades reflects declining carbon sequestration capacity, and points to the need for concerted efforts to preserve natural capital like forests for essential sequestration services.

1. Introduction

The environment functions both as a source of resources and a sink of wastes, and it maintains the critical ecosystem resources during the process of economic growth which is vital to ensure sustainability. When market prices fail to reflect the true social cost of environmental resources, it leads to severe over-exploitation of resources, as often observed in the developing countries. In this context, the Environmental Kuznets Curve (EKC) hypothesis provided an optimistic long-run solution, suggesting that environmental degradation is not permanent since pollution would eventually taper off. The EKC hypothesis postulated that, along the growth path, the environmental quality would initially deteriorate, but after reaching a peak level of deterioration, it would improve with further growth in economic well-being. In the initial phase of growth, as industrial output increases so would pollution since the scale and structural effects would dominate; while in the later phase, with a shift from industry towards services (driven by knowledge and human capital) pollution would plateau, and increased income would lead to greater demand for better environmental quality. Consequently, beyond a threshold level of well-being the technique effect (adoption of cleaner technologies due to higher demand for environmental quality) would dominate, and pollution would decline as the economy progresses. Conventionally, per capita income or gross domestic product (GDP) was taken to represent well-being in EKC, but GDP per capita is recognized to be a poor indicator of development. A true indicator of economic development should reflect the growth in wealth or stock of productive capital assets of an economy, not just growth in GDP per capita or increase in other ad hoc indicators of human development (Dasgupta 2007). The focus on the trade-off between pollution and economic well-being in the EKC tends to ignore the system-wide consequences of that pollution (Arrow *et al* 1995). After the initial phase of growth that results in environmental degradation, the economy can improve environmental quality as per the EKC only if its ecological system

© 2026 The Author(s). Published by IOP Publishing Ltd

remains resilient. Such resilience requires maintaining threshold level of the critical capacity of the ecosystem in the form of various natural assets like forests, soil, watersheds, wetlands, etc, for their interlinked ecological services. In this regard, *comprehensive wealth* of a country provides a more holistic and consistent measure of well-being, as it reflects the aggregate value of anthropogenic and natural assets available for economic activity (Hamilton 1994, Hamilton and Clemens 1999), and provides a better measure of sustainable development. Comprehensive investment or genuine savings capture the change in the comprehensive wealth,[3] that is adjusted for resource depletion and environmental degradation during economic growth.

In a cross-country EKC analysis, (Neve and Hamaide 2017) compared the growth-environment relationship using per capita genuine savings or comprehensive investment, and observed an inverted U-shaped EKC with GDP per capita but a N-shaped EKC when genuine savings per capita is used as indicator of development. They also showed that the results are sensitive to the countries included in the sample, in particular, inclusion of wealthy countries like Singapore and Hong Kong that significantly alter results towards an inverted U-shaped relationship as these countries have succeeded in cutting back carbon emissions at higher income levels. This implies that the growth-environment relationship could be very different for individual countries, and would also depend on the indicator of development taken in the analysis. Our study adds to the literature that GDP is not an appropriate indicator of development, and shows that high GDP growth in the case of India camouflaged the decline in critical natural capital that is revealed using the sustainability indictor of *comprehensive investment*. Our study intends to nudge policy focus away from 'GDP growth' to 'sustainable development', encouraging the use of more indicators of well-being like comprehensive investment. Ours is the first study in the Indian context which relates the EKC hypothesis to the capital approach for sustainability. We first estimate the comprehensive wealth of India, and then use comprehensive investment and its components (produced capital, human capital and natural capital), as indicator of sustainable development *vis a vis* the carbon dioxide (CO_2) emission. By taking natural capital investment, the direct linkage to carbon emissions is highlighted with forests serving as carbon sink and subsoil resources being the source of carbon-based fuels. The analysis covers four decades (1972–2013), including the period when India witnessed high growth following a series of market reform policies and liberalization initiated in 1991. The period also witnessed the establishment of domestic environmental legislation and regulatory institutions,[4] and India's ratification of the multilateral agreements of United Nations Framework Convention on Climate Change in 1993. To the best of our knowledge, no study for India has analysed the dynamics of growth and environment based on a holistic measure of well-being like comprehensive investment or genuine savings. In particular, we incorporate remote sensing data on forest cover from (Reddy *et al* 2016) within the measure of natural capital (apart from agricultural land, fuels, and minerals) that better captures ecosystem services capacity like carbon sequestration.

Moreover, given the major regime changes through the nineties, we also check for the presence of endogenous structural breaks in our data series and analyse the impact of structural breakpoints on the EKC relationship. We find N-shaped EKCs with comprehensive investment, and produced capital investment, indicating increasing carbon emissions in India's current growth path. Only the use of alternative energy forms is found to have helped reduce carbon emissions. We observe that as per a-priori expectations, natural capital has a monotonic decreasing impact on emissions. These results hold significance in the context of other dynamic studies on EKC which use GDP per capita as a measure of welfare since GDP does not account for the underlying natural capital depletion (on the contrary, GDP increases when there is greater depletion of minerals or cutting of forests for timber). Our analysis brings to the fore, the critical role played by natural capital in the well-being of an economy. To decouple economic development from environmental degradation, it is important to ensure a balance in the asset composition of comprehensive wealth in India, through investment in natural capital rather than only anthropogenic capital. It would enhance the regenerative and assimilative limits of the ecological system essential for sustainable development. The paper is structured as follows. Section 2 presents the Literature Review followed by section 3 which covers the Methodology and Data for testing the EKC hypothesis. The 'Results and Discussion' are given in section 4 followed by 'Impact of Structural Breaks' in section 5. Section 6 concludes.

2. Literature review

In the growth-environment trade-off debate, the EKC hypothesis provides some comfort as it suggests that long run growth will eventually lead to a better environment. An *inverted U-shaped* EKC relationship between

[3] *Comprehensive investment* and *genuine savings* refer to the same concept: while the World Bank (2006, 2011) uses the term '*genuine savings*' to refer to change in comprehensive wealth or productive base, the UNU-IHDP and UNEP (2012) use the term '*comprehensive investment*'

[4] Beginning with the Water Act in 1974, Air Act in 1981, establishment of the Department of Environment in 1980 (subsequently the Ministry of Environment in 1985), the umbrella legislation of the Environmental Protection Act in 1986, etc.

environmental degradation and income is the result of the simultaneous operation of the scale effect, composition effect and technique effect (Stern 2004). Together, these three effects trace out the bell-shaped curve, which means that after a certain threshold income, environmental quality improves. Looking at the demand side factors, economic agents are mainly concerned about survival and fulfilment of basic needs in the early stages, hence, the quest for growth. It is only when they are sufficiently rich, that economic agents' value clean environment and are willing to pay for it, as reflected in defensive expenditures and shift to environmental-friendly products. High income consumers could also press for institutional reforms and more stringent environmental regulations.

The EKC literature also throws light on several other explanations for the EKC such as role of international trade. While trade increases pollution through scale effect by expanding the size of the economy, it may reduce pollution through the import of cleaner technologies. But developing economies typically specialize in pollution-intensive industries due to lax environmental regulations, in contrast to their developed counterparts who specialize in service-intensive or *clean* production (Stern *et al* 1996). However, considering contradictory evidence on the pollution haven effects, it cannot provide a clear explanation of the EKC (Cole 2004, Stern 2004). Apart from these, the EKC literature also discusses several other factors responsible for the EKC such as diffusion of technology, policy changes, formal and informal regulation, foreign direct investment, etc (see Dinda 2004 for an extensive review).

2.1. The capital approach to sustainability and EKC

The capital approach to sustainability emphasises four main types of assets which form the productive base of the economy, viz., produced capital, human capital, natural capital and institutional capital. Along the path of structural transformation of a country transitioning from an agrarian to industrial and then service-oriented economy, natural capital is relatively abundant in the initial stages and emissions are low. With industrialization, exploitation of natural capital (K_N) is accompanied by accumulation of produced capital (K_M) and increase in emissions. When quantitative or tangible natural capital is utilised, such as burning of fossil fuels or cutting of forests, the qualitative or intangible natural capital such as air quality deteriorates. As the economy further gravitates towards a service driven economy with dominance of knowledge and human capital (K_H), emissions start to decline. This stage is accompanied by development of technological capital and environmental-friendly institutions encouraging shift to sustainable living and use of cleaner energy sources.

Hence, it is the composition of 'comprehensive wealth' that impacts emissions. Accumulation of produced capital increases emissions, while human and natural capital accumulation has a negative impact on emissions. The portfolio of the three forms of capital and technological progress, along with institutional capital and norms to protect the environment, have the potential to cause a downturn in emissions in the long run.

2.2. Empirical studies on EKC

The extensive literature on empirical analyses of EKC have covered different pollutants and observed different pollution-income relationships (e.g., Grossman and Krueger 1991, Shafik and Bandyopadhyay 1992, Jha and Murthy 2003, Cole 2004, Mukherjee and Kathuria 2006, Managi and Jena 2008, Kumar and Managi 2009, Mukherjee and Chakraborty 2009, Sinha and Bhattacharya 2016, Sinha and Sen 2016, Sinha and Shahbaz 2018, Rana and Sharma 2019). Typically, local pollutants like suspended particulate matter, sulphur dioxide, nitrous oxides and carbon monoxide exhibited an inverted-U shaped relationship with income per capita (see Dinda 2004, Kaika and Zervas 2013), while for pollutants that can be disposed in distant areas, like municipal waste, the EKC was monotonically increasing (Shafik and Bandyopadhyay 1992, Dinda 2004).

For carbon emissions too, a diverse set of EKC relationships have been observed in the literature ranging from *inverted U-shaped* curve (Dutt 2009, Fosten *et al* 2012, Kanjilal and Ghosh 2013, Tiwari *et al* 2013, Kasman and Duman 2015, Chakravarty and Mandal 2016, Destek *et al* 2016, Sugiawan and Managi 2016), to *N-shaped* curve (e.g., Friedl and Getzner 2003, Pal and Mitra 2017, Sinha *et al* 2017, Murthy and Gambhir 2018), and *monotonically increasing* EKC (e.g., Shafik and Bandyopadhyay 1992, Shafik 1994, Seetanah and Vinesh 2010, Gill *et al* 2017), or *no relationship* (e.g., Roca *et al* 2001, Ben Nasr *et al* 2015). The different shapes of the EKC curve are attributed to differences in model specification, methodologies, time periods and contexts (Shahbaz and Sinha 2018). Even when considering analyses in the context of single country versus cross-country studies, the EKC results for carbon emissions are inconclusive in both sets of studies (Shahbaz and Sinha 2018).

For India, (Sinha and Shahbaz 2018) estimated an inverted U-shaped EKC for CO_2 emissions with GDP per capita for the period 1971–2015. Similarly, (Ahmad *et al* 2016) also found an inverted U-shaped EKC using ARDL approach for energy use with income per capita for the Indian economy during 1971–2014; and (Özgür *et al* 2022) found an inverted U-shaped curve for carbon emissions with GDP during 1970–2016 using a Fourier ARDL model. (Jayanthakumaran *et al* 2012) and (Kanjilal and Ghosh 2013) too observed an inverted U-shaped EKC using quadratic model specification for India over the period 1971–2008. On the other hand, with a cubic specification, (Murthy and Gambhir 2018) found an N-shaped EKC for CO_2 emissions for the period 1991–2014, as did (Pal and Mitra 2017) for the period 1971–2012.

Based on these findings in the literature, we conclude that empirical evidence on EKC is mixed in cross-country analyses, as well as those pertaining specifically to India mainly due to varying time periods, model specification, econometric techniques and control variables used.

2.3. An alternative to GDP per capita in the EKC analysis

The mixed empirical evidence on the EKC hypothesis and the lack of evidence on an eventual downturn in carbon emissions, contrary to the theoretical underpinnings of the hypothesis, suggests that the de-coupling of environmental degradation from economic growth may not be occurring. If economic production jeopardizes the pollution buffering capacity of the ecosystem, then environmental degradation will invariably result. The exhaustion of K_N would not be problematic if it is easily substitutable by other factors, but if not, then their exhaustion may prove to be catastrophic (Solow 1974). Such a catastrophe is multi-edged as exhausting natural resources would destroy qualitative environment, and at the same time, economic production would be adversely affected until a new technology (called 'backstop technology' in Solow 1974), that frees economic production from resource dependence, takes over.

Few studies have explored the linkages between natural capital, environmental quality and economic growth. (Kurniawan *et al* 2021) proxied environment quality by the 'natural capital component' of inclusive wealth and found that economic growth has a non-linear impact on natural capital. However, they did not study the impact of the loss of natural capital on emissions. One study, by (Neve and Hamaide 2017), used 'genuine savings' instead of GDP in the EKC hypothesis. They considered *genuine savings* or *comprehensive investment*, and its components in per capita terms and examined the EKC hypothesis for a cross-section of countries (including India). (Wang *et al* 2024) also explore the natural capital component by taking 'natural resource rents' as one of the explanatory variables in the EKC hypothesis apart from other variables such as institutional quality, digital economy, energy transition, artificial intelligence among others. Their country database is wide covering 214 countries which includes both emerging and developed economies. In a recent EKC analysis with conventional income measure, (Caporin *et al* 2024) observe that a linear EKC is more coherent with ecological footprint, energy consumption, climate change adaptation and GDP as independent variables. They found that higher energy consumption and higher ecological footprint is associated with increased carbon emissions in the long run. The increasing ecological footprint and energy consumption due to economic production and consumption poses greater pressure on natural resources (air, water, land), and the resultant waste generation and waste assimilation can be interpreted as a decline in natural capital stock. Few studies have exclusively focussed on emerging economies, for example, (Bekun *et al* 2021) apply the EKC hypothesis to E7 economies (viz., emerging economies such as China, India, Mexico, Brazil, Russia, Indonesia and Turkey). They explore the combined impact of renewables and institutional quality on environment and find that weak institutions dampen environmental quality and renewables improve environmental quality.

Income per capita or GDP per capita has long been under the scanner as a poor indicator of welfare or well-being, and its use in EKC studies have also drawn criticism (e.g., Stiglitz *et al* 2009). The GDP per capita may increase in the face of increasing environmental degradation. For example, timber production through deforestation increases GDP, as the loss in forests and accompanying flow of ecosystem services are not accounted for. However, comprehensive investment accounts for depletion of forests, mineral resources, and air pollution damages (Lange *et al* 2018), and better captures the relationship between development and environment (Munasinghe 1999).

3. Methodology and data for testing EKC Hypothesis

3.1. Empirical model

The early EKC hypothesis in (Grossman and Krueger 1995) considered a reduced form approach and modelled environmental pollution as a cubic function of GDP per capita. While several analysts used quadratic specifications, subsequent analyses showed, that after 'delinking' from higher income beyond a threshold, pollution may 're-link' with increasing income such that the inverted-U changes to a N-shaped curve (de Bruyn and Opschoor 1997). To incorporate the re-linking hypothesis of the EKC, we use a cubic polynomial model specification as follows:

$$\ln e_t = \alpha + \beta_1 x_t + \beta_2 {x_t}^2 + \beta_3 {x_t}^3 + \beta_4 z_t + \varepsilon_t \quad (1)$$

Where subscript 't' denotes year, e represents environmental pollution, x is an indicator of well-being (GDP per capita or comprehensive investment per capita), z is a vector of control variables, and ε is the error term.

Our log-linear model better captures the non-linearities, non-convexities and irreversibilities in environmental processes as emphasized in the scientific literature (see Dasgupta, Mäler 2009). The EKC pattern depends on the $\beta's$. If $\beta_1 > 0; \beta_2 = \beta_3 = 0$, then EKC would be an increasing monotone. If $\beta_1 < 0; \beta_2 = \beta_3 = 0$, the EKC would be a decreasing monotone. If $\beta_1 > 0; \beta_2 < 0; \beta_3 = 0$, the EKC would be inverted U-shaped. If $\beta_1 < 0; \beta_2 > 0; \beta_3 = 0$, the EKC would U-shaped. If $\beta_1 > 0; \beta_2 < 0; \beta_3 > 0$, the EKC would N-shaped. If $\beta_1 < 0; \beta_2 > 0; \beta_3 < 0$, the EKC would be inverse N-shaped. If $\beta_1 = \beta_2 = \beta_3 = 0$, there would be no relationship between development and pollution.

In the EKC literature, the environmental stress *e* has been taken in aggregate as well as per capita emissions. Per capita emissions are better suited in the context of cross-country analysis where they serve as a basis of comparison after controlling for country size. In our analysis here, we consider the aggregate measure of carbon emissions as it is a *stock* pollutant and our interest is to track the dynamics of the impact of well-being on emissions of the stock pollutant over four decades in India.

In the literature the variables have been taken in absolute as well as logarithmic forms, using linear, semi-log linear or double-log linear specifications as per the case. (Hasanov *et al* 2021) noted that the estimated coefficients and the significance of the lower power terms in the polynomial are scale-sensitive and unit dependent, i.e. the magnitude and significance of β_1 and β_2 in the cubic form, (and β_1 in the quadratic form), are affected in double logarithmic specification. So, we estimate a semi-log specification of the EKC model in equation (1), with *e* measured as log carbon emissions.

Our model estimation uses five indicators of development: beginning with the benchmark indicator in the EKC literature, namely GDP per capita, followed by comprehensive investment per capita and its components of produced, human and natural capital investment per capita. We control for the economic structure with the share of industry-value added to GDP, and for technique effect through FDI inflows and alternative energy.

We use the ARDL model by (Pesaran *et al* 1996, 2001) for our analysis spanning a period of 42 years as it allows for the optimal lags of variables and analyse the long run relationship between variables. The ARDL approach corrects for potential endogeneity of the regressors since all the variables enter the model with lags (Pesaran and Shin 1999).

3.2. Constructed components of comprehensive wealth and data sources

We construct the comprehensive investment per capita and its components for India following the methodology in the literature (summarized in appendix table A1). Comprehensive wealth 'W' is the sum of produced capital K_M, human capital K_H and natural capital K_N:

$$W(t) = K_{M(t)} + K_{H(t)} + K_{N(t)} \tag{2}$$

$$K_N = Agriland\_Wealth + Subsoil\_Wealth + Forest\_Wealth \tag{3}$$

We compute the real value of each of the above types of capital at constant shadow prices at 2004-05 level. We observe that the share of manufactured capital has increased overtime at the expense of natural capital, the share of which decreased from close to 50% in 1975 to only 11.31% in 2013 (figure A1 in appendix). The change in comprehensive wealth referred to as comprehensive investment is given as:

$$Comprehensive\ Investment = CI = \Delta W(t) \tag{4}$$

Next, we estimate the comprehensive investment per capita ($CI\ pc$), and its components, viz., produced capital investment per capita ($\Delta K_M pc$), human capital investment per capita ($\Delta K_H pc$), and natural capital investment per capita ($\Delta K_N pc$).

It is important to note here that natural forest cover and its associated native biodiversity differs from patchy plantations in terms of ecological significance, and the two cannot be treated as same. The Forest Survey of India (FSI) defines forest cover as 'all lands more than one hectare in area, with a tree canopy density of more than 10%, irrespective of ownership and legal status' in its reports 1987–2013. The FSI data on forest cover includes plantation expansion, monocultures, and small patchy reforestation, - which obscures the information on native forest (Puyravaud *et al* 2010), and the decline in dense forest cover is overshadowed by the increasing plantation area (Lele 2025).

To track native forest cover, we rely on the recent remote sensing native forest cover data published in (Reddy *et al* 2016), which defined forest cover as 'land spanning more than 1 ha, dominated with native tree species, having a minimum stand height of 5 m with an overstorey canopy cover greater than 10%' (pp 96). This data captures natural forests in the country more accurately, but is available only for select time points until 2013 (specifically for six years, namely 1930, 1975, 1985, 1995, 2005 and 2013). This remote sensing data exclude cultivated and managed systems like plantations, unlike the annual FSI data that do not distinguish

Table 1. Data description and sources.

Variable	Description	Data source
CO_2	CO_2 Emissions	World Development Indicators (WDI) Database.
GDP pc	Gross Domestic Product Per Capita at Factor Cost (1972 to 2013) in thousand rupees	GDP at Factor Cost at 2004-05 prices is obtained from National Accounts Statistics, CSO, MOSPI
CI pc	Comprehensive Investment Per Capita (1972 to 2013) in thousand rupees	Comprehensive Wealth is obtained by adding Physical Capital Wealth, Human Capital Wealth and Natural Capital Wealth, at 2004-05 prices.Comprehensive Investment is the change in Comprehensive Wealth.
$\Delta K_M pc$	Produced Capital Investment Per Capita (component of CI), or Change in Produced Capital Per Capita (1972 to 2013) in thousand rupees	Authors' estimates at 2004-05 shadow prices.
$\Delta K_H pc$	Human Capital Investment Per Capita (component of CI), or Change in Human Capital Per Capita (1972 to 2013) in thousand rupees	Authors' estimates at 2004-05 shadow prices.
$\Delta K_N pc$	Natural Capital Investment Per Capita (component of CI), or Change in Natural Capital Per Capita (1972 to 2013) in thousand rupees	Authors' estimates at 2004-05 shadow prices.
FDI	Foreign Direct Investment (net inflows) as share of GDP (%)	WDI Database.
industry_share	Share of industry (including construction), value added in GDP (%)	WDI Database.
alternative_energy	Share of alternative and nuclear energy (including hydropower, nuclear, geothermal, solar power, etc) in total energy use (%)	WDI Database.

them from native forests. More importantly, the FSI data is not comparable overtime due to revisions in the definition of forest cover. Our choice of the period of analysis here is based on data availability of native forest cover for India. Given this data limitation, we interpolated the data for the intervening years to obtain the time series for 1972–2013.[5] This is one of the limitations of our study, however since data on native forest cover is not available, we had a constrained choice to make, and this seemed to be the best fit. Additionally, we checked for statistical consistency of our interpolated forest cover series (as explained in footnote 5).

A complete description of variables along with data sources is summarized in table 1, and the descriptive statistics given in table 2. All the variables appear to be clustered around the mean except for FDI which shows more variability. While produced capital investment per capita, human capital investment per capita are found to exhibit an increasing trend, natural capital investment is seen to decline. Alternatively, natural capital disinvestment is seen to increase overtime. The aggregate of the three, comprehensive investment per capita is also found to be increasing overtime. Among the control variable, FDI inflows, 'industry share in GDP' and 'share of alternative energy in total energy use', all display an increasing trend.

3.3. Unit root tests

We check for stationarity of variables, and conduct the standard unit roots tests for application of ARDL. The variables are found to satisfy the stationarity criterion for application of ARDL, and exhibit a combination of I(0) and I(1), with the lag length for variables based on the Akaike Information Criteria, as given summarized in table 3.

4. Results and discussion

The results of our ARDL model estimations are presented in tables 4 and 5, which depict our ARDL outputs in the model without structural breaks and with structural breaks respectively. This facilitates easy comparison. Beginning with the standard indicator of economic well-being, namely GDP per capita (R1, table 4), we find a N-shaped EKC, which indicates that after a downturn in emissions with higher per capita income, there has been a rebound in emissions. Figure A2 illustrates that after a mild de-linking of emissions from economic growth (first turning point at around **GDP pc** = 22), a stronger re-linking of carbon emission is observed at the

[5] To verify the accuracy of interpolated data, we used WDI forest cover data (available from 1990) as the benchmark since it is a complete series unlike Forest Survey of India data that is available biennially. We used Z-test on difference between the two series and found that it satisfies the 'less than 2 standard deviation' rule. Hence, our interpolated forest cover data is 'statistically consistent' with the forest cover data obtained from WDI.

Table 2. Descriptive statistics.

Variable	Observations	Mean	Std. dev.	Min	Max
ln CO_2	42	13.404	0.684	12.292	14.526
GDP pc	42	21.092	10.475	10.597	45.898
CI pc	42	6.057	3.225	2.983	13.539
$\Delta K_M pc$	42	3.731	2.983	1.236	10.979
$\Delta K_H pc$	42	2.527	0.431	1.805	3.319
$\Delta K_N pc$	42	−0.201	0.078	−0.285	0.0023
FDI	42	0.629	0.852	−0.029	3.620
industry_share	42	27.094	2.311	21.411	31.136
alternative_energy	42	2.139	0.256	1.696	2.721

Table 3. Unit root tests.

	ADF t-statistic		PP Z(t)		
Variables	Level	1st Diff.	Level	1st Diff.	Decision
ln CO_2	−1.803 (1)	−5.669 (0)***	−1.850 (1)	−5.669 (0)***	I(1)
GDP pc	0.246 (2)	−2.988 (1)	1.194 (2)	−4.463 (1)***	I(1)
CI pc	−1.514 (2)	−3.488 (1)*	−1.450 (2)	−4.152 (1)**	I(1)
$\Delta K_M pc$	−1.429 (1)	−4.410 (0)***	−1.213 (1)	−4.410 (0)***	I(1)
$\Delta K_H pc$	−1.565 (1)	−6.363 (0)***	−1.648 (1)	−6.363 (0)***	I(1)
$\Delta K_N pc$	−2.806 (3)	−5.856 (2)***	−5.356 (3)***	−19.415 (2)***	I(0)
FDI	−2.545(1)	−7.310 (0)***	−2.823 (1)	−7.310 (0)***	I(1)
industry_share	−3.193 (3)	−7.231(0)***	−2.101 (3)	−7.231(0)***	I(1)
alternative_energy	−1.460 (1)	−7.840 (0)***	−2.167 (1)	−7.840 (0)***	I(1)

***, ** and * are statistically significant at 1, 5 and 10%, respectively. The optimal lag length is based on Akaike Information Criterion (AIC), Schwarz's Bayesian Information Criterion (SBIC) and Hannan-Quinn Information Criterion (HQIC). For all series, trend regression is used. Figures in parentheses ( ) at Level and 1st Diff. are the optimal lags.

second turning point at around **GDP pc** = 40). The cointegrating relationship is confirmed by the Bounds test F-statistic and long-run convergence between the variables is confirmed by the Error Correction Term. Our finding is similar to (Murthy and Gambhir 2018) and (Pal and Mitra 2017) who reported N-shaped EKC for India; and (Neve and Hamaide 2017) for low-income and high-income countries (but not middle-income countries).

Using our sustainable development indicator of comprehensive investment per capita (R2, table 4), we again observe a N-shaped EKC. Both the turning points are well within the study period with first turning point at around **CI pc** = 7 and second turning point at around CI **pc** = 10). The composition effect, captured by the share of industry in total output, has had a significant adverse impact increasing carbon emission. Figure A3 illustrates that the falling part of EKC is barely conspicuous due to the absence of a clear downturn, and the Indian economy is now situated on the rising part of the curve. One reason for steep climb upturn in the curve could be the rapid deterioration of natural capital. Our finding is similar to (Neve and Hamaide 2017), who also observed an N-shaped EKC using genuine savings per capita.

Distinguishing between the three components of comprehensive investment, we observe a N-shaped EKC only for produced capital investment (R3, table 4), and no relationship of emissions with human and natural capital investment (R4-R5, table 4). For produced capital accumulation, a steep rebound in emissions after the inflection point (figure A4), elucidates that it has come at the cost of environmental degradation. The first turning point around $\Delta \boldsymbol{K_M pc} = 4$ is hardly conspicuous while the second turning point at around $\Delta \boldsymbol{K_M pc} = 10$ shows a steep delinking. The N-curve is this case is rather shallow. Our focus is primarily on the delinking-relinking aspect of emissions-income relationships, rather than on the exact points at which such delinking-relinking is happening which are referred to as the *turning points*. EKC studies have reported various 'turning points'. Hence, there may be a range of turning points for a range of EKC curves which incorporate various control variables and structural breaks. That a relinking of emissions with growth is happening is something commonly reported by most studies in the literature. From a policy perspective, a range of turning points from various EKC studies should be considered. (Neve and Hamaide 2017) had also reported an N-shaped EKC with the manufactured capital component of genuine savings or comprehensive investment.

Table 4. Estimated ARDL model for GDP per capita, comprehensive investment per capita and components.

Dependent variable: ln CO_2	X= GDP pc ARDL(1, 2, 3, 3, 0, 1, 3) R1	X= CI pc ARDL(2, 0, 0, 3, 0, 0, 2) R2	$X = \Delta K_M pc$ ARDL (1,0,0,1,0,1,0) R3	$X = \Delta K_H pc$ ARDL (2,2,2,1,2,0,0) R4	$X = \Delta K_N pc$ ARDL(1, 4, 4, 3, 4, 4, 4) R5
X	0.682*** (0.065)	1.105*** (0.387)	0.709*** (0.255)	−241.632 (461.695)	−4.179 (14.139)
X^2	−0.0238*** (.0028)	−0.134** (0.049)	−0.117** (0.043)	94.263 (176.77)	12.427 (112.0407)
X^3	0.0003*** (0.000)	0.0052** (0.0019)	0.0063** (0.002)	−11.872 (21.932)	−18.011 (270.029)
FDI	0.047** (0.022)	−0.107 (0.111)	−0.038 (0.099)	−1.083 (2.639)	0.728** (0.231
industry_share	−0.014 (0.0178)	0.141** (0.063)	0.179*** (0.047)	0.036 (0.302)	−0.138 (0.139)
alternative_energy	0.065 (0.061)	−0.465 (0.286)	−0.454** (0.201)	0.047 (1.215)	−0.465* (0.235)
Intercept	4.653** (1.378)	0.825** (0.396)	1.039** (0.405)	−4.331* (1.608)	2.798** (1.126)
Shape of EKC	*N-shaped*	*N-shaped*	*N-shaped*	—	—
Turning Points Range	Within 'study period'	Within 'study period'	Within 'study period'		
Bounds Test F-Statistic	5.272**	4.357*	3.345	3.424	2.37
Speed of Adjustment (ECM_{t-1})	−0.601*** (0.173)	−0.098*** (0.046)	−0.118*** (0.041)	0.021 (0.043)	−0.171**(−0.067)
Result of Bounds Test and ECM_{t-1}	Cointegration	Cointegration	Cointegration	No Cointegration	Cointegration
JB Normality test Statistic	2.095*** [0.351]	4.929** [0.085]	2.628*** [0.268]	0.276*** [0.871]	1.465*** [0.480]
Ramsey RESET test F-Statistic	0.400*** [0.758]	0.480*** [0.699]	0.240*** [0.867]	0.760*** [0.527]	2.40*** [0.208]

Standard Errors are in parentheses ( ). Model Selection is based on the Akaike Information Criterion. ***, ** and * are statistically significant at 1, 5 and 10%, respectively. p values of diagnostic tests are in brackets [ ].

Table 5. Re-estimated ARDL model incorporating structural break-dates.

Dependent Variable: *ln* CO_2	X= GDP pc ARDL(1, 2, 3, 3, 0, 1, 3, 0) R1	X= CI pc ARDL (2, 0, 0, 3, 0, 0, 2, 0) R2	$X = \Delta K_M pc$ ARDL (1,0,0,1,0,1,0,0) R3	$X = \Delta K_H pc$ ARDL ((2,2,2,1,2,0,0,0)) R4	$X = \Delta K_N pc$ ARDL (1,4,4,3,4,4,3,2) R5
X	0.685*** (0.068)	1.127** (0.413)	0.721** (0.337)	−198.741 (248.383)	6.072 (13.105)
X^2	−0.0238*** (0.0028)	−0.133** (0.052)	−0.118** (0.051)	78.010 (95.329)	105.402 (107.019)
X^3	0.00025*** (0.00003)	0.0051** (0.002)	0.0064** (0.002)	−9.859 (11.837)	198.929 (218.786)
FDI	0.047* (0.022)	−0.100 (0.118)	0.0404 (0.106)	−0.621 (1.179)	0.646*** (0.135)
industry_share	−0.017 (0.0262)	0.131* (0.0732)	0.178*** (0.054)	0.041 (0.202)	−0.098 (0.088)
alternative_energy	0.078 (0.094)	−0.432 (0.320)	−0.449** (0.225)	0.238 (0.701)	−0.540** (0.207)
D_Y	−0.012 (0.057)	−0.068 (0.263)	−0.011 (0.214)	−0.743 (1.152)	−0.105 (0.295)
Intercept	4.697*** (1.432)	0.809* (0.408)	1.038** (0.413)	−5.474** (2.081)	3.551** (1.233)
Shape of EKC	N-shaped	N-shaped	N-shaped	—	—
Bounds Test F-Statistic	4.835***	3.681	2.833	3.061	—
Speed of Adjustment (ECM_{t-1})	−0.604*** (0.178)	−0.094* (0.048)	−0.118*** (0.042)	0.032 (0.045)	−0.227** (0.070)
Result of Bounds Test and ECM_{t-1}	Cointegration	Cointegration	Cointegration	No cointegration	Cointegration
JB Normality test Statistic	2.123*** [0.346]	4.537*** [0.103]	1.240*** [0.538]	0.317*** [0.853]	1.150*** [0.563]
Ramsey RESET test F-Statistic	0.410*** [0.750]	0.870*** [0.474]	0.230*** [0.872]	0.540*** [0.658]	0.480*** [0.731]

Note: Break years are 1999, 1998, 1998, 1995, 1986 in R1, R2, R3, R4, and R5 respectively.
D_y represents the time dummy that takes the value 0 prior to the break year and 1 from the break year onwards.
Standard errors in parentheses ( ) are heteroskedasticity and autocorrelation consistent. Model Selection is based on the Akaike Information Criterion. ***, ** and * are statistically significant at 1, 5 and 10%, respectively.
p values of diagnostic tests are in [ ] brackets. Critical Values of Bounds test F-Statistic: at 10 per cent, I(0) = 2.03, I(1) = 3.13; at 5 per cent, I(0) = 2.32, I(1) = 3.50; at 1 per cent, I(0) = 2.96, I(1) = 4.2

The lack of any significant relationship of carbon emissions with human capital investment per capita, however contrasts with the results of (Neve and Hamaide 2017), as they observed an inverted-U EKC for comprehensive human capital investment in the cross-country analysis (covering low-income, middle-income and high-income countries). Since investment in human capital leads to productivity improvement and technological gains, it reduced carbon emissions at higher levels of human capital investment per capita. Our result, however, suggests that India is yet to reach the level of human capital investment sufficient to reduce carbon emissions. Although India has immense human capital potential based on demographics, its investment has fallen short of the levels required to yield benefits observed in the richer countries of the (Neve and Hamaide 2017) sample.

Similarly, there is no EKC with natural capital investment per capita (R5, table 4). We note that natural capital investment per capita in India has been largely negative (average value negative as seen in the descriptive statistics), while carbon emissions have been increasing. The continued disinvestment in natural capital through the years, translates to a monotonically decreasing relationship between carbon dioxide and natural capital stock over the years. Again, our finding does not match the cross-sectional results obtained by (Neve and Hamaide 2017), who found a N-shaped EKC between carbon emissions and natural capital investment. Interestingly, however, the authors had observed that one would have expected 'a monotonic increasing relation between natural resource depletion instead of a N-shaped curve', as we find in our study.

Among the control variables, FDI inflow has had a significant impact in increasing carbon emissions in the specification with GDP per capita (R1, table 4) and natural capital investment (R5, table 4), suggesting that foreign investment rather than aiding carbon mitigation in India, has increased emissions. The composition of aggregate output (as measured by the share of industry in GDP) has also significantly increased carbon emissions as evident in two specifications - with comprehensive investment and produced capital investment (R2 and R3, table 4). This reflects that the economic structural change in India has had an adverse environmental impact. As expected, the use of alternative non-fossil fuel-based energy consumption significantly reduced emissions (R3and R5, table 4).[6]

Our findings with respect to control variables are consistent with the results of existing studies in the literature. While import of energy-efficient technologies decreases emissions, in case of the developing economies, FDI inflows could have a positive impact on emissions if such economies act as ‘pollution havens’ attracting more polluting industries due to lax environmental regulations (Panayotou 2003, Cole 2004). Indeed, (Xiaoping and Xin 2017) found significant impact of FDI on EKC relationships, validating the Pollution Haven hypothesis. (Murthy and Gambhir 2018) also found that FDI has a positive impact on emissions. Similarly, the increasing share of manufacturing in GDP was seen to contribute to a rise in carbon emissions in (Neve and Hamaide 2017) and (Sikder *et al* 2022). Finally, carbon emission reduction due to renewable energy was observed in studies such as (Rahman *et al* 2022). Our measure of alternative energy use includes both renewable and nuclear energy. While the positive impact of renewable energy on emissions reduction is largely undeniable, nuclear energy usage is subject to other environmental concerns especially in the safe handling and management of nuclear waste.

Summing up, our analysis highlights that the structural change of the Indian economy led to an adverse environmental impact with industrial growth, but the use of renewable energy forms played a significant role in abating carbon emissions. Contrary to several EKC studies done for India on carbon pollution which found an inverted U-shaped EKC (Kanjilal and Ghosh 2013, Ahmad *et al* 2016, Sinha and Shahbaz 2018, Özgür *et al* 2022), we find a N-shaped EKC using the sustainable development indicator of comprehensive wealth investment and its produced capital component. Our findings resonate with (Pal and Mitra 2017) and more so with the cross-country study of (Neve and Hamaide 2017), which found a N-shaped EKC using comprehensive investment per capita as the measure of well-being. Our findings provide important insight in the dynamics of India’s development over the last four decades, that while development has been ‘weakly sustainable’ (Agarwal and Sawhney 2021), the trajectory of environmental degradation is a cause for concern as the country continues to be on rebound of increasing pollution.

Using comprehensive investment to gauge well-being, instead of the conventional yardstick of GDP, allowed us to account for underlying depletion and degradation of the environmental resources. We found that the EKC hypothesis on de-linking of growth and pollution beyond a threshold level of well-being does not hold for India, or perhaps the country has not yet reached the threshold level of well-being for that turnaround to occur. The steady decline in natural capital stock does not augur well for the development path ahead, as the natural capacity to sequester carbon continues to decline over time. The depreciation in natural capital in our analysis subsumes the decline in subsoil wealth, native forest wealth and agricultural land wealth. Declining subsoil mineral wealth and increasing carbon emissions are directly related to each other, reflecting the reliance on fossil fuel-based energy. Besides burning of fossil fuels, land use changes are also responsible for carbon emissions. Deforestation, soil degradation and other land use changes determine whether land acts as a net carbon source or sink. With the decline of such natural capital, both the resource and sink function of nature are adversely affected since within natural capital, all three types, viz., subsoil wealth, forest wealth and land wealth are declining. On one hand, carbon emissions are increasing due to extraction of subsoil resources for energy, on the other hand, carbon-sequestering forests are wiped out. This has acted like a double-edged sword in increasing greenhouse pollution.

4.1. Long-run cointegration and robustness check

In our ARDL model estimations, we confirmed the cointegrating relationship with the Bounds test as reported in the table 4. While the F-statistic of the Bounds test is significant in the specifications with GDP per capita, and comprehensive investment per capita (R1- R2, table 4), it is found to lie in the inconclusive region in the other specifications. Several studies have noted that when the calculated F-statistic is found to be inconclusive (falling between the lower and upper bounds), the alternative efficient way of establishing cointegration is to test for the significance of the negative lagged error-correction term (Kremers *et al* 1992, Bahmani-Oskooee 2001, Iwata *et al* 2012, Shahbaz *et al* 2012, Kyophilavong *et al* 2013). We find that the error correction term (ECM_{t-1}) is significant and lies between 0 and −1, in all our specifications except that of human capital (R4, table 4). The negative lagged error correction term indicates the speed at which (short-run) disturbances from long-run equilibrium level of carbon emissions are corrected by the following year, signifying stable long-run relationship between the variables and carbon emissions.

This establishes co-integration in our ARDL models with GDP per capita, comprehensive investment per capita, produced capital investment per capita (R1-R3 in table 4), and natural capital investment per capita (R5, table 4). We

[6] According to WDI database the definition for of *alternative and nuclear energy* is defined as follows: ‘Clean energy is noncarbohydrate energy that does not produce carbon dioxide when generated. It includes hydropower and nuclear, geothermal, and solar power, among others’.

also conducted diagnostic tests such as the Jarque-Bera Normality test and the Ramsey Reset test. The normality assumption is met in all the models and models are correctly specified as per the results of these diagnostic tests.

5. Impact of structural breaks

In an analysis tracking the dynamics of an economy, identifying, and controlling for structural breaks in the time-series variables is important. However, among the various dynamic EKC studies on India covering the period from 1970s to 2000 and beyond, few have identified the presence of endogenous structural breaks in the data. For example, the study by (Pal and Mitra 2017) for the period 1971–2012 used the ARDL approach for examining the EKC in India but did not control for structural breaks in the data. On the other hand, Sinha and Shahbaz (2018) checked for the stationarity of variables for the period 1971–2015, using the unit-root test with multiple structural breaks, before applying the ARDL model. Although they identified multiple break points in various series such as renewable energy generation per capita, income per capita, electric power consumption per capita, etc, these break-points were not incorporated in the main regression framework. However, (Jayanthakumaran *et al* 2012) and (Kanjilal and Ghosh 2013) while testing the EKC hypothesis for India for 1971–2007 and 1971–2008 respectively, incorporated the endogenously determined structural breaks in the cointegration framework. As noted by the authors, structural breaks should be incorporated in the cointegration analysis, otherwise the results could be misleading.

Structural breaks account for important policy changes, regime shifts, economic crisis, etc (Jayanthakumaran *et al* 2012). In case of India, it is important to control for such breaks keeping in mind the major policy shift the country witnessed especially since 1991 with liberalization reforms. Other policy measures followed through the post-liberalization period in the country, and their impact on the time-series need to be controlled for. To this effect, we identify the endogenous structural breaks in the data using 'breakpoint unit root test' and then incorporate these break dates in our ARDL regression analysis. We test each variable series for the presence of endogenous structural breaks. We observe most of the series to be non-stationary with structural breaks in the post-liberalization years during 1995–2005, except for natural capital investment and alternative energy in the later eighties (table A2 in appendix). We re-estimate our models incorporating the identified break years.

Our re-estimated model results are presented in table 5, and show that structural breaks had no significant qualitative impacts on carbon emissions, and our results obtained on the EKC hypothesis are robust to inclusion of structural break years in the model. Our results are consistent with findings in (Jayanthakumaran *et al* 2012), that structural breaks did not significantly impact carbon emissions in India. There is also no change in the shapes of the curves as we obtained earlier in the previous section.

6. Conclusion and policy implications

An important link between natural capital and emissions is missed out when a conventional output measure like GDP is taken as a yardstick of well-being in the growth-environment nexus of an economy. In the EKC studies of India, the use of GDP per capita as an indicator of development fails to represent the well-being of the economy, as it misses out on the true productive capacity of the economy, and the sustainability of economic development. Our study tries to fill this gap, being the first India-specific study linking EKC hypothesis to comprehensive wealth and examining the relationship with carbon emissions over the period 1972–2013. We find an N-shaped EKC with comprehensive investment per capita as well as the manufactured capital component of comprehensive investment, with a pronounced rebound in carbon emissions. Moreover, disinvestment in natural capital has steadily reduced the natural capital base and the capacity for carbon sequestration. We note that an overwhelming focus on increasing produced capital wealth and GDP, camouflaged the severe erosion in the natural capital wealth of the country, which plays a critical role in providing environmental services and ensuring sustainability of economic well-being.

As envisioned by Herman Daly, a steady-state economy would use materials and energy within the regenerative and assimilative limits of ecological sustainability. In such an economy, GDP-growth is in principle possible if changes in technology and consumption patterns allow higher incomes without any increases in the use of energy and materials, - enabling the de-coupling of environment from economic growth. That we are unable to observe an inverted-U curve for carbon emissions also takes away the hope that development itself will be able to take care of the environmental sustainability. Our analysis of the Indian growth experience clearly demonstrates that it is important to shift the development policy focus of India onto the comprehensive asset mix of produced, human and natural capital, with special emphasis on building human capital and preserving critical natural capital. Only then can one expect the due emphasis on native forests protection for natural carbon sequestration. Based on these findings, a comprehensive and robust policy framework is essential, one which protects native forests from exploitation, incentivises renewable and clean energy, and builds the human capital base of the economy through investments in education and knowledge creation. The Green India Mission implemented in 2014, under the *National Action Plan for Climate Change* 2008, has focussed on increasing forest cover, but the value and protection of native forests have been ignored. India has accelerated harnessing of renewable energy, especially solar, and recently adopted the 'carbon credit trading scheme', in a significant attempt at decarbonization in the manufacturing sector, however a concerted focus on carbon sequestration is imperative. More research is needed in the area of genuine wealth for India and how carbon emissions erode the qualitative natural capital base. Although studies have conducted 'genuine wealth accounting' exercises for all-India, a disaggregated analysis is lacking and has the potential to provide interesting insights.

Declarations

The authors have no relevant financial or non-financial interests to disclose. The authors declare that no funds, or grants were received during the preparation of this manuscript.

Conflict of interest

None

Funding

None

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

Appendix

The Appendix contains detailed estimation methods which were used for estimating each of the three types of capital, viz., produced, human and natural capital (in table A1). Table A2 gives the Breakpoint Unit Root tests for the variables employed in the study. These tables are followed by select figures. Figure A1 shows the percentage shares of different types of capital in comprehensive wealth. Figures A2, A3 and A4 plot various shapes of EKC using different indicators.

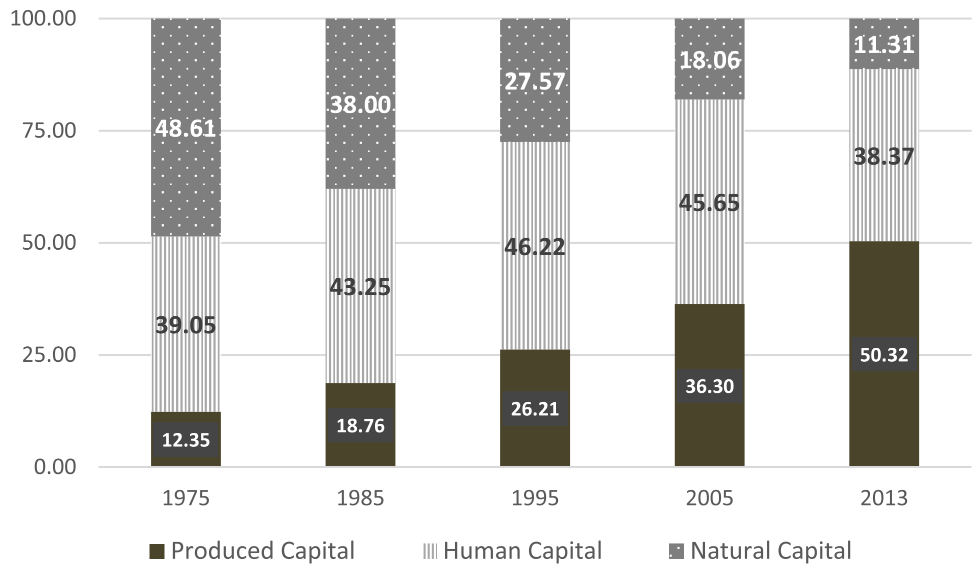

Figure A1. Percentage shares of different types of capital in comprehensive wealth.

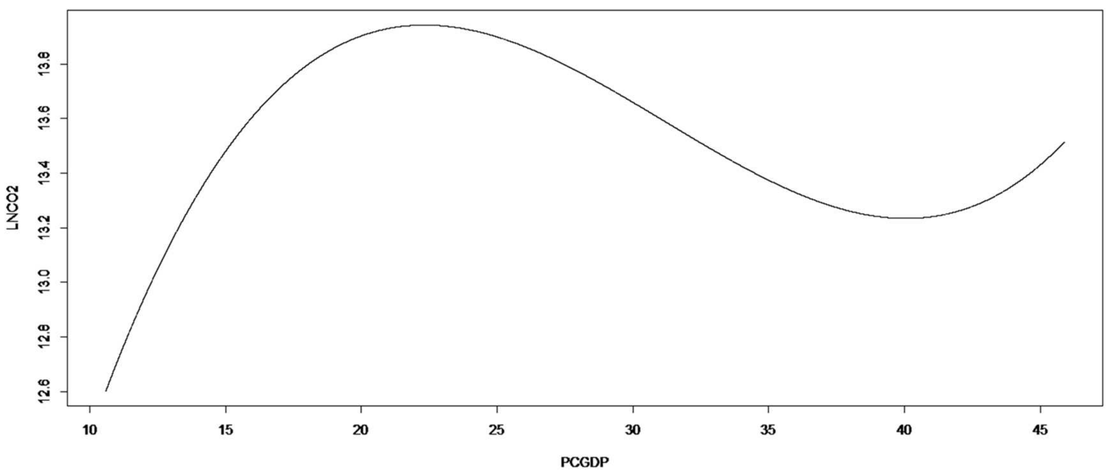

Figure A2. EKC for GDP Per Capita (in Thousand Rupees at 2004-05 Prices).

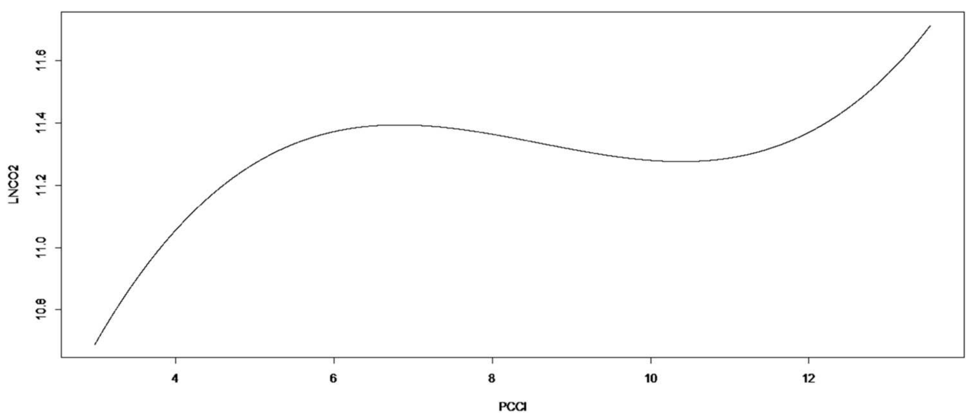

Figure A3. EKC for comprehensive investment per capita (in Thousand Rupees at 2004-05 Prices).

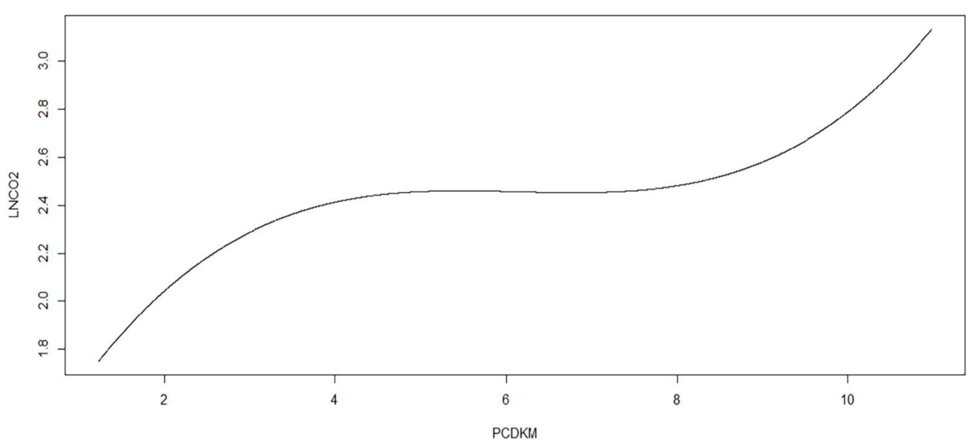

Figure A4. EKC for produced capital investment per capita (in Thousand Rupees at 2004-05 Prices).

Table A1. Methodology for estimating produced-, human-, and natural capital.

Capital Type	Notes on Estimation Method
***Produced Capital*'K_M'**	Produced capital stock series (at 2004-05 prices) is estimated using Gross Fixed Capital Formation (GFCF) data for the period 1971 to 2013. GFCF data is obtained from National Accounts Statistics, CSO, MOSPI. We apply the Perpetual Inventory Method (PIM) which is a widely used method. The aggregate capital stock value in period 't' is given by 'K_{M_t}' as: $K_{M_t} = (1-\alpha)^{t-1}K_{M_0} + \sum_{j=0}^{t-1}(1-\alpha)^j I_{M\,t-1-j}$ Here, 'I_M' is the value of investment at constant 2004–05 prices, 'α' is the rate of depreciation equal to 5%. 'K_{M_0}' is the initial capital stock which is estimated as follows: $K_{M_0} = \frac{I_{M0}}{g_Y + \alpha}$ Here, I_{M_0} is investment for the year 1971-72. g_Y is the trend growth rate of investment.
***Human Capital*'K_H'**	We estimate human capital (at 2004-05 prices) for the period 1971 to 2013 as follows: $K_{H(t)} = e^{(EDU(t)*\theta)} * Pop_{15-64}(t) * \int_{t=0}^{48} Compensation\_Employees.\ e^{-\theta t}dt$ EDU is the average educational attainment obtained from Barro-Lee Educational Attainment Dataset, Pop_{15-64} is the population in the age bracket 15-64. Rate of return to education is given by θ which is assumed to be 8.5%. 'Compensation of Employees' is obtained from WDI database.
***Natural Capital*'K_N'**	$K_N = Agriland\_Wealth + Subsoil\_Wealth + Forest\_Wealth$ Agricultural land wealth at 2004-05 prices is estimated for the period 1971 to 2013 as: $Agriland\_Wealth_t = \left[RPA\left(1+\frac{1}{\gamma}\right)\right]_{2004-05} * Agricultural\_land_t$ RPA is the average rental price per hectare and γ is the discount rate (5%). Agricultural land area is obtained from *Land Use Statistics*, Ministry of Agriculture and Farmers Welfare. Subsoil wealth of fuels (coal, oil, natural gas) and minerals (bauxite, iron-ore, copper, zinc, lead, rock phosphate, gold, silver) at 2004-05 prices is estimated for the period 1971 to 2013. The reserves at any point in time is multiplied with a constant unit rental price to obtain its real value. $Subsoil\_Wealth_t = Reserves_t * Implicit\ Unit\ Rental\ Price$ $Reserves_{t-1} = Reserves_t + Production_t$ Forest wealth at 2004-05 prices is estimated for the period 1971 to 2013 as: $Forest\ Wealth = \text{PHB} * Forest\ Area * 0.1\left(1+\frac{1}{\gamma}\right)$ PHB is the annual per hectare benefits from moderately dense forests. γ is the discount rate (5%). *Forest Area* is the data on native forest cover as obtained from Reddy *et al* (2016).

Table A2. Breakpoint unit root test.

Variables	t-statistic	Break Date
$ln\ CO_2$	−3.686 (0)	2000
GDP pc	−3.155 (1)	1999
CI pc	−3.406 (1)	1998
$\Delta K_M pc$	−3.406 (1)	1998
$\Delta K_H pc$	−5.629** (3)	1995
$\Delta K_N pc$	−7.896*** (1)	1986
FDI	−5.629** (0)	2005
industry_share	−3.891 (3)	1995
alternative_energy	−4.103 (0)	1989

Note: The Breakpoint Unit Root test is conducted using EVIEWS 12. It tests the null hypothesis that the series has a unit root with break. We check for breaks in both trend and intercept. Breakpoint selection is based on Dickey-Fuller min-t. AIC (Akaike Information Criterion) is used for optimal lag length selection. Figures in parentheses ( ) are the optimal lag lengths chosen by the models. The t-statistic is meant for checking stationarity of the series. ***, ** and * are statistically significant at 1%, 5% and 10%, respectively.

Author contributions

Aparna Sawhney 0000-0003-4878-7773
Conceptualization (equal), Data curation (equal), Formal analysis (equal), Investigation (equal), Methodology (equal), Project administration (equal)

References

Agarwal P and Sawhney A 2021 Sustainability and comprehensive wealth accounting: The case of India *Environment, Development and Sustainability* **23** 3762–86

Ahmad A, Zhao Y, Shahbaz M, Bano S, Zhang Z, Wang S and Liu Y 2016 Carbon emissions, energy consumption and economic growth: an aggregate and disaggregate analysis of the Indian economy *Energy Policy* **96** 131–43

Arrow K *et al* 1995 Economic growth, carrying capacity, and the environment *Ecol. Econ.* **15** 91–5

Bahmani-Oskooee M 2001 How stable is M2 money demand function in Japan? *Japan and the World Economy* **13** 455–61

Bekun F V, Gyamfi B A, Onifade S T and Agboola M O 2021 Beyond the environmental Kuznets Curve in E7 economies: accounting for the combined impacts of institutional quality and renewables *J. Clean. Prod.* **314** 127924

Ben Nasr A, Gupta R and Sato J 2015 Is there an environmental Kuznets curve for South Africa? A co-summability approach using a century of data *Energy Econ.* **52** 82–94

Caporin M *et al* 2024 New insights on the environmental Kuznets curve (EKC) for Central Asia *Empirical Economics* **66** 2335–54

Chakravarty D and Mandal S K 2016 Estimating the relationship between economic growth and environmental quality for the BRICS economies - A dynamic panel data approach *The Journal of Developing Areas* **50** 119–30

Cole M A 2004 Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages *Ecol. Econ.* **48** 71–81

Dasgupta P and Mäler K-G 2009 Environmental and resource economics: some recent developments *Handbook of Environmental Economics in India* ed K Chopra and V Dayal (Oxford University Press) pp 17–66

Dasgupta P 2007 Nature and the economy *J. Appl. Ecol.* **44** 475–87

de Bruyn S M and Opschoor J B 1997 Developments in the throughput-income relationship: Theoretical and empirical observations *Ecol. Econ.* **20** 255–68

Destek M A, Balli E and Manga M 2016 The relationship between CO2 emission, energy consumption, urbanization and trade openness for selected CEECs *Research in World Economy* **7** 52–8

Dinda S 2004 Environmental kuznets curve hypothesis: a survey *Ecol. Econ.* **49** 431–55

Dutt K 2009 Governance, institutions and the environment-income relationship: A cross-country study *Environment, Development and Sustainability* **11** 705–23

Fosten J, Morley B and Taylor T 2012 Dynamic misspecification in the environmental kuznets curve: evidence from CO_2 and SO_2 emissions in the United Kingdom *Ecol. Econ.* **76** 25–33

Friedl B and Getzner M 2003 Determinants of CO_2 emissions in a small open economy *Ecol. Econ.* **45** 133–48

Grossman G M and Krueger A B 1991 Environmental impacts of a north american free trade agreement *NBER Working Paper* National Bureau of Economic Researchhttps://www.nber.org/papers/w3914

Grossman G M and Krueger A B 1995 Economic growth and the environment *The Quarterly Journal of Economics* **110** 353–77

Gill A, Viswanathan K K and Sallahuddin H 2017 A test of the environmental Kuznets curve (EKC) for carbon emission and the potential of renewable energy to reduce greenhouse gases (GHG) in malaysia *Environment, Development and Sustainability* **20** 1103–14

Hamilton K 1994 Green Adjustments to GDP *Resour. Policy* **20** 155–68

Hamilton K and Clemens M 1999 Genuine savings rates in developing countries *World Bank Economic Review* **13** 333–56

Hasanov F J, Hunt L C and Mikayilov J I 2021 Estimating different order polynomial logarithmic environmental Kuznets curves *Environ. Sci. Pollut. Res.* **28** 41965–87

Iwata H, Okada K and Samreth S 2012 Empirical study on the determinants of CO_2 emissions: evidence from OECD countries *Applied Economics* **44** 3513–9

Jayanthakumaran K, Verma R and Liu Y 2012 CO_2 emissions, energy consumption, trade, and income: a comparative analysis of China and India *Energy Policy* **42** 450–60

Jha R and Murthy K V B 2003 An inverse global environmental kuznets curve *Journal of Comparative Economics* **31** 352–68

Kaika D and Zervas E 2013 The Environmental Kuznets Curve (EKC) theory—part a: concept, causes and the CO_2 emissions case *Energy Policy* **62** 1392–402

Kanjilal K and Ghosh S 2013 Environmental Kuznets curve for India: evidence from tests for cointegration with unknown structural breaks *Energy Policy* **56** 509–15

Kasman A and Duman Y S 2015 CO_2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis *Economic Modelling* **44** 97–103

Kremers J J, Ericson N R and Dolado J J 1992 The power of cointegration tests *Oxford Bulletin of Economics and Statistics* **54** 325–47

Kumar S and Managi S 2009 Environmental Productivity and Kuznets Curve *Economics of Sustainable Development, Natural Resource Management and Policy* vol 32 (Springer) (https://doi.org/10.1007/978-0-387-98176-5_11)

Kurniawan R, Sugiawan Y and Managi S 2021 Economic growth—environment nexus: an analysis based on natural capital component of inclusive wealth *Ecol. Indic.* **120** 106982

Kyophilavong H, Shahbaz M and Uddin G S 2013 Does J-curve phenomenon exist in case of Laos? An ARDL approach *Economic Modelling* **35** 833–9

Lange G-M, Wodon Q and Carey K 2018 The changing wealth of nations 2018: Building a sustainable future *License: Creative Commons Attribution CC BY 3.0 IGO* (World Bank) (https://doi.org/10.1596/978-1-4648-1046-6.)

Lele S 2025 21 January https://frontline.thehindu.com/environment/forest-plantations-forest-survey-of-india-conservationists-environment-land-cover/article69123710.ece India's forest surveys conceal a deep institutional failureThe Frontline

Managi S and Jena P R 2008 Environmental productivity and Kuznets curve in India *Ecol. Econ.* **65** 432–40

Mukherjee S and Chakraborty D 2009 Environment, human development and economic growth: a contemporary analysis of Indian states *International Journal of Global Environmental Issues* **9** 20–49

Mukherjee S and Kathuria V 2006 Is economic growth sustainable? Environmental quality of Indian States after 1991 *Int. J. Sustainable Dev.* **9** 38–60

Munasinghe M 1999 Is environmental degradation an inevitable consequence of economic growth: tunneling through the environmental Kuznets curve *Ecol. Econ.* **29** 89–109

Murthy K V B and Gambhir S 2018 Analyzing Environmental Kuznets Curve and pollution haven hypothesis in India in the context of domestic and global policy change *Australasian Accounting, Business and Finance Journal* **12** 134–56

Neve M and Hamaide B 2017 Environmental Kuznets Curve with adjusted net savings as a trade-off between environment and development *Australian Economic Papers.* **56** 39–58

Özgür Ö, Yılancı V and Kongkuah M 2022 Nuclear energy consumption and CO_2 emissions in India: evidence from Fourier ARDL bounds test approach *Nuclear Engineering and Technology* **54** 1657–63

Pal D and Mitra S K 2017 The environmental Kuznets curve for carbon dioxide in india and china: growth and pollution at a crossroad *Journal of Policy Modeling* **39** 371–85

Panayotou T 2003 Economic Growth and the Environment *UNECE Spring Seminar ∀Sustainable Development in the ECE Region∀ (2003 : Geneva) (DHLAUTH)638020 (Geneva, Feb 2003)* https://digitallibrary.un.org/record/488313?v=pdf

Pesaran M H, Shin Y and Smith R J 1996 *Testing for the existence of a long-run relationship Department of Applied Economics Working* Paper No. 9622 University of Cambridge

Pesaran M H and Shin Y 1999 An autoregressive distributed lag modelling approach to cointegration analysis ed S Strom *Econometrics and Economic Theory in the 20th Century: The Ragnar Frisch Centennial Symposium.* (Cambridge University Press)

Pesaran M H, Shin Y and Smith R J 2001 Bounds testing approaches to the analysis of level relationships *Journal of Applied Econometrics* **16** 289–326 JSTORhttp://jstor.org/stable/2678547

Puyravaud J P, Davidar P and Laurance W F 2010 Cryptic destruction of India's native forests *Conservation Letters* **3** 390–4

Rahman M M, Alam K and Velayutham E 2022 Reduction of CO_2 emissions: the role of renewable energy, technological innovation and export quality *Energy Reports* **8** 2793–805

Rana R and Sharma M 2019 Dynamic causality testing for EKC hypothesis, pollution haven hypothesis and international trade in India *The Journal of International Trade & Economic Development* **28** 348–64

Reddy C S *et al* 2016 Quantification and monitoring of deforestation in India over eight decades *Biodiversity and Conservation* **25** 93

Roca J, Padilla E, Farré M and Galletto V 2001 Economic growth and atmospheric pollution in Spain: discussing the environmental Kuznets curve hypothesis *Ecol. Econ.* **39** 85–99

Seetanah B and Vinesh S 2010 *On the Relationship between CO_2 Emissions and Economic Growth: The Mauritian Experience.* (University of Mauritius)

Shafik N and Bandyopadhyay S 1992 *Economic growth and environmental quality: time series and cross-country evidence Policy Research Working paper No. WPS* World Bank https://documents.worldbank.org/curated/en/833431468739515725/Economic-growth-and-environmental-quality-time-series-and-cross-country-evidence

Shafik N 1994 Economic development and environmental quality: an econometric analysis *Oxford Economic Papers* **46** 757–73

Shahbaz M, Jalil A and Islam F 2012 Real exchange rate changes and the trade balance: the evidence from Pakistan *The International Trade Journal* **26** 139–53

Shahbaz M and Sinha A 2018 Environmental Kuznets curve for CO_2 emissions: a literature survey *Journal of Economic Studies* **46** 00–

Sikder M, Wang C, Yao X, Huai X, Wu L, Yeboah F K, Wood J, Zhao Y and Dou X 2022 The integrated impact of GDP growth, industrialization, energy use, and urbanization on CO_2 emissions in developing countries: evidence from the panel ARDL approach *Sci. Total Environ.* **837** 155795

Sinha A and Bhattacharya J 2016 Confronting environmental quality and societal aspects: an environmental Kuznets curve analysis for Indian cities *International Journal of Green Economics* **10** 69–88

Sinha A and Sen S 2016 Atmospheric consequences of trade and human development: a case of BRIC countries *Atmospheric Pollution Research* **7** 980–9

Sinha A, Shahbaz M and Balsalobre D 2017 Exploring the relationship between energy usage segregation and environmental degradation in N-11 countries *J. Clean. Prod.* **168** 1217–29

Sinha A and Shahbaz M 2018 Estimation of environmental Kuznets curve for CO_2 emission: role of renewable energy generation in India *Renew. Energy* **119** 703–11

Solow R M 1974 The economics of resources or the resources of economics *The American Economic Review* **64** 1–14 JSTOR. http://jstor.org/stable/1816009

Stern D I, Common M S and Barbier E B 1996 Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development *World Development* **24** 1151–60

Stern D I 2004 The rise and fall of the environmental Kuznets curve *World Development* **32** 1419–39

Stiglitz J, Sen A and Fitoussi J 2009 The measurement of economic performance and social progress revisited: reflections and overview *OFCE Working paper* HAL-01069384

Sugiawan Y and Managi S 2016 The environmental Kuznets curve in Indonesia: exploring the potential of renewable energy *Energy Policy* **98** 187–98

Tiwari A K, Shahbaz M and Hye Q M A 2013 The environmental Kuznets curve and the role of coal consumption in India: cointegration and causality analysis in an open economy *Renew. Sustain. Energy Rev.* **18** 519–27

UNU-IHDP and UNEP 2012 *Inclusive Wealth Report 2012: Measuring Progress Toward Sustainability* (Cambridge University Press)

Wang Q, Li Y and Li R 2024 Rethinking the environmental Kuznets curve hypothesis across 214 countries: the impacts of 12 economic, institutional, technological, resource, and social factors *Humanities and Social Sciences Communications* **11** 292

World Bank 2006 *Where is the Wealth of Nations?* (World Bank)

World Bank 2011 *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium.* (World Bank)

Xiaoping H and Xin Y 2017 Foreign direct investments and the environmental Kuznets curve: new evidence from chinese provinces *Emerging Markets Finance and Trade* **53** 12–25