Environmental Science and Pollution Research (2023) 30:103212–103224
https://doi.org/10.1007/s11356-023-29237-7

RESEARCH ARTICLE

Reinvigorating the environmental Kuznets curve hypothesis in the context of highly polluted nations: evidence using advanced panel estimation techniques

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Received: 24 November 2022 / Accepted: 4 August 2023 / Published online: 8 September 2023

Abstract

China, United States, India, Russia, and Japan are regarded as the top five carbon dioxide-emitting nations in the world. These countries altogether account for more than half of the global annual discharges of carbon dioxide. Consequently, impeding the carbon emission-led environmental adversities in these countries is of critical emphasis for establishing environmental sustainability worldwide. In this regard, this study checks how economic progress, energy use intensification, and renewable energy use affect the annual growth rates of per capita carbon dioxide emission in these highly-polluted economies considering the study period from 1990 to 2021. Besides, for analytical purposes, advanced panel data estimation techniques have been utilized for detecting and neutralizing the impacts of cross-sectional dependency and slope heterogeneity-related problems in the data. Overall, the findings endorse that economic progress deteriorates environmental quality both in the short and long run. However, since the long-run unfavorable environmental impacts of economic growth are relatively lower compared with the short-run impacts, the environmental Kuznets curve hypothesis can be deemed valid. Besides, more intensive use of energy resources is witnessed to impose negative long-run environmental consequences while the adoption of renewable energy instead of fossil fuels is found to improve environmental well-being, both in the short and long run. Furthermore, the results affirm that economic progress and energy use intensification jointly degrade environmental conditions. By contrast, economic progress alongside greater adoption of renewable energy is observed to inflict an environmental quality-improving effect. Considering these findings, a couple of carbon dioxide mitigating policies are suggested to the concerned highly polluted developed and developing nations.

Keywords CO_2 emissions · EKC hypothesis · Energy intensity · Economic growth · Renewable energy consumption

Nomenclature

CO_2	Carbon dioxide
COP27	27th Conference of Parties
CRSADF	Cross-sectionally adjusted Augmented Dickey-Fuller
CRS-ARDL	Cross-sectional autoregressive distributed lag
CRSD	Cross-sectional dependency
CRSIPS	Cross-sectionally adjusted Im–Pesaran–Shin
EKCH	Environmental Kuznets Curve hypothesis

Responsible Editor: Philippe Garrigues

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GDP	Gross domestic product
PMG-ARDL	Pooled mean group-autoregressive distributed lag
PPP	Purchasing power parity
SLHET	Slope heterogeneity
UNSDG	United Nations Sustainable Development Goals

Introduction

Atmospheric releases of carbon, in all forms, have persistently inflicted ominous consequences on the prospects of establishing environmental sustainability, especially due to the significant contributions of carbon emissions to global warming-related adversities across the globe (Ibrahim et al. 2022; Pan et al. 2022). As a result, the world economies have gathered under one umbrella through the ratification of the Paris Accord. Notably, by signing this historic environmental agreement, nations worldwide have reached a consensus in committing to both independently and collectively strategize plans that can effectively reduce carbon dioxide (CO_2) emission rates while sequestrating the already discharged carbon from the atmosphere, in tandem (Abban et al. 2023; Adebayo and Kirikkaleli 2021). Besides, the recently staged 27th Conference of Parties (COP27 from hereafter) in Glasgow has further highlighted the necessity of adopting more proactive environmental policies since the ones adopted after the Paris Accord came into effect are yet to be successful in substantially mitigating emissions and limiting global warming (Adebayo et al. 2023; Dai et al. 2023). Moreover, the global economies have signed the United Nations Sustainable Development Goals (UNSDG) agenda, as well, whereby these nation expressed willingness to integrate clean environmental strategies within their national socioeconomic development policies (Sinha et al. 2020; Xue et al. 2022; Wu et al. 2023).

Therefore, for ensuring compliance with the aforementioned international environmental agreements, identifying the mechanisms relevant to reducing and sequestrating CO_2 emissions is deemed important, from perspectives of both developed and developing countries. This is because, it has been widely acknowledged in the literature that environmental problems are experienced irrespective of the development status since the topmost polluted economies in the world comprise both developing and developed nations (Iqbal et al. 2023). Notably, as per the World Bank's estimates of 2020, the top five CO_2-emitting counties comprised a mix of underdeveloped and developed nation including China, United States, India, Russia, and Japan, respectively (World Bank 2023). Moreover, it is noteworthy mentioning that these nations collectively acquired around 60% of the global discharges of CO_2 in 2020 (World Bank 2023). Hence, it can be said that these countries are major contributors to global warming-related problems which are not only assumed to impede their respective environmental well-being but deteriorate environmental welfare in other world economies, as well. Moreover, these nations are considered critically important drivers of the global economic output through different globalization channels (World Bank 2023). As a result, it is of paramount significance for these highly polluted nations to design relevant CO2 reduction and sequestration policies so that the global environmental sustainability agenda can be effectively realized within due course.

Several macroeconomic factors are alleged to instigate environmental distresses, especially through the atmospheric discharges of CO_2. Among these, economic progress is often believed to initially dampen environmental quality, especially due to the intensive use of unclean energy resources (Alam 2022; Shan et al. 2021; Kirikkaleli et al. 2022). However, these detrimental environmental impacts of economic progress are hypothesized to be reversed later on, given that technologies are developed to reduce the traditional dependency on unclean energy resources for economic output generation purposes while enhancing use of cleaner alternative energy resources, in tandem (Akadiri and Adebayo 2022). These equivocal inter-temporal repercussions of economic progress on environmental conditions are theoretically explained by the Environmental Kuznets Curve hypothesis (EKCH) that was postulated by Grossman and Krueger (1992). According to this hypothesis, the initial unfavorable and ultimate favorable impacts of economic progress on the environment can be depicted as an inverse U shaped figure (Agozie et al. 2022; Saqib et al. 2023). However, several existing empirical studies having failed to verify the authenticity of the EKCH (Abbasi et al. 2023); thus, the general applicability of the EKCH can somewhat be doubted.

Apart from economic progress, as mentioned within the extant literature, another major environmental quality influencing factor is energy employment (Wang et al. 2022; Ge et al. 2022). Accordingly, the role of the energy sector in safeguarding the well-being of environmental traits cannot be ignored. However, it is worth mentioning that the environmental repercussions linked with energy employment can be multi-dimensional. For instance, in terms of energy production and consumption, more employment of fossil fuels is argued to cause environmental damages (Rehman et al. 2022; Huang et al. 2023). Contrarily, enhancing renewable energy consumption is believed to exert favorable environmental impacts (Aydin and Bozatli 2023; Idris et al. 2023). Moreover, the efficiency rate at which energy resources are consumed is also assumed to induce equivocal environmental impacts. Notably, it is said that using energy intensively (or less productively) can trigger greater discharges of CO_2 into the atmosphere (Islam and Rahaman 2023; Khan and Liu 2023). On the other hand, productiveuse of energy resources, provided there is no rebound effect, can limit the atmospheric releases of CO_2 (Mirza et al. 2022). Hence, it is apparent that environmental impacts of energy use are quite uncertain and are largely conditional on the type of energy resources consumed and on whether the energy utilization process is efficient.

Against this backdrop, considering the importance of reducing CO_2 emissions in the topmost polluted global economies, this study aims to assess the impacts of economic progress, energy intensity, and renewable energy on CO_2 emissions in China, United States, India, Russia, and Japan. Since these five nations contribute to more than half of the global annual discharges of CO_2, the outcomes from this study can be utilized for creating an environmental sustainability blueprint that can be adopted by other world economies which are experiencing difficulties in controlling their respective discharges of carbon. Consequently, the policy takeaways from this study can be expected to facilitate environmental quality improvement across the globe. Besides, this study offers two unique contributions to the related literature. First, this study assesses the authenticity of the EKCH in the context of the aforementioned countries using their annual growth rates of per capita CO_2 emissions. In contrast, the preceding studies have mostly used the annual per capita volume of CO_2 emissions as the environmental proxy (Xu et al. 2022; Jahanger et al. 2023). However, from the perspective of establishing a sustainable global environment, it is not only important to reduce the annual discharges of CO_2; rather, reducing the annual CO_2 emission growth rate is of paramount significance, as well. Second, this study simultaneously evaluates the energy sector's environmental impacts in responses to changes in the levels of energy use intensity and renewable energy use. Contrastingly, the earlier studies have separately assessed the environmental impacts of these two energy sector-related factors (Danish et al. 2020; Ehigiamusoe and Dogan 2022). Nevertheless, simultaneously assessing these on the environment helps in understanding the multidimensional channels through which the energy sector influences environmental well-being in the concerned nations.

Precisely, the following research questions are explored in this study:

- Does the per capita CO_2 emission growth rate-related EKCH hold in the case of the top five most-polluted global economies?
- Does the energy sector affect the environment through multiple channels?
- Is intensification of energy use detrimental to environmental quality?
- Can undergoing a renewable energy transition establish environmental sustainability?
- Do economic progress and energy sector-related indicators jointly affect the environment?

In the forthcoming section, a review of the extant literature is presented to highlight the gaps bridged by this current study. Next, the research methodology is put forward for explaining the empirical models used and for demonstrating the estimation techniques utilized for analytical purposes. Subsequently, the results obtained from the empirical analyses are reported and discussed in the following section. Finally, in the last section, concluding remarks are provided along with relevant policy suggestions.

Literature review

Several empirical studies have checked whether the CO_2 emission-related EKCH holds in the context of China, United States, India, Russia, and Japan. However, these studies have mostly examined how economic progress affects the annual volume of CO_2 emitted by these countries. Among these, Pata and Caglar (2021) used data from China for the 1980–2016 period and found that economic progress initially reduces and later on boosts the volume of CO_2 emissions in China. Consequently, the authors concluded that the EKCH does not hold. Besides, the authors remarked that more consumption of renewable energy does not influence CO_2 emission levels, human capital development reduces CO_2 emission levels, and globalization boosts CO_2 emission levels in China. Similarly, using Chinese data from 1980 to 2018, Zeraibi et al. (2022) also found statistical evidence regarding the invalidity of the CO_2 emission-related EKCH. Notably, the authors mentioned that the economic progress–CO_2 emissions nexus rather depicts an N-shaped relationship in the context of China. Furthermore, the authors asserted that expansionary monetary and fiscal policies pursued by the Chinese government respectively exert inhibiting and boosting impacts on the nation's short- and long-run annual per capita CO_2 emission levels. On the other hand, Naminse and Zhuang (2018) concluded that intensification of energy use is responsible for amplifying the annual CO_2 emission figures of China. In addition, the results validated the authenticity of the EKCH by statistically verifying the inverse U-shaped association between China's economic progress and its annual discharges of CO_2.

Considering similar studies that have featured the United States, the empirical work conducted by Pata (2021) verified the validity of the CO_2 emission-related EKCH for this highly polluted developed nation. In addition, the results affirmed that renewable energy employment and globalization activities are conducive to reducing annual CO_2 emission figures in the United States while non-renewable energy consumption imposes environmental complications. Besides, considering annual data from 1980 to 2016, Dogan and Turkekul (2016) argued that economic progress initially declines CO_2 emissions but later on amplifies the emission figures in the United States; consequently, the findings confirmed a U-shaped association between these variables whereby the EKCH could not be statistically verified. Moreover, other key findings from that study showed that in the long-run more energy consumption leads to higher discharges of CO_2

while urbanization was also evidenced to exert a similar environmental quality-degrading impact. Contrarily, international trade activities were associated with lower annual discharges of CO_2 in the United States. In another recent study by Alola and Ozturk (2021), the authors found statistical support validating the CO_2 emission-related EKCH for the case of the United States. In addition, the results revealed that consuming renewable energy resources induces environmental improvements in the United States by reducing the nation's annual CO_2 emission levels, both in the short and long run.

Several existing studies have also documented mixed findings regarding the validity of the carbon emission-related EKCH in the context of the developing economy of India. Among these, Danish et al. (2021) used Indian data for the period 1971–2018 and reported evidence that economic progress at first induces a trade-off between economic well-being and environmental distress (in the form of more CO_2 emissions), but eventually, this trade-off is phased out whereby economic progress and environmental improvement (in the form of lower CO2 emissions) take place simultaneously. Thus, the CO_2 emission-related EKCH was found to hold for the case of India. Besides, the results confirmed that the consumption of nuclear energy, which is a clean energy source, is conducive to mitigating India's annual discharges of CO2 in the long run. Accordingly, based on this particular finding, the authors pointed out that using nuclear energy instead of conventional fossil fuels helps in validating the authenticity of the EKCH in India's context. Similarly, Sinha and Shahbaz (2018) verified the CO_2 emission-related EKCH for India by considering data from 1971 to 2015. Furthermore, the authors highlighted that renewable energy consumption assists in mitigating India's annual CO_2 emission levels while a rise in the total energy consumption level was evidenced to boost the nation's long-run emission figures. Contrastingly, in another study conducted by Itoo and Ali (2023), the authors considered Indian data between the period 1980–2018 but could not validate the CO_2 emission-related EKCH. Besides, the other major findings from that study portrayed that population boom and more consumption of energy boost CO_2 emissions in India, while natural resource utilization, remittance receipts, and industrialization help in reducing the nation's annual long-run CO_2 emission figures.

Next, among the existing studies exploring the validity of the CO_2 emission-related EKCH in the context of Russia, Liu et al. (2023) considered annual data from 1995 to 2020 and found that the CO2 emission-related EKCH was valid. In addition, the authors concluded that infrastructure development and international trade participation exert adverse environmental consequences in Russia. Likewise, Yang et al. (2017) statistically verified the authenticity of the EKCH concerning CO_2 emissions in Russia. However, the authors expressed deep concerns regarding the issue that Russia was yet to achieve the threshold level of economic progress (i.e., the turning point of the environmental Kuznets curve) required for offsetting the adverse environmental impacts associated with economic progress. Lastly, in the context of Japan, Wang et al. (2023) used annual data from 1995 to 2020 and found the CO_2 emission-related EKCH to hold in the long run. Further, the authors mentioned that investment in the development of roads, railways, and aviation in Japan creates environmental problems by boosting the nation's annual CO_2 emission figures. Moreover, it was found that involvement in international trade and receipts of foreign direct investments impose environmental quality-degrading impacts in Japan. Likewise, Adebayo et al. (2021) also statistically confirmed the existence of the CO_2 emission-related EKCH for the case of Japan. Besides, the authors emphasized that the fossil fuel-intensive structure of the Japanese energy sector is largely responsible for environmental adversities experienced by this developed nation. Notably, the authors asserted that more consumption of natural gas, coal, and oil within the Japense economy contributes to higher discharges of CO_2 in the long run. On the other hand, using data from 47 prefectures in Japan, Ito (2021) concluded that economic progress monotonically amplifies CO_2 emission levels whereby the validity of the EKCH could not be verified.

Therefore, it is quite obvious that prior studies have not adequately emphasized the pertinence of reducing the growth rate of CO_2 emissions under the theoretical framework of the EKCH. Mostly, these studies emphasized the need for reducing the annual volume of CO_2 discharges while overlooking the issue of reducing the emission growth rates. Nevertheless, persistently reducing the annual rate of growth in CO_2 emissions is of critical importance so that the global net zero agenda can be realized at the earliest. Besides, it is also apparent that the previous studies have predominantly looked into the environmental effects linked with renewable energy use while a few of the existing studies explored the energy intensity–environmental quality nexus for the concerned highly polluted countries. Accordingly, this study identifies these major gaps in the extant literature and aims to bridge them.

Methodology

Model specifications

Although most empirical studies explore the EKCH considering environmental quality as a quadratic function of economic progress, in recent times, such an approach has been criticized (Murshed et al. 2022). Nevertheless, we check the authenticity of the EKCH using a linear model; however, we predict this model inter-temporarily to check how economic progress affects environmental quality over the short and long run. Notably, the EKCH can be deemed valid if in the short-run economic progress degrades the quality of the environment while in the long-run it promotes environmental well-being. Accordingly, the baseline model considered in this study is shown as follows:

$$\textbf{Model 1}:\ \underbrace{\text{CO2GR}_{i,t}}_{\text{Environmental Impact}} = \partial_0 + \underbrace{\partial_1\text{RYGR}_{i,t}}_{\text{Economic Effect}} + \underbrace{\partial_2\text{LnEINT}_{it} + \partial_3\text{RECS}_{i,t}}_{\text{Energy sector's Effect}} + \varepsilon_{i,t} \quad (1)$$

In Model 1, the dependent variable CO2GR abbreviates for the annual growth rate of per capita CO_2 emissions which is used as the proxy variable for calibrating environmental quality. Since establishing environmental sustainability requires reducing the CO_2 emission growth rate, negative signs of the predicted parameters ∂_1,∂_2, and ∂_3 would implicate environmental welfare-improving impacts of economic progress, energy intensity, and renewable energy use, respectively. Conversely, positive signs of these predicted parameters would implicate environmental welfare-declining impacts. Among the independent variables, RYGR stands for annual growth rate of per capita real gross domestic product (GDP) which is considered as a proxy for measuring the extent of economic progress in the concerned nations. If economic progress involves the expansion of unclean economic activities, it can be assumed to exert negative environmental consequences whereby the growth rate of annual per capita CO_2 emissions can be expected to rise and the predicted parameter ∂_1 is likely to show a positive sign. On the other hand, economic progress resulting from clean economic activities can be assumed to induce environmental betterment whereby the growth rate of annual per capita CO_2 emissions may decline and the predicted parameter ∂_1 is likely to show a negative sign.

The other two independent variables LnEINT and RECS are the two energy sector-related factors that are anticipated to influence environmental quality. Firstly, the variable LnEINT is the natural logarithm level of energy intensity which indicates the level of energy intensiveness of economic output produced in the concerned nations. Notably, a rise in the level of energy intensity would imply that more energy is being required for producing a solitary unit of economic output and vice-versa. Since more use of energy can be linked with greater atmospheric discharges of energy-related CO_2 emissions, a rise in the energy intensity level can be assumed to boost the annual growth rate of per capita CO_2 emissions in the concerned nations. Consequently, the predicted parameter ∂_2 is likely to depict a positive sign. Contrarily, making productive (less-intensive) use of energy could make sure that less energy resources are used for producing economic output whereby the adverse environmental consequences associated with energy use are likely to be contained. As a result, the predicted parameter ∂_2 is likely to depict a negative sign. Secondly, the variable RECS stands for renewable energy's share in the national energy consumption portfolio of the respective nations. This variable is used as a proxy for denoting the extent of fossil fuel intensiveness of the energy sectors of the concerned nations; notably, the lower the share the greater the fossil fuel dependency and vice-versa. Since renewable energy is relatively cleaner than fossil fuels, a rise in this share can be assumed to reduce energy-related atmospheric discharges of CO_2. Consequently, the sign of the predicted parameter ∂_2 is likely to be negative.

Further, to check whether the impact of economic progress on environmental conditions is indirectly influenced (i.e., mediated/moderated) by the energy sector, the joint environmental impacts of energy intensity and economic progress and those associated with renewable energy use and economic progress are explored using the following models:

$$\textbf{Model 2}:\ \underbrace{\text{CO2GR}_{i,t}}_{\text{Environmental Impact}} = \partial_0 + \underbrace{\partial_1\text{RYGR}_{i,t}}_{\text{Economic Effect}} + \frac{\partial_2\text{LnEINT}_{it} + \partial_3\text{RECS}_{i,t}}{\text{Energy sector's Effect}} + \underbrace{\beta_1(\text{RYGR}_{i,t} * \text{LnEINT})}_{\substack{\textit{Economic and Energy sector's} \\ \textit{joint Effect}}} + \varepsilon_{i,t} \quad (2)$$

In Model 2, the variable RYGR*LnEINT is added to the baseline for checking how intensification of energy use influences the economic progress–CO_2 emissions growth rate nexus, which is to be ascertained from the sign of the predicted parameter β_1. Theoretically, if the energy intensity level rises, then economic activities are likely to become more pollution-intensive. Accordingly, the growth rate of per capita CO_2 emissions can go up and the sign of β_1 is likely to be positive. Alternately, less intensive use of energy resources can be expected to make economic output relatively less pollution-intensive whereby the growth rate of per capita CO_2 emissions can decline and the sign of β_1 is likely to be negative.

$$\textbf{Model 3}:\ \underbrace{\text{CO2GR}_{i,t}}_{\text{Environmental Impact}} = \partial_0 + \underbrace{\partial_1\text{RYGR}_{i,t}}_{\text{Economic Effect}} + \underbrace{\partial_2\text{LnEINT}_{it} + \partial_3\text{RECS}_{i,t}}_{\text{Energy sector's Effect}} + \underbrace{\beta_2(\text{RYGR}_{i,t} * \text{RECS})}_{\substack{\textit{Economic and Energy sector's} \\ \textit{joint Effect}}} + \varepsilon_{i,t} \quad (3)$$

Similarly, in Model 3, the variable RYGR*RECS is added to the baseline model for checking how refraining from consuming fossil fuels and utilizing renewable energy instead influences the economic progress–CO_2 emissions growth rate nexus, which is to be ascertained from the sign of the predicted parameter β_2. Notably, reducing fossil fuel dependency is also likely to make economic activities less pollution-intensive. Consequently, more production of renewable energy use-led economic output can reduce the annual growth rate of per capita CO_2 emissions whereby the sign of the parameter β_2 is likely to be negative.

Data and sources

Based on data availability, the empirical analysis to be conducted in this study involves the use of annual frequency panel data from 1990 to 2021. However, the issue of missing data points is resolved using the linear interpolation method. The units of the variables CO2GR, RYGR, and RECS are in terms of percentage while the variable LnEINT is measured in terms of megajoules per 2017 Purchasing Power Parity (PPP) United States dollars. Data concerning all variables are acquired from the World Bank's World Development Indicators database (World Bank 2023). Fig. 1 presents the 5-year average trends in the changes in the annual growth rate of per capita CO_2 emissions in the five most-polluted nations considered in this study. It is evident that among the selected nations, the average annual growth rates of per capita CO_2 emission of China and India have never been negative during the period from 1990 to 2021. Besides, it is also observed that collectively the average annual growth rates of per capita CO_2 emissions of the five concerned nations (as indicated by the green line plot) display a downward trend from the period 2002–2005 onwards. However, given the understanding that the annual CO_2 discharges of these nations have persistently grown over time (World Bank 2023), the downward trend shown in Fig. 1 is most likely to be influenced by the high population growth rates of these nations.

Estimation procedure

Since panel data-related analysis requires checking whether the data set being utilized is free from slope heterogeneity (SLHET) and cross-sectional dependency (CRSD), the forthcoming pre-estimation tests are performed. First, using the method proposed by Pesaran (2021), the data set is tested for CRSD-related concerns. In this test, for each variable, a test statistic is predicted to test the null hypothesis of independent cross-sectional units (Gao et al. 2023). Hence, if any of the predicted test statistics is found to be statistically significant, then the issue of CRSD can be confirmed. Second, employing the method introduced by Pesaran and Yamagata (2008), the data set is tested for SLHET-related concerns. In this estimation technique, for each of the three models considered in this study, two test statistics are estimated to test the null hypothesis of homogeneous slope coefficients across all cross-sectional units (Li et al. 2023). In this regard, the statistical significance of either of the two test statistics shall affirm the problem of SLHET. Table 1 displays the results from these two tests whereby it can be observed that both issues of CRSD and SLHET exist in the data used in this study.

Table 1 Results from CRSD and SLHET tests

Pesaran's (2021) test (null hypothesis: cross-sectional independence)				
Variable	CO2GR	RYGR	LnEINT	REC
Test Statistic	−0.910	1.618	4.639***	−0.932
Probability	0.363	0.105	0.000	0.351
Existence of CRSD	No	No	Yes	No
Pesaran and Yamagata's (2008)test (null hypothesis: homogeneous slope coefficients)				
Model	Model 1	Model 2	Model 3	
Delta statistic	6.905***	5.463***	6.984***	
Probability	0.000	0.000	0.000	
Existence of SLHET	Yes	Yes	Yes	
Adjusted delta statistic	7.517***	6.061***	6.750***	
Probability	0.000	0.000	0.000	
Existence of SLHET	Yes	Yes	Yes	

***Statistical significance at 1% level

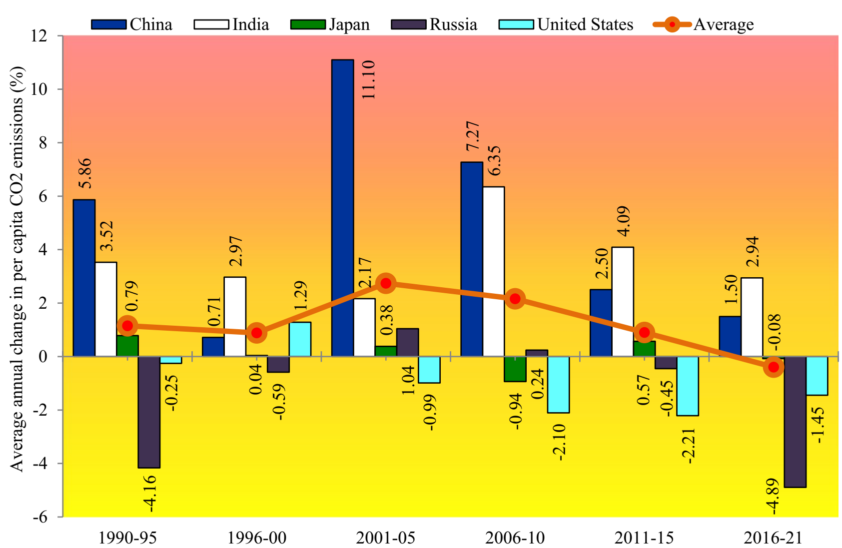

Fig. 1 Period-wise trends in the changes in the annual growth rates of per capita CO2 emissions. Source: World Bank (2023)

Following the pre-estimation tests, the next step involves assessing whether the concerned variables suffer from problems related to unit root (non-stationarity). Conducting this test is important because it allows checking whether the respective data series of the variables revert to their mean values. If there is the presence of a unit root, the associated variable is said to be non-stationary whereby regression outcomes generated using this variable can be deemed spurious (Verbič et al. 2022; Ahmad and Satrovic 2023). In this regard, using the approach put forward by Pesaran (2007), two panel unit root tests are conducted: (a) cross-sectionally adjusted augmented Dickey–Fuller (CRSADF) and (b) cross-sectionally adjusted Im–Pesaran–Shin (CRSIPS). Both these techniques are adept in neutralizing the impacts of CRSD in the data and predicting a single test statistic for each variable in order to test the null hypothesis that the series of the variable in question is not stationary (i.e., it has a unit root problem) (Ozturk et al. 2019; Usman et al. 2023). Subsequently, the next step involves examining whether the concerned variables included in the empirical models have long-run associations or not. This is important since without the existence of such associations, predicting the long-run marginal impacts of the independent variables on the dependent variable is not theoretically appropriate. Accordingly, using the method suggested by Westerlund (2007), the panel cointegration analysis is conducted. Under this method, which effectively neutralizes the impacts of CRSD and SLHET, four test statistics are predicted for testing the null hypothesis that no cointegrating association exists among the model's variables.

Once the unit root and cointegration tests are performed, the next estimation step involves predicting the short- and long-run marginal impacts of economic progress, energy intensification, and renewable energy consumption on the annual growth rate of per capita CO_2 emissions in the selected most-polluted nations. In this regard, the cross-sectional autoregressive distributed lag (CRS-ARDL) panel regression method of Chudik et al. (2016) is used in this study. According to Azam et al. (2022), the CRS-ARDL method is superior compared to the conventional panel pooled mean group-autoregressive distributed lag (PMG-ARDL) estimator when the issues of CRSD and SLHET exist in the data. Besides, the CRS-ARDL technique is ideal for handling panel data sets with time dimensions within the range from 30 to 50 (Chudik et al. 2016). Hence, this regression technique suits the data set used in this study which considers annual data from 1990 to 2021. Another major advantage of this method is that it can predict both the short- and long-run effects (Mehmood 2022; Khan et al. 2023) and it is also effective in handling models containing variables with a mixed integration order up to a maximum of the first difference (Khan et al. 2023; Usman et al. 2023).

Notably, the issues of CRSD and SLHET are neutralized within the CRS-ARDL regression analysis by including one-period lagged cross-sectional averages of the explanatory variables as additional regressors within the conventional ARDL model (Azam et al. 2022; Khan et al. 2023). Regarding our baseline model (i.e., Model 1), it can be shown using CRS-ARDL model specifications as follows:

$$\mathrm{CO2GR}_{i,t} = \sum_{j=1}^{p} \delta_{ij}\mathrm{CO2GR}_{i,t-j} + \sum_{j=1}^{q} \gamma_{ij}\mathrm{RYGR}_{i,t-j} + \sum_{j=1}^{r} \varnothing_{ij}\mathrm{LnEINT}_{i,t-j} + \sum_{j=1}^{s} \vartheta_{ij}\mathrm{RECS}_{i,t-j} + \underbrace{\sum_{j=1}^{t} \sigma_{ij}\overline{Z}_{t-1}}_{\substack{cross-sectional\ averages \\ of\ regressors}} + \omega_{i,t} + \mu_{i,t} \quad (4)$$

In Eq. 4, $\overline{Z}_{t-1}$ represents the one-period lagged cross-sectional averages of the explanatory variables [i.e., $\overline{Z}_{t-1} = (\overline{CO2GR}_{i,t-j}, \overline{RYGR}_{i,t-j}, \overline{LnEINT}_{i,t-j}, \overline{RECS}_{i,t-j})$]. Furthermore, for checking the robustness of the regression outcomes using an alternative estimator, the regression analysis is also performed using the conventional panel PMG-ARDL regression technique.

Finally, the panel causality analysis is performed using the method proposed by Dumitrescu and Hurlin (2012) which is adept at handling the issues of CRSD and SLHET in the data. Notably, this causality estimator neutralizes the impacts of CRSD by using a bootstrapping approach. On the other hand, it neutralizes the impacts of SLHET by confirming causal relationships between a pair of variables if it is found for at least one of the cross-sectional units. In contrast, the conventional panel causality estimation techniques endorse causality only if it exists for all cross-sectional units. For detecting causation, a test statistic is estimated for testing the null hypothesis that the independent variable does not Granger cause the dependent variable (Caglar et al. 2022).

Results and discussions

The findings from panel unit root analysis, conducted using the CRSADF and CRSIPS tests of Pesaran (2007), are displayed in Table 2. Considering the CRSADF test's outcomes, it is evident that neither of the variables is stationary at the level while all variables are stationary at the first difference. Thus, these outcomes endorse a common integration order among the concerned variables. However, considering the CRSIPS test's outcomes, the common integration order among the variables cannot be established. Notably, it is evident that the variable RYGR is stationary both at the level and the first difference while the other variables are stationary at the first difference. Nevertheless, the findings from both these panel unit root tests certify that all concerned variables are stationary, albeit in a mixed order, whereby using these variables for performing regression analysis is not likely to generate spurious outcomes.

Table 2 Results from panel unit root tests

Variable	CO2GR	ΔCO2GR	RYGR	ΔRYGR	LnEINT	ΔLnEINT	RECS	ΔRECS
Pesaran's (2007) CRSADF test (null hypothesis: series is not stationary)								
t-bar statistic	−2.294	−5.777***	−2.305	−6.011***	−1.637	−3.979	−1.294	−3.371***
Prob	0.547	0.000	0.535	0.000	0.963	0.000	0.996	0.004
Stationary	No	Yes	No	Yes	No	Yes	No	Yes
Pesaran's (2007) CRSIPS test (null hypothesis: series is not stationary)								
Test statistic	−2.681	−3.217***	−3.815***	−6.011***	−1.411	−3.979***	−1.150	−3.371
Stationary	No	Yes	Yes	Yes	No	Yes	No	Yes

Δ = first difference

***Statistical significance at 1% level

Table 3 Results from panel cointegration analysis

Westerlund's (2007) test (null hypothesis: variables are not cointegrated)				
Model	Model 1	Model 2	Model 3	Cointegrated
Gt statistic	−5.088***	−5.692***	−4.592***	Yes
Probability	0.000	0.000	0.000	
Ga statistic	−28.462***	−22.677***	−23.081***	Yes
Probability	0.000	0.000	0.000	
Pt statistic	−10.372***	−10.450***	−8.813***	Yes
Probability	0.000	0.000	0.000	
Pa statistic	−26.191***	−20.418***	−20.120***	Yes
Probability	0.000	0.000	0.000	

Bootstrapped replications = 10,000

***Statistical significance at 1% level

Table 3 displays the findings from the panel cointegration analysis that is conducted using the test proposed by Westerlund (2007). It is evident from the reported results that in all three models the concerned variables have cointegrating relationships. As a result, it is now appropriate to predict the long-run marginal impacts of economic progress, energy intensification, and renewable energy use on the annual growth rate of per capita CO_2 emissions in the selected most-polluted economies.

The short- and long-run marginal effects, derived using the CRS-ARDL panel regression estimator of Chudik et al. (2016), are displayed in Table 4. Firstly, considering the estimates for all three models, it is observed that both in the short and long run, economic progress is associated with environmental adversities. The corresponding elasticity estimates show that a 1% rise in the per capita real GDP growth rate of the concerned nations leads to a rise in their growth rate of per capita CO_2 emissions by around 0.35–0.44% in the short run and by around 0.09–0.19% in the long run. Therefore, these findings suggest that the initial environmental adversities linked with economic progress are not phased out later on for ensuring a complementary relationship between economic progress and environmental well-being. However, since the long-run effects are relatively smaller, it can be said that along with time as the concerned economies continue to expand, the negative environmental impacts associated with economic progress tend to decline in relative terms. Consequently, it can be asserted that economic activities in the concerned nations tend to become relatively cleaner over time. On that note, the EKCH can be deemed partially valid which corroborates the findings reported by Pata (2021) in the context of the United States.

Secondly, the results endorse that in the long-run if energy resources are intensively utilized (i.e., not efficiently used), adverse environmental consequences take place. Specifically, a rise in the energy intensity level by 1% is observed to amplify the annual growth rate of per capita CO_2 emissions on average by 0.82–1.10%. By contrast, the corresponding short-run impact of energy intensification on the environment is statistically inconclusive. Arguably, the long-run result might be justified because the nations under consideration have traditionally been highly reliant on fossil fuels, whereby a rise in their energy intensity rates is likely to trigger higher demand for energy resources. Under such circumstances, assuming the population growth rates in the concerned nations to be more or less constant, the rise in energy intensity levels is likely to amplify their energy demands which, in turn, may enhance the growth rates of their energy-related CO_2 emissions. Hence, this finding stresses the relevance of making energy utilization processes productive

Table 4 Results from Chudik et al.'s (2016) CRS-ARDL panel regression analysis

Dep. variable: CO2GR			
Model	Model 1	Model 2	Model 3
Short-run results			
RYGR	0.353***	0.386***	0.439**
	(0.029)	(0.034)	(0.220)
LnEINT	1.947	1.705	2.518
	(3.269)	(4.419)	(4.168)
RECS	−2.103***	−2.540**	−3.033***
	(0.761)	(0.986)	(1.085)
RYGR*LnEINT		0.071	
		(0.089)	
RYGR*REC			0.076
			(0.084)
Long-run results			
RYGR	0.152***	0.091**	0.194***
	(0.005)	(0.045)	(0.027)
LnEINT	0.895***	0..821***	1.100**
	(0.370)	(0.337)	(0.554)
RECS	−0.953***	−1.116**	−1.313***
	(0.341)	(0.433)	(0.470)
RYGR*LnEINT		0.038**	
		(0.019)	
RYGR*REC			−0.034**
			(0.016)
ECT(-1)	−0.854***	−0.799***	−0.773***
	(0.112)	(0.080)	(0.077)
Observations	155	155	155

ECT(-1) one-period lagged error-correction term

Standard errors are shown inside ()

***Statistical significance at 1% level

**Statistical significance at 5% level

so that the energy sector-related CO_2 emissions can be effectively contained on a long-term basis. Similarly, Naminse and Zhuang (2018) concluded that the energy-intensive structure of the Chinese energy sector is largely responsible for the persistent rise in the nation's annual discharges of CO_2.

Thirdly, the findings shown in Table 4 reveal that withdrawing from fossil fuel consumption and adopting renewable energy instead can be a credible move towards establishing environmental sustainability within the concerned nations. Specifically, the predicted elasticity parameters portray that if renewable energy additionally acquires a 1% share in the national energy portfolio (implicating that the corresponding fossil fuel share would decline by 1%), the annual growth rate of per capita CO_2 emissions shall decline by around 2.10–3.03% and 0.95–1.31% in the short and long run, respectively. These findings are pretty much in line with the related theories postulating the relevance of amplifying clean energy usage in containing anthropogenic discharges of CO_2 into the atmosphere. However, an alarming issue that is showcased by the corresponding short- and long-run findings is that over time the favorable environmental quality-improving effects of renewable energy adoption are not sustained. This statement is verified by the finding that the predicted long-run elasticities are comparatively lower than the short-run elasticities. Although this finding is not in line with establishing environmental sustainability on a long term basis, this particular result is somewhat expected since the respective shares of renewables in the national energy mixes of the selected nations have rather declined instead of exhibiting a rising trend over the last couple of decades (World Bank 2023). Nevertheless, similar studies have also highlighted the critically important role of undergoing the renewable energy transition for safeguarding the well-beings of environmental traits (Hamid et al. 2023; Pata 2021; Alola and Ozturk 2021).

Now, particularly focusing on the CRS-ARDL outcomes related to Models 2 and 3, it is apparent that only in the long run the predicted elasticity parameters associated with the interaction terms RYGR*LnEINT and RYGR*RECS are statistically significant with positive and negative signs, respectively. Hence, it can be said that in the long run, the environmental impacts of economic progress are conditional on the intensity level of energy utilization and the extent of renewable energy adoption. Firstly, in the context of Model 2, the positive sign of the estimated parameter concerning the interaction term RYGR*LnEINT implies that jointly both economic progress and intensification of energy use impose detrimental impacts on the environment. This finding is of critical relevance since it highlights the fundamental issue that if economic activities are performed using energy-intensive mechanisms, the overall energy demand can be expected to rise, which, in turn, may amplify the annual growth rate of CO_2 discharges in the concerned nations. As a result, this finding further endorses the necessity of making productive use of energy resources for ensuring a simultaneity between economic progression and environmental development. Moreover, by considering this finding, it can be argued that the economic progress–environmental quality nexus in the concerned economies is moderated by their respective rates of energy intensity.

Secondly, in the context of Model 3, the negative sign of the estimated parameter associated with the interaction term RYGR*RECS suggests that collectively making use of clean energy resources and producing economic output with these resources can assist in establishing a sustainable environment in the concerned nations. This is an expected finding since renewable energy resources are usually not composed of hydrocarbons, and therefore, their carbon footprints are significantly lower compared with the carbon footprints of fossil fuels. Nevertheless, this finding can be deemed important from a couple of perspectives. For instance, it highlights the core issue that by not employing fossil fuels and adopting renewable energy instead, it is possible to partially offset the trade-off between economic progression and environmental degradation. Besides, it is also evident that the economic progress-environmental condition nexus in the concerned nations is moderated by their respective shares of renewables in the national energy consumption profiles. Accordingly, it is pertinent for these nations to green their energy sectors by gradually, albeit effectively, reducing fossil fuel reliance.

Further, for assessing whether the outcomes generated from the CRS-ARDL regression technique are robust when the PMG-ARDL method is used as the alternative estimator, the models are re-estimated using the conventional regression technique. The results from this robustness analysis are displayed in Table 5. It is evident that although the signs of the predicted elasticity parameters coincide with the corresponding signs of parameters derived from the CRS-ARDL analysis, the results differ in terms of statistical significance. Notably, in most cases, it found that the PMG-ARDL analysis led to the estimation of statistically insignificant elasticity parameters whereby it is difficult to judge the marginal impacts of economic progress, energy intensification, and renewable energy use on the annual growth rates of per capita CO_2 emissions in the concerned nations. However, since the PMG-ARDL method is not ideally suited to neutralizing the impacts of CRSD and SLHET in the data (Azam et al. 2022), the predicted regression outcomes reported in Table 5 can be deemed biased, to some extent. Accordingly, the outcomes derived from the CRS-ARDL analysis can be considered for designing CO_2 emission growth rate-inhibiting policies in these nations.

Lastly, the causal relationships among the variables of concern are tested by performing the panel causality analysis suggested by Dumitrescu and Hurlin (2012). The corresponding causality-related findings are displayed in Table 6. Overall, it is found that there is no reverse causality/bidirectional causality among the concerned variables whereby the endogeneity concerns can be ruled out to a large extent. Notably, the causality findings support the regression findings derived from the CRS-ARDL analysis (shown in Table 4) by statistically endorsing the presence of unidirectional causalities running from economic progress, energy intensification, and renewable energy use to annual growth rate of per capita CO_2 emissions.

Table 5 Results from robustness analysis conducted using the PMG-ARDL regression technique

Dep. variable: CO2GR			
Model	Model 1	Model 2	Model 3
Short-run results			
RYGR	0.090	0.134	0.032
	(0.086)	(0.105)	(0.043)
LnEINT	0.875	0.828	1.050
	(0.599)	(0.692)	(0.800)
RECS	−0.343***	−0.634***	−0.797***
	(0.031)	(0.023)	(0.032)
RYGR*LnEINT		−0.079	
		(0.062)	
RYGR*REC			−0.010
			(0.011)
Long-run results			
RYGR	1.418**	1.261***	1.782***
	(0.710)	(0.326)	(0.617)
LnEINT	1.276	4.375	2.279
	(5.348)	(4.094)	(2.374)
RECS	−4.520***	−4.899***	3.297***
	(0.967)	(1.435)	(0.787)
RYGR*LnEINT		0.365	
		(0.265)	
RYGR*REC			−0.511
			(0.518)
ECT(-1)	−0.268*	−0.304**	−0.280*
	(0.146)	(0.152)	(0.151)
Observations	155	155	155

ECT(-1) one-period lagged error-correction term; standard errors are shown inside ()

***Statistical significance at 1% level

**Statistical significance at 5% level

*Statistical significance at 10% level

Conclusion and policy implications

Collectively contributing to more than half of the global discharges of CO2 in 2020, the World Bank has categorized China, United States, India, Russia, and Japan as the five topmost polluted economies in the world. As a result, impeding the CO_2 emission-led environmental adversities in these countries is deemed critically important for establishing

Table 6 Results from Dumitrescu and Hurlin's (2012) panel causality analysis

Null hypothesis	*t*-bar statistic	Probability	Decision
RYGR ≠ CO2GR	4.438***	0.000	Unidirectional causality
CO2GR ≠ RYGR	1.329	0.079	RYGR → CO2GR
LnEINT ≠ CO2GR	7.468***	0.000	Unidirectional causality
CO2GR ≠ LnEINT	0.149	1.000	LnEINT → CO2GR
RECS ≠ CO2GR	7.098***	0.000	Unidirectional causality
CO2GR ≠ RECS	1.001	0.132	RECS → CO2GR

≠ does not Granger causes

Bootstrapped replications = 10,000

***Statistical significance at 1% level

environmental sustainability worldwide. In this regard, this study checked how economic progress, energy use intensification, and renewable energy use affect the annual growth rates of per capita CO_2 emissions in the abovementioned countries considering the analysis period from 1990 to 2021. Besides, for analytical purposes, advanced panel data estimation techniques have been utilized for detecting and neutralizing the impacts of CRSD and SLHET-related problems in the data. Overall, the findings endorsed that both in the short and long run, economic progress deteriorates environmental quality. Nevertheless, due to the unfavorable environmental impacts in the long-run outweighed the corresponding short-run impacts, the EKCH was verified. Besides, more intensive use of energy resources was evidenced to impose negative long-run environmental consequences while the adoption of renewable energy instead of fossil fuels was evidenced to improve environmental well-being, both in the short and long run. Furthermore, the results affirmed that in the long-run economic progress and energy use intensification jointly degrade environmental conditions. By contrast, economic progress alongside greater adoption of renewable energy, in the long run, was seen to exert an environmental quality-improving effect.

Considering these key findings, there is no alternative other than greening economic activities in the concerned nations. However, achieving environmentally friendly economic growth is likely to be difficult given the understanding that these nations are still vastly reliant on fossil fuels and their respective renewable energy sectors are yet to be adequately develop. Thus, proactive initiatives are required so that the underdeveloped renewable energy sectors are developed at the earliest which, in turn, necessitates technological innovation relevant for generating power using primary renewable energy inputs. Thus, greening economic progress is conditional on the amplification of renewable electricity generation capacities in the concerned economies which can not only guarantee energy security but also make sure that the associated environmental hardships are contained over time. In addition, it is also pertinent to invest in the development of technologies relevant for carbon sequestration and carbon capture which can further prevent atmospheric discharges of CO_2.

Furthermore, enhancing energy productivity (i.e., reducing energy intensity) is of paramount significance in improving environmental quality in these countries. However, in this regard, it is essential to ensure that the energy rebound effect of energy efficiency improvement does not take place. Notably, since the energy rebound effect-related concerns can undermine the efficacy of energy efficiency improvement initiatives in controlling atmospheric discharges of CO_2, monitoring energy demand during the post-energy efficiency improvement phase is absolutely crucial. Accordingly, the replacement of energy-intensive consumer durables with energy-efficient alternatives is required, as well. At the same time, behavioral changes are also needed to refrain from undue wastage of electric power, especially by switching off power supplies following evacuation from buildings. This, in turn, obligates the introduction of awareness-building programs that can educate energy consumers regarding the adversities linked with energy use, especially those associated with unnecessary utilization of electric power.

Data unavailability is a concerning limitation experienced while conducting this study whereby the empirical analysis could not control for some critically important macroeconomic factors. Besides, due to this study focusing on only the top five most polluted economies in the world, it is unclear whether expanding the sample of countries would alter the findings. Thus, future studies can look to address these limitations and conduct similar empirical exercises using different samples of countries for testing the overall reliability of this study's findings.

Authors' contributions AKMAR, JCG, and MM conceptualized, wrote the original draft, wrote the revised draft, and conducted the analysis. HM compiled the literature review and generated the graphical illustrations, and reviewed and edited the final draft. DB supervised, compiled data, and wrote the original draft. MEH compiled the literature review, conducted the econometric analysis, and contributed to the methodology section.

Funding This study is supported via funding from Prince Sattam bin Abdulaziz University project number PSAU/2023/R/1444.

Data availability Data sources are mentioned in the text.

Declarations

Ethics approval This is not applicable.

Consent to participate This is not applicable.

Consent for publication This is not applicable.

Competing interests The author declares no competing interests.

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