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# Does income inequality reshape the environmental Kuznets curve (EKC) hypothesis? A nonlinear panel data analysis

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## ABSTRACT

The COVID-19 pandemic has further increased income inequality. This work is aimed to explore the impact of income inequality on the environmental Kuznets curve (EKC) hypothesis. To this end, income inequality is set as the threshold variable, economic growth is set as the explanatory variable, while carbon emission is set as the explained variable, and the threshold panel model is developed using the data of 56 countries. The empirical results show that income inequality has changed the relationship between economic growth and carbon emissions from an inverted U-shaped to an N-shaped, which means that income inequality redefines the environmental Kuznets curve and increases the complexity of the decoupling of economic growth and carbon emissions. Specifically, economic growth significantly increases carbon emissions during periods of low income inequality, however, as income inequality increases, economic growth in turn suppresses carbon emissions. In the period of high income inequality, economic growth inhibits the increase of carbon emissions. However, with the increase of income inequality, the impact of economic growth on carbon emission changes from inhibiting to promoting. Panel regressions for robustness tests show that this phenomenon is more pronounced in high-income countries. We therefore contend that the excessive income inequality is bad for the win-win goal of economic growth without carbon emission growth, and the income distribution policy should be included in the carbon neutral strategy.

## 1. Introduction

In response to the frequent occurrence of extreme weather, the “Paris Agreement” sets out the goal of keeping the global average temperature rise below 2 °C over pre-industrial times, with efforts to limit the temperature increase to 1.5 °C. We are facing the twin challenges of economic development and environmental quality. Over the last few decades, the dynamic link between economic growth and environmental quality has been extensively and deeply studied by scholars (Cole et al., 1997; Kais and Sami, 2016; Van Hoa and Limskul, 2013; Zafar et al., 2019). The economist Kuznets first proposed the Kuznets curve back in the 1950s (Kuznets, 1955). Grossman and Krueger (1991) was one of the first scholars to study the link between environmental pollution and economic growth. They found that for both pollutants (sulfur dioxide and “smog”), at lower levels of national income, the concentrations of both pollutants increased with per capita GDP, but decreased with per capita GDP at higher income levels. Panayotou (T., 1993) further

confirmed the inverted “U” curve between environmental degradation and income. Thus, the relationship between environment and income was formally recognized for the first time as the Environmental Kuznets Curve (EKC). The EKC scenario shows an inverse u-shaped correlation in the quality of the environment and economic growth. With the growth of income, carbon emissions will grow up to a certain income “threshold” (tipping point), and then carbon emissions will tend to decrease. Empirical studies about the relationship between carbon emissions and economic growth under the EKC hypothesis has been a research hotspot for more than two decades (Balsalobre-Lorente et al., 2018; Ben Cheikh et al., 2021; Lean and Smyth, 2010; Selden and Song, 1994) (Stern, 2004).

However, few of these studies reassess the EKC hypothesis from the perspective of other social factors. Although the macroeconomic variables in modern society show different characteristics, they influence each other and permeate each other. This mutual influence gradually complicates the relationship between economic growth and

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environmental quality, i.e., it may depend on other variables that require further study. In other words, it is necessary to re-examine the EKC hypothesis formed by the overlapping of scale effect, technology effect and structure effect from the perspective of other social factors. Previous studies have used advanced experimental methods to measure the growth of particles that may contribute to carbon emissions, and these studies have examined the factors that influence urban ambient air quality and global climate at the microscopic level (Chen et al., 2018; Li et al., 2022c).

On the other hand, some figures clearly reflect the dramatic effects of the COVID-19 pandemic: The death toll has exceeded 3.1 million and the number continues to grow, with 120 million people in acute poverty, in addition to the large-scale worldwide economic depression that began in the wake of the COVID-19 pandemic. Along with the increase in suffering and poverty, some figures reveal an expansion of riches at the other pole: the billionaires' wealth. Along with the increase in extreme poverty and billionaire wealth, it's clear that the COVID-19 pandemic has exacerbated even more income inequality (IMF). WID. world data shows that the richest 1% have accounted for 38% of all added wealth since the mid-1990s, with growth accelerating since 2020. There are still very significant inequalities in the distribution of wealth in any region or country. The World Inequality Report 2022 shows that while at the global level, the difference between the average income of the richest 10% and the poorest 50% has fallen from about 50 times to under 40 times, at the same time, inequality within countries has increased phenomenon increased significantly. Within countries, the gap between the top 10 percent of income earners and the bottom 50 percent has nearly doubled, from 8.5 times to 15 times (Chancel, 2022). Greater inequality in income distribution means more economic injustice, which brings political instability, unequal political power, and financial crises (Chiu and Lee, 2019). Thus, "how to improve income inequality" has become an urgent policy dilemma for many countries (Lee et al., 2022). The 2030 Agenda for Sustainable Development emphasizes three perspectives of sustainability: Society, Economy and Environment, while also setting ambitious targets for reducing inequalities within and among countries (UN, 2022). So, how will rising income inequality in the wake of the COVID-19 pandemic affect the achievement of the SDGs across the three perspectives of social, economic and environmental? To know the answer, first of all, it should be necessary to clarify what kind of impact does the increasing income inequality have on the causality of economic growth and carbon emissions? That is, will the level of income inequality, which is an important factor in macroeconomic society, change the inverted U-shaped EKC that has been widely studied? If so, how does income inequality affect the EKC hypothesis?

Therefore, we consider re-examining the traditional EKC hypothesis from an income inequality perspective. Our study uses a panel threshold regression model to examine the impact of income inequality on the EKC curve, and investigates the relationship between economic growth and per capita carbon emissions in 56 countries from different income groups from 2003 to 2018 in different income inequality zoning systems. It innovatively integrates economic growth, carbon emissions and income inequality in a composite analytical frame, examines the validity of the EKC hypothesis when considering a social factor - income inequality, and answers the question "Does the impact of economic growth on carbon emissions vary with income inequality?" to help policymakers make effective policy decisions. The rest sections are presented below. Section 2 is literature review. Section 3 is the data and method description. Section 4 is the discussion of the results, and Section 5 is the conclusion.

## 2. Literature review

Early studies mainly used econometric analysis models, focusing on the estimation of econometric models and prediction of emissions, and explored the impact of per capita income on per capita emissions. Holtz-Eakin and Selden (1995) estimated from global panel data that the

marginal propensity (MPE) to emit carbon dioxide decreases as GDP per capita increases. Still, global carbon dioxide emissions are set to grow at a rate of 1.8% per year for the foreseeable future. De Bruyn et al. (Balsalobre-Lorente et al., 2018) analyzed data from four OECD countries from 1960 to 1993 and found that, economic growth has a direct positive impact on nitrogen oxide or carbon dioxide emissions. Marzio Galeotti et al. (Galeotti and Lanza, 1999) found that the nonlinear estimation model was found to better describe the realistic relationship between CO<sub>2</sub> and income, rather than the more common linear and log-linear functional forms. Their projections indicate that global emissions will rise in the future, with the average growth rate of world carbon dioxide emissions between 2000 and 2020 of about 2.2% per year. It is not difficult to find that, although some studies have introduced other emissions-related variables into the EKC model (Agras and Chapman, 1999; Sun, 1999), the earlier studies were limited by the econometric modeling techniques and selected datasets (List and Gallet, 1999), the conclusions drawn are biased, and the accuracy needs to be verified.

Later CO<sub>2</sub>-EKC studies incorporated a broader theoretical context, reassessed traditional EKC assumptions, and introduced explanatory variables that had not previously been included in the study. However, there is heterogeneity between the estimated coefficients for each country because the subjects may be in different developmental periods. Differences in the explanatory variables used in the analysis framework and the econometric models used in the study, as well as heterogeneity between them in the economic development history, are all possible reasons for the different EKC findings. Shi (Shi, 2003) used the STIRPAT model to study carbon emissions on a global scale. Halicioglu (Halicioglu, 2008) studied the dynamic relationship between CO<sub>2</sub> emissions and income in Turkey. The results of the study did not confirm the EKC of Turkey. He and Richard (He and Richard, 2010) studied carbon dioxide emissions in Canada using time-series emissions data from 1948 to 2004. They replaced the traditional polynomial EKC model to take advantage of a more flexible model, namely semiparametric and flexible nonlinear parametric models, and found no evidence of EKC using flexible nonlinear parametric models. From the research conclusions, these studies can be roughly divided into two categories, one is the evidence supporting the EKC hypothesis. Examples include Tao et al. (Tao, 2008) for China, Fujii and Managi (2013) for paper, wood, and construction industries, and Chaabouni et al. (2016) for 51 countries worldwide. The other category is studies that find other relationships between these two factors, such as N-shaped curves, U-shaped curves, monotonically increasing relationships, etc. Friedl and Getzner (Friedl and Getzner, 2003) studied the link of Austrian economic development and CO<sub>2</sub> emissions from 1960 to 1999 according to EKC hypothesis, describing the relationship between them as an "N"-shaped relationship. Azomahou et al. (2006) analyzed the relationship between these two factors in 100 countries between 1960 and 1996 using the Poolability test of Baltagi et al. (1996). The results indicated that there was an upward-sloping link between them. Cialani (2007) tested the EKC hypothesis using Italian time series data. The results indicated that there is a positive relationship between carbon dioxide emissions and economic growth. At the same time, the inverted U-shaped pattern of EKC has not been verified. Sahbi Farhani and Lihan Ozturk (Farhani and Ozturk, 2015) investigated and found a positive monotonic relationship in Tunisia for the period 1971–2012. There are still methodological and data-related issues with the findings at this stage, and examples include bias from impractical assumptions about homogeneity, endogeneity bias, and issues that arise from the non-stationarity of data (Tenaw and Beyene, 2021). Another key restriction of existing research is the hypothesis of cross-sectional independence. However, disregarding those concerns may result in false, skewed, inferior, and incompatible estimates (Tenaw and Beyene, 2021).

Recent studies have revisited problems arising from unrealistic homogeneity assumptions, endogeneity biases, assumptions of cross-sectional independence, and problems caused by non-stationarity in

the data, resulting in further improvements to methods and models. Abdul Haseeb et al. (2018) explored the effect of economic growth on CO<sub>2</sub> emissions in BRICS countries under the framework of the EKC hypothesis. The findings support the EKC hypothesis for BRICS economies. Because the estimation methods they used take into account heterogeneity and cross-sectional dependencies in their model construction process, the empirical results obtained have strong robustness. Muntasir Murshed (Murshed and Dao, 2022) used panel data of 1972–2014 and found that the EKC hypothesis was tested only in Bangladesh and India, while in Pakistan, the relationship of these two factors depicts a U-shaped curve. On the contrary, economic growth in Sri Lanka and Nepal can monotonically reduce carbon dioxide emissions. Hongbo Liu (Liu et al., 2019) used empirical regression equations with Driscoll and Kraay standard errors to correct for prospective heteroskedasticity issues and autocorrelation troubles. The interaction term of economic development and export diversification facilitates comparisons across income levels: economic development in low-income countries has a U-shaped relationship with CO<sub>2</sub> emissions, while OECD countries still show an inverted U-shaped relationship.

From the perspective of research methods, a large number of studies in the past five years have mainly used Panel VECM, Dynamic Autoregressive Distributed Lag (DARDL) Model and Common Correlation Effects (CCE) and Augmented Mean Group (AMG) estimator (Ali et al., 2021; Danish et al., 2021; Ganda, 2019; Isik et al., 2019; Işık et al., 2019; Tenaw and Beyene, 2021). See Table 1 for details.

The panel ARDL model yields accurate outcomes no matter whether the regression variables are endogenous or not and regardless of the sequence of integrals of the variables (De V. Cavalcanti et al., 2015). This approach can solve the questions posed by sequence correlation and endogeneity. The slope coefficients are well supported by this estimation model whether homogeneous or heterogeneous. Dagmawe Tenaw (Tenaw and Beyene, 2021) investigates the linkages between environment and development in the framework of Sustainable EKC in 20 SSA countries between 1990 and 2015. And they support the improved EKC hypothesis, but the link depends on the degree of natural resource endowment. Muhammad Uzair Ali (Ali et al., 2021) investigated the permanent and temporary elasticity of economic development, economic development squared, and emissions, using the autoregressive distributional lag in Pakistan from 1975 to 2014 (ARDL) constraint testing techniques. The results for the short- and long-term dynamics confirm the inverted U-shaped link between them. Fortune Ganda (Ganda, 2019) study of EKC in South Africa shows total energy consumption and the sum of hydrocarbon gas and oil consumption consistent with EKC evidence. Other isolated data do not show evidence of long-term EKC. Beşe Emrah et al. (Emrah and Salih, 2021) studied the EKC hypothesis in 3 developed countries from 1960 to 2014, namely Denmark, the United Kingdom and Spain. For those countries the EKC hypothesis does not hold, and the neutral hypothesis was confirmed in these 3 developed countries. The CCE-MG and AMG estimation methods considering cross-sectional correlation, heterogeneity, internal homogeneity, and serial correlation problems are also widely used in some empirical studies. Rana Muhammad et al. (Adeel-Farooq et al., 2021) verified the effectiveness of the methane EKC hypothesis using MG and PMG. That is, economic growth reduces CH<sub>4</sub> emissions. Cem Işık et al. (Isik et al., 2019; Işık et al., 2019) tested the EKC hypothesis for the ten states with the highest CO<sub>2</sub> emissions in the US. Empirical results show that the EKC applies only to five states. Additionally, their another study investigated the effectiveness of the EKC in 50 states and federal districts in the US. The results indicate that CCE estimators don't verify the EKC hypothesis, but AMG does. A study by Seyi Saint Akadiri et al. (2021) on BRICS countries discovered that the EKC hypothesis is effective only in small groups of countries. The same carbon reduction results are obtained when economic freedom and economic output are used together.

There are many studies that establish panel vector error correction models and conduct pairwise Granger causality tests. Kong Y et al. (Y and R, 2019) used the EKC Hypothesis to study the data of 29 countries from

1977 to 2014. The results demonstrate the validity of the EKC hypothesis in the manufacturing and construction industries. Mohammed Kharbach (Kharbach and Chfadi, 2017) assessed the road transport sector in Morocco, a developing country undergoing an energy transition, from an environmental perspective. They found that the Environmental Kuznets Curve (EKC) hypothesis applies to Morocco's transport sector. Yu Sun et al. (2021) verified the existence of inverted U-shaped curve between economic growth and carbon emissions; that is, carbon emissions increase with economic growth, reach a peak and then gradually decline, showing an inverted U-shaped curve in the graph. Besides, economic factors and solar technology innovation have a dampening impact on carbon emissions.

The generalized method of moments is the most widely used method for estimating parameters and is the most used econometric models in panel data. There are quite a few studies using this method to validate EKC curves. For example, Khalid Zaman (Zaman and Moemen, 2017) and others examined the connection between them. Results support the EKC hypothesis in different regions of the world, and an integrated group during the period 1975–2015. Atif Jahanger et al. (Jahanger, 2022) survey the growth data of 78 developing economies from 1990 to 2016. Empirical results were found to approve the inverted U-shaped EKC hypothesis.

In addition, there are many studies using other quantitative research methods. Roberto Balado-Naves (Balado-Naves et al., 2018) and others applied the spatial econometric model to the study of EKC curves. They used a panel dataset of 173 countries from 1990 to 2014 to estimate the Environmental Kuznets Curve (EKC). The results show that standard EKC exists in most regions. Nidhaleddine Ben Cheikh (Ben Cheikh et al., 2021) proposes a new method to analyze the dynamic relationship between carbon dioxide (CO<sub>2</sub>) emissions, energy use and income in the MENA region. Their study utilizes a state-switching model-PSTR, and the empirical findings suggest that pollutant emissions have a nonlinear response to energy consumption and GDP growth. In a sense, environmental quality is rising above the endogenous income threshold in the model.

Different researchers have chosen different environmental and economic variables, the data sets of the subjects studied and the empirical research methods are different, so that the research on the EKC hypothesis does not reach consistent conclusions. Previous studies are limited by measurement techniques and sample datasets, and there are many problems. First, in terms of econometric models, a lot of research focuses on traditional regression models such as PMG, GMM, FMOLS, and ARDL. Due to the limitations of the linear model setting, more possible regression relationships between variables are easily ignored. In addition, the complexity and variability of the relationship between the economy and the environment are better characterized by flexible nonlinear models.

Secondly, in terms of variable selection, the traditional EKC hypothesis mainly considers the relationship between two variables, economic and environmental quality. Few studies have attempted to incorporate social factors into the framework of the EKC hypothesis. This easily leads to biases in the comprehend of the EKC hypothesis, which leads to doubts about the existence of the EKC curve. Finally, because of the different stages of development in every country, there are many differences in the per capita income of countries with different economic scales, and the relationship between the economy and the environment may also be different. Therefore, heterogeneity analysis in the study is necessary.

Considering the inadequacies of the above existing researches, this paper has the following innovative contributions to fill these gaps: (1) The current research mainly spotlights on the connection of economic growth and carbon emissions. Hardly any works have examined the EKC hypothesis from the perspective of other social factors, our study just fills this gap from the perspective of income inequality threshold, our work innovatively incorporates income inequality into the EKC hypothesis framework, it also enriches and expands the research on the

**Table 1**  
Summary of research on the relationship between economic growth and carbon emissions.

Authors	Methods or models	Sample period	Sample countries	Findings
<b>Abdul Haseeb et al</b>	Econometric techniques robust to heterogeneity and cross-sectional dependencies	1995–2014	BRICS	Findings Support EKC Hypothesis for BRICS Economies
<b>Muhammad Uzair Ali et al</b>	ARDL Constraint Testing Techniques	1975–2014	Pakistan	an inverted U-shaped relationship between economic development and CO2 emissions In the long run, combined (total energy consumption) as well as hydrocarbon gas and oil consumption justify the EKC evidence. Other isolated data (primary coal, secondary coal and electricity consumption) showed no evidence of long-term EKC.
<b>Fortune Ganda et al</b>	ARDL	1980–2014	South Africa	
<b>Beş Emrah et al</b>	VAR Granger causality/blocking exogenous Wald test and Johansen cointegration test	1960–2014	Denmark, UK and Spain	The EKC hypothesis was not confirmed in Denmark, the United Kingdom and Spain, and the neutral hypothesis was confirmed in these 3 developed countries.
<b>Muntasir Murshed et al</b>	Econometric Analysis of Group Data	1972–2014	Bangladesh, India, Pakistan, Sri Lanka and Nepal	The EKC hypothesis has only been tested in Bangladesh and India, while in the context of Pakistan, the relationship between economic growth and CO2 emissions depicts a U-shaped association. In contrast, economic growth in Sri Lanka and Nepal can monotonically reduce carbon dioxide emissions.
<b>Kong et al</b>	Panel Vector Error Correction Model, cointegration test	1977–2014	29 countries (14 developed and 15 developing)	The results confirm the EKC hypothesis in the case of emissions of solid, liquid, gases, manufacturing industries and also construction.
<b>Nidhaleddine Ben Cheikh et al</b>	Panel smooth transition modeling	1980–2015	12 MENA countries: Algeria, Bahrain, Egypt, Jordan, Kuwait, Lebanon, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, and United Arab Emirates (UAE)	Non-linear response of pollutant emissions to energy consumption and GDP growth. They find an inverted U-shaped pattern for the impact of energy on CO2, in the sense that environmental degradation is declining beyond a given income threshold, which is estimated endogenously within the PSTR model.
<b>Rana Muhammad Adeel-Farooq et al</b>	Mean Group (MG) and Pooled MG (PMG) Techniques	1985–2012	six ASEAN countries	The findings reveal that the EKC hypothesis for the CH4 emission in these economies proves to be valid. In other words, economic growth causes CH4 emissions to decrease.
<b>Cem Isik et al</b>	Common Correlation Effects (CCE) and Augmented Mean Group (AMG) estimation procedures	1980–2015	50 U.S. states and federal districts	While the CCE estimates do not support the EKC assumption, the AMG does. Empirical results from the AMG estimates suggest that only 14 states have validated the EKC hypothesis.
<b>Dagmawe Tenaw et al</b>	ARDL, CCE-PMG	1990–2015	20 countries in sub-Saharan Africa (SSA)	The results confirm the existence of the improved EKC hypothesis in SSA, but the link depends on the degree of natural resource endowment.
<b>Yu Sun et al</b>	Vector Error Correction Model	1990–2017	China	The relationship between economic growth and carbon emissions is inverted “U”, and strengthening the innovation of solar technology has a positive effect on reducing carbon dioxide emissions.
<b>Khalid Zaman et al</b>	Difference GMM Estimator	1975–2015	90 countries from these three strata	The results supported the EKC hypothesis, IPAT hypothesis.
<b>Muhammad Wasif Zafar et al</b>	Continuous Update Full Modification (CUP-FM) and Continuous Update Bias Correction (CUP-BC) methods	1990–2015	Emerging economies	Renewable energy consumption has a negative impact on CO2 emissions, while non-renewable energy consumption has a positive impact on CO2 emissions. The study also supports the EKC hypothesis.
<b>Roberto Balado-Naves et al</b>	Spatial econometric model	1990–2014	173 countries	Most regions support the standard EKC, and there appears to be an inverted U-shaped relationship between neighboring per capita income and national per capita emissions in Europe, Asia, and the world at large.
<b>Danish et al</b>	Dynamic Autoregressive Distributed Lag (DARDL) Model	1971–2018	India	Nuclear energy and population density contribute to the EKC curve.
<b>Seyi Saint Akadirin et al</b>	The pooled mean group (PMG) estimation	1995–2018	BRICS (Brazil, Russia, India, China and South Africa)	When economic freedom and output are used together, they produce the same carbon reduction effect in the short and long term. In the long run, the EKC hypothesis is only valid for the group of countries. Second, we find that economic freedom mimics the pattern of economic output.
<b>Mohammed Kharbach et al</b>	Vector Error Correction Model (VECM)	1971–2011	Morocco	The Environmental Kuznets Curve (EKC) hypothesis applies to Morocco’s transport sector.
<b>Eyup Dogan et al</b>	The fully modified OLS (FMOLS) long-run estimators	1980–2014	European countries	The main finding of the study is that the overall economic growth is the factor with which CO2 emissions exhibit an inverted U-shaped relationship in the studied country group. On the contrary, when using their industrial share as a proxy to capture the

(continued on next page)

Table 1 (continued)

Authors	Methods or models	Sample period	Sample countries	Findings
Cem Işık et al	Fixed Effect and CCE estimator	1980–2015	US states (California, Florida, Illinois, Indiana, Louisiana, Michigan, New York, Ohio, Pennsylvania, and Texas)	countries' economic structure, the EKC hypothesis is not confirmed – but a U-shaped relationship is confirmed. The EKC (inverted U-shaped) hypothesis applies only to Florida, Illinois, Michigan, New York and Ohio.
Michael Kaku Minlah et al	Time-varying methods and rolling-window Granger causality tests	1960–2014	Ghana	The empirical results show that the Environmental Kuznets Curve for carbon dioxide emissions for Ghana is upward sloping, contrary to the standard Environmental Kuznets Curve theory.
Atif Jahanger et al	Generalized Moment Method (GMM) for Robust Systems	1990–2016	78 developing economies	The empirical results support the inverted U-shaped environmental Kuznets curve (EKC) hypothesis.
Hongbo Liu et al	Empirical regression equation with Driscoll and Kraay standard errors	2000–2014	125 countries	Economic development in low-income countries has a U-shaped relationship with carbon dioxide emissions, while OECD countries still maintain an inverted U-shaped EKC curve.

traditional EKC hypothesis. (2) This work uses a panel threshold model to verify the threshold effect of income inequality in the relationship between economic growth and carbon emissions, which is different from previous works that have linear regressions or include quadratic terms when studying the link between income and emissions. Our research model can more accurately capture jumps or structural breaks in the relationship between economic growth and environmental quality. (3) Our study re-examines the validity of EKC hypothesis from the perspective of income inequality. In previous studies, few studies in previous research have concentrated on exogenous factors affecting the relationship between economic growth and carbon emissions. Our research considers the impact of income inequality, an exogenous factor, on the relationship between economic growth and carbon emissions and provides a reasonable explanation for the mechanism of action between them. Our work provides new ideas and references for future research on the relationship between them.

### 3. Data and methods

#### 3.1. Data

We collected data from the World Bank's countries excluding low-income group (the data for the low-income group is too missing for empirical research). Due to the incomplete data of some countries in the upper-middle-income group and the lower-middle-income group, we selected 56 countries as research objects. Because of the availability of income inequality data, we selected data from these countries from 2003 to 2018. Appendix 1 shows the countries studied. To study the impact of income inequality on the connection between economic growth and carbon emissions, we included urbanization level, renewable energy consumption, trade openness, and industrial structure as control variables into the model. The settings for these variables are described in detail below.

We select per capita carbon dioxide emissions as the explained variable. The burning of fossil fuels and the production of cement both produce carbon dioxide emissions. Carbon dioxide is emitted when fueled with either solid, liquid or gaseous fuels. Data obtained from the World Bank. We also used per capita GDP as the core explanatory variable. To ensure data consistency, economic growth is measured by per capita GDP. GDP per capita is based on purchasing power parity.

The threshold variable in the model is income inequality. The Gini coefficient is often seen as an indicator that portrays the degree of income inequality. Usually the Gini coefficient is classified as being ground on net income or gross income. Although the data for the gross income indicator are less than those for net income, the data for the gross income indicator do not take into account redistributive policies, which is a unique feature of the indicator. Therefore, we use total

income type data to incorporate into the model. The Gini coefficient gives a quantitative boundary reflecting the extent of the gap between the rich and the poor, which can reflect and monitor the gap between the rich and the poor of the population more objectively and intuitively. The Lorenz curve shows the relationship between the cumulative percentage of total income and the cumulative number of recipients, beginning with the poorest individual or household. The Gini coefficient weighs the region between the Lorenz curve and the absolute equality assumption line, represented as a proportion of the largest area below that line. So a Gini index of 0 represents complete equality, and a Gini index of 100 represents complete inequality.

While this is a useful measure, the Gini coefficient is known to be more sensitive to changes in the center of the distribution than to extremes. The Gini index better reflects the inequality in the middle of the income distribution, and somewhat ignores changes at the top and bottom. Therefore, we use Income share held by highest 10% to measure income inequality instead of the Gini coefficient as the threshold variable when performing the robustness test. The fraction of income or consumption is the share of population subgroups expressed in deciles or quintiles (Fig. 1). The employment of these two different inequality measurements ensures the robustness of the study results. All data are from the World Bank database.

On the control variables, we add the degree of urbanization, renewable energy consumption, trade openness and industrial structure as control variables. Urbanization has a huge contribution to make in driving economic growth (Li et al., 2022a), and half of the world's population is expected to migrate to urban areas by 2050. While urbanization brings many good results, such as more jobs, higher revenues and living standards, the mass migration of people from rural to urban areas can put pressure on urban facilities, including water supply, sewage treatment, parklands, greens, schools, hospitals and transportation use, which in turn leads to increased pollution and environmental degradation (Sun et al., 2022; Wang et al., 2022c). Urban population is defined by the National Bureau of Statistics as the population residing in rural areas. This data is collected and collated by the United Nations Population Division. We denote the degree of urbanization by the proportion of urban population to the total population. Some scholars have studied the impact of renewable energy consumption on emissions in different regions or countries. The compatibility of renewable energy consumption and economic growth is the key to the development of renewable energy and the key to sustainable economic development (Wang et al., 2022b). Although the results of the survey are inconclusive, a large number of empirical analyses have shown that renewable energy is an important factor of carbon emissions reduction in these countries (Li et al., 2021, 2022b). Dogan and Ozturk (2017) report that usage of renewable energy reduces environment degradation, while the use of non-renewable energy increases environmental

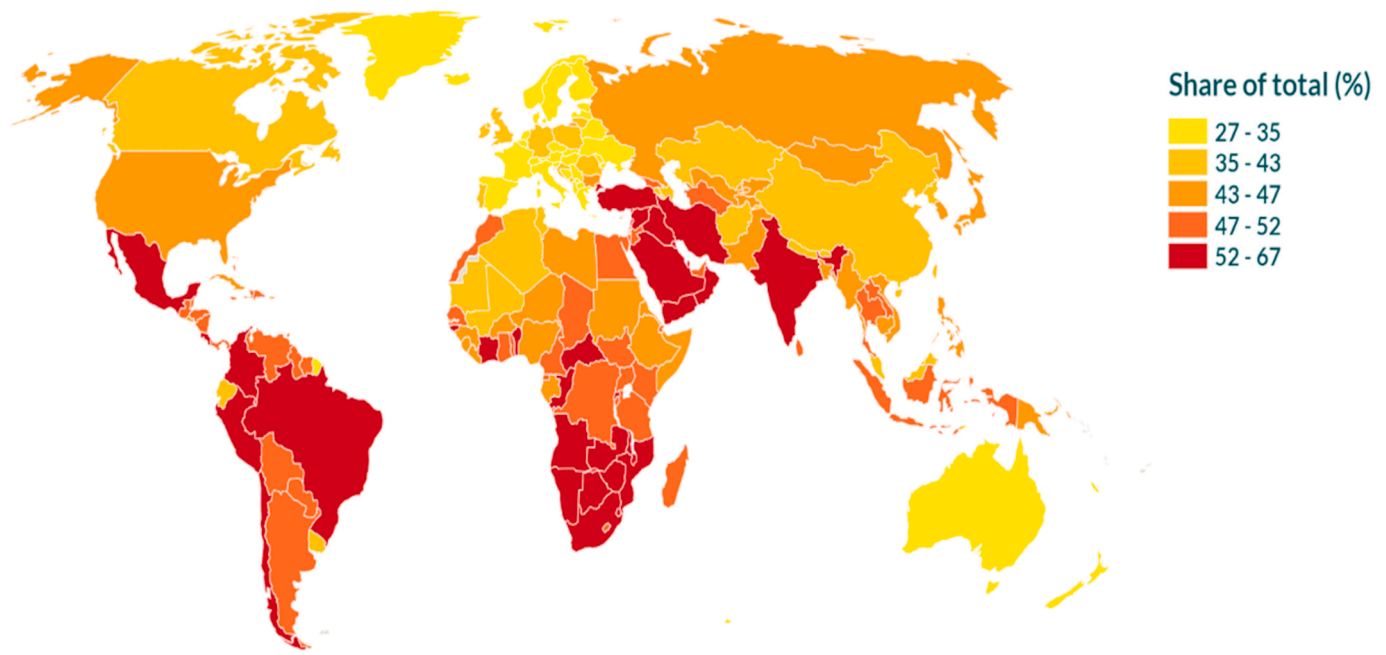


Fig. 1. Top 10% national income share.

degradation. Dogan and Seker (2016) also revealed that increased renewable energy consumption reduces emissions. Therefore, we included renewable energy consumption as a control variable. Renewable energy consumption refers to the ratio of renewable energy in gross ultimate energy consumption. Antweiler et al.(Shahbaz et al., 2017) highlighted three major classes of environmental impacts of trade, namely scale, technology and composition effects for the first time. The relative magnitudes of the capital-labor and environmental adjustment effects determine the positive and negative net effects of the composition effect of trade openness (Kahuthu, 2006). Hence, we incorporate trade openness into the specification, expressed as a percentage of total GDP in terms of exports and imports. On one side, many scholars focus on examining the carbon emission reduction impact of industrial restructuring, arguing that accelerating industrial restructuring can availably mitigate the incrementally serious greenhouse effect(Chang and Li, 2017; Li and Wei, 2015; Zhu et al., 2014). On the other hand, it has also been confirmed that the tertiary sector has a statistically important carbon reducing influence and the secondary sector has a positive carbon emission influence(Liu and Bae, 2018). We also included industrial structure as a control variable in the model, expressed as a

percentage of industrial added value in GDP. These data are all from the World Bank database. The specific variable information is shown in Table 2. To guarantee the smoothness of the data, mitigate the effects of heteroskedasticity and auto-correlation, and prevent false regressions, we adopt the logarithm form of all data into the model. Table 3 is a statistical description of the variables.

### 3.2. Baseline regression model

To test the validity of the EKC hypothesis for these 56 countries, we developed the following empirical model using the level of economic growth and other explanatory variables to estimate carbon emissions.

$$\ln CO_{2it} = \alpha_1 \ln GDP_{it} + \alpha_2 (\ln GDP_{it})^2 + \beta x + \mu_i + \varepsilon_{it}$$

In this formula, where the subscript i represents countries selected for the sample and t represents the year. We take a logarithmic form to mitigate the effect of heteroskedasticity,  $\ln CO_{2it}$  represents the per capita carbon emissions of every country in the corresponding year, and  $\ln GDP_{it}$  represents degree of the economic development for country, the squared term was added to investigate the validity of the EKC hypothesis. X delegates the set of control variables, and includes the level of urbanization, renewable energy consumption, trade openness and industrial structure;  $\mu_i$  represents the individual effect,  $\varepsilon_{it}$  represents a random disturbance term, obeying independent distribution.

Recently, a growing literature has begun to consider cross-sectional dependence of regression models and to highlight the importance of econometric methods that address this aspect. This is particularly

Table 2  
Variable descriptions.

Name	Variable	Definition	Data sources
<b>Carbon Emission</b>	lnCO2	CO2 emissions per capita	World Bank
<b>Economic Growth</b>	lngdp	GDP per capita, PPP (constant 2017 international \$)	World Bank
<b>Degree of Urbanization</b>	lnurb	The ratio of urban population to total population	World Bank
<b>Renewable Energy Consumption</b>	lnren	The share of renewable energy in total final energy consumption	World Bank
<b>Trade Openness</b>	lnopen	Imports and exports as a percentage of total GDP	World Bank
<b>Industrial Structure</b>	lnind	Industrial value added as a percentage of GDP	World Bank
<b>Income Inequality</b>	lngini	Gini index	World Bank
<b>Income Inequality</b>	ln10%	Income share held by highest 10%	World Bank

Table 3  
Descriptive statistics of variables.

Variable	Obs	Mean	Std.Dev.	Min.	Max.
lnCO2	840	-0.00014	0.028741	-0.16395	0.121043
lngdp	840	0.010957	0.016132	-0.06785	0.093419
lnurb	840	0.001928	0.002612	-0.00401	0.015001
lnren	840	0.014346	0.052926	-0.20106	0.679856
lnopen	840	0.002189	0.043768	-0.15655	0.526863
lnind	840	-0.00284	0.020853	-0.13025	0.189783
lngini	840	-0.00157	0.015812	-0.11988	0.097456
ln10%	840	-0.00161	0.017011	-0.10116	0.073083

important because most traditional panel econometric methods do not take cross-sectional dependence into account. The AMG estimator is an alternative to the CCE-MG approach (Eberhardt and Bond, 2009; Teal and Eberhardt, 2010), which considers cross-sectional dependence by adding the “common dynamic process” to the country regressions. The AMG method considers cross-sectional dependence by adding a “common dynamic process” to the country regression. This method takes into account cross-sectional dependence and provides heterogeneous slope coefficients among panelists. Moreover, since this estimation method predicts the arithmetic mean of the co-integration coefficients by weighing them, it is stronger than other coefficient estimation methods. Given these, we obtain estimates of the coefficients of the benchmark model by applying the augmented mean group (AMG) estimator. The AMG estimator uses time dummy variables and dynamic functions to address serial correlation and endogeneity, using the following two-step approach.

$$\Delta y_{it} = \alpha_i + \beta_i \Delta X_{it} + \sum_{t=2}^T \delta_i D_t + \xi_i F_t + \varepsilon_{it}$$

where  $\Delta$  denotes the first-order difference operator and  $D_t$  denotes the time dummy variable. The AMG estimates can be obtained by averaging each coefficient of the cross section.

### 3.3. Panel threshold regression model

Threshold effect, also known as threshold effect, stands for that the influence of some independent variables on the dependent variable is not purely linear, but may be due to the influence of other exogenous factors, the independent variable shows a significant nonlinear effect on the dependent variable. Threshold regression models describe jumps or structural breaks in relationships between variables. When the changes of these exogenous factors are located in different threshold intervals, the independent variables will have different effects on the dependent variables. Introducing the threshold effect in the research can not only describe the effect of independent variables on dependent variables more accurately, but also examine the influence of exogenous factors on the relationship between the independent variable and the dependent variable. In this work, we highlight the impact of economic development on carbon emissions at different stages or levels of threshold variables. Hansen (Hansen, 1999) developed an improved threshold regression approach that is inherently static and can avoid the drawbacks of the traditional threshold regression model of Tong and Lim (2009). It does not need to set nonlinear equations to express the relationship between variables (Bick, 2010; Brana and Prat, 2016), and the value and number of thresholds are determined entirely according to the sampled data. This applies to studying relationships between variables.

We now analyze a simple single-threshold model:

$$y_{it} = \mu + X_{it}(q_{it} < \gamma)\beta_1 + X_{it}(q_{it} \geq \gamma)\beta_2 + u_i + e_{it}$$

The variable  $q_{it}$  represents the threshold variable, and  $\gamma$  represents the threshold parameter which splits the expression into two parts, the elasticity coefficients corresponding to each of the different intervals are  $\beta_1$  and  $\beta_2$ . The parameter  $u_i$  refers to the individual effect and  $e_{it}$  refers to the perturbation term. That could be written as

$$y_{it} = \mu + X_{it}(q_{it}, \gamma)\beta + u_i + e_{it}$$

$$X_{it}(q_{it}, \gamma) = X_{it}I(q_{it} < \gamma)$$

$$X_{it}(q_{it}, \gamma) = X_{it}I(q_{it} \geq \gamma)$$

Known  $\gamma$ , the ordinary least squares estimate of  $\beta$  is

$$\hat{\beta} = \{X^*(\gamma)'X^*(\gamma)\}^{-1}\{X^*(\gamma)'y^*\}$$

Among them,  $y^*$  and  $X^*$  are within-group deviations. The Residual Sum of Squares (RSS) is equal to  $\hat{e}'\hat{e}$ . To obtain an estimation of  $\gamma$ , we

can find a subsection of the threshold variable  $q_{it}$ . Rather than doing a walk-through of the data for the entire sample, we limit the scope to the range  $(\underbrace{\gamma, \bar{\gamma}})$ , which is the quantile of  $q_{it}$ . The estimated value of  $\gamma$  is the value that minimizes the RSS

$$\hat{\gamma} = \arg \min S_1(\gamma)$$

If  $\gamma$  is known, the model is the same as the normal linear model. But if  $\gamma$  is uncertain, then it suffers from an annoying parameter issue that causes the distribution of the  $\gamma$  estimator to be non-standard. Hansen (1999) demonstrated that  $\hat{\gamma}$  is a consensus estimated measure of  $\gamma$ , he believes that the best method to test  $\gamma = \gamma_0$  is to use the “No Rejection Region” method to form confidence intervals with the likelihood ratio (LR) statistic, as follows:

$$LR_1(\gamma) = \frac{\{LR_1(\gamma) - LR_1(\hat{\gamma})\}}{\hat{\sigma}^2} \xrightarrow{Pr} \xi$$

$$Pr(x < \xi) = (1 - e^{-x})^2$$

Under the premise of the significant level  $\alpha$ , the lower bound is corresponding to the largest value of the LR sequence under  $\alpha$  quantile, and the upper bound is corresponding to the smallest value of the LR sequence under  $\alpha$  quantile. The quantile may be calculated by the inverted equation:

$$c(\alpha) = -2 \log(1 - \sqrt{1 - \alpha})$$

The test for threshold effects is equivalent to a test of if the coefficient is the same for every case. The null and alternative hypotheses are, respectively

$$H_0 : \beta_1 = \beta_2 \quad H_a : \beta_1 \neq \beta_2$$

Construct the F-statistic

$$F_1 = \frac{(S_0 - S_1)}{\hat{\sigma}^2}$$

Under  $H_0$ , the threshold  $\gamma$  is not recognized and  $F_1$  has a non-standard asymptotic distribution. We used a bootstrap for the critical value of the F-statistic to check the significantness. The same goes for RSS for linear models. Hansen (1996) proposed a method:

- Step 1 Fitting a model under  $H_a$  to get residual  $\hat{e}_{it}^*$ .
- Step 2 Use the replacement method for clustering resampling  $\hat{e}_{it}^*$  to get a new residual  $v_{it}^*$ .
- Step 3 Have a new sequence under the  $H_a$  data generation process,  $y_{it}^* = X_{it}^*\beta + v_{it}^*$ , where  $\beta$  could be taken as any value.
- Step 4 Fitting a model under  $H_a$  and  $H_0$ , using (3) to calculate the F-statistic.
- Step 5 Repeat steps 1–4 B times, the probability of F is  $Pr = I(F > F_1)$ , that is, the proportion of  $F > F_1$  in the bootstrap number B. The procedure 1–4 is repeated B times with the probability of F being  $Pr = I(F > F_1)$ , i.e., the ratio of  $F > F_1$  in bootstrap number B.

If multiple thresholds exist (i.e., multiple mechanisms), we will perform the fitting of the model in order. Let’s take the two-threshold model as an example.

$$y_{it} = \mu + X_{it}(q_{it} < \gamma_1)\beta_1 + X_{it}(\gamma_1 \leq q_{it} < \gamma_2)\beta_2 + X_{it}(q_{it} \geq \gamma_2)\beta_3 + u_i + e_{it}$$

The thresholds  $\gamma_1$  and  $\gamma_2$  separate the formula into three regions, and the coefficients corresponding to each region are  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  respectively. This  $(N \times T)^2$  needs to be calculated twice by the grid search way, it is not feasible in reality. According to Bai (1997) and Bai and Perron (1998), the sequence estimators are uniform, and our estimated thresholds are as follows:



Step 1 Fit a single threshold model to get the threshold estimated value  $\gamma_1$  and RSS  $S_1(\hat{\gamma})$ .

Step 2 Knowing  $\hat{\gamma}_1$ , the second threshold and its confidence interval can be obtained as

$$\hat{\gamma}_2^r = \arg \min \{S_2^r(\gamma_2)\}$$

$$S_2^r = S\{\min(\hat{\gamma}_1, \gamma_2)\max(\hat{\gamma}_1, \gamma_2)\}$$

$$LR_2^r(\gamma_2) = \frac{\{S_2^r(\gamma_2) - S_2^r(\hat{\gamma}_2^r)\}}{\hat{\sigma}_{22}^2}$$

Step 3  $\hat{\gamma}_2^r$  is valid, but  $\hat{\gamma}_1^r$  is not. We re-estimate the first threshold as

$$\hat{\gamma}_1^r = \arg \min \{S_1^r(\gamma_1)\}$$

$$S_1^r = S\{\min(\gamma_1, \hat{\gamma}_2^r)\max(\gamma_1, \hat{\gamma}_2^r)\}$$

$$LR_1^r(\gamma_1) = \frac{\{S_1^r(\gamma_1) - S_1^r(\hat{\gamma}_1^r)\}}{\hat{\sigma}_{21}^2}$$

If the null hypothesis in the single-threshold model is rejected, we have to examine whether the double-threshold model exists. The original hypothesis is a single-threshold model and the alternative hypothesis is a double-threshold model(Wang, 2015). Constructing the F-statistic

$$F_2 = \frac{\{S_1(\hat{\gamma}_1) - S_2^r(\hat{\gamma}_2^r)\}}{\hat{\sigma}_{22}^2}$$

Its bootstrap design is identical to the one-threshold model. In step 3, we have a new sequence under  $H_0$  DGP,  $y_{it} = X_{it}^* \beta_s + v_{it}^*$  is a single-threshold model. This work uses predicted values.

The steps for testing models that have multiple thresholds are performed similarly to the previous section. We build the following model to investigate the link between income inequality and the EKC curve.

$$\ln CO_{2it} = \beta x + \alpha_1 \ln GDP_{it} * I(q_{it} \leq \lambda_i) + \alpha_2 \ln GDP_{it} * I(q_{it} > \lambda_i) + \mu_i + \varepsilon_{it}$$

$q_{it}$  represents the set threshold variable (that is, the degree of income inequality), and  $I(*)$  is the schematic function.  $\lambda_i$  represents the threshold value to be estimated. This equation denotes a single-threshold panel model; in practice, there could also exist double-threshold, triple-threshold, and other cases, where different threshold values classify the model into more different segments.

### 3.4. Cross-sectional correlation test

Assessing cross-sectional dependence (CD) is a top priority in panel data model analysis. We applied the Pesaran (2021) test to evaluate CD. The examination of CD is very important in panel data model analysis, and the neglect of CD causes inaccurate results.

Pesaran's CD test looks like this:

$$CD = \sqrt{\frac{2T}{M(M-1)} \sum_{i=1}^{M-1} \sum_{p=i+1}^M \rho_{pi}}$$

T in the equation stands for time, the size of the panel data is denoted by M, and the  $\rho_{pi}$  stands for correlation coefficient. Rejecting the null hypothesis indicates the existence of CD, and accepting the null hypothesis means that there exists no CD.

## 4. Empirical results and analysis

### 4.1. Cross-sectional correlation test and unit root test results

First, the smoothness of the data is checked by a unit root test. However, before applying unit root tests, cross-sectional dependencies

(CDs) must be checked. Commonly used unit root tests include Levin et al.'s LLC test, Phillips and Perron's PP test, or other tests if the sample data are independent in cross section. Conversely, if the sample data show cross-sectional dependencies, then a new unit root test needs to be used instead. To examine cross-sectional dependencies of sample data, we use the CD test proposed by Pesaran(Pesaran, 2015). Table 4 presents the results of Pesaran's cross-sectional correlation test, which shows that at the 1% significance level, the null hypothesis of cross-sectional correlation of all variable is rejected, proving that all variable is cross-sectionally related.

Therefore, we use Pesaran's CIPS test (Pesaran, 2007) to perform the unit root test, since this unit root test takes into account cross-sectional dependencies using a common factor structure (Chang, 2015). Pesaran's CIPS test results are shown in Table 5, the table shows all series have a unit root process. However, all variable series in first-order differential form are stationary. Therefore, we employ an integrated dataset of the same order.

### 4.2. Baseline model regression results

The results of the previous CD tests across variables or economies indicate that the original hypothesis of cross-sectional independence is strongly rejected at the 1% significance level. The selected variables have significant cross-sectional dependence over the study period of 2003–2018. Therefore, the use of AMG estimator is more reasonable in estimating the long-run impact coefficients. The results of AMG estimation are shown in Table 6. The coefficient of the quadratic term of economic growth is -2.49 and significant at the 10% level, while the coefficient of the primary term is 5.25 and passes the 5% significance test. The negative coefficient of the secondary term indicates the existence of an inverted U-shaped curve between economic growth and environmental pollution, which suggests that the EKC hypothesis is valid for the selected country study period. This result is in line with the study of Festus Victor Bekun et al. on 27 economies of the European Union(Bekun et al., 2021) and Fatima Bibi et al. on six different regions including Latin America and the Caribbean, East Asia and the Pacific, Europe and Central Asia, South Asia, the Middle East and North Africa, and Sub-Saharan Africa(Bibi and Jamil, 2021). At the initial stage of income growth, along with the decline of air quality, economic expansion needs to consume a large number of nonrenewable resources such as fossil fuels. The burning of fossil fuels is an important source of air pollution. In this period, the scale effect of economic growth dominated. Observing the development process and experience of different economies, the improvement of income level gave birth to the development and progress of science and technology. The following new technologies have replaced the old high emission, high energy consumption and high pollution technologies, and the industrial structure has also changed from capital intensive industries and labor-intensive industries to technology intensive industries. The technology effect and structure effect reversed the phenomenon that the environmental quality was deteriorating with economic growth at the beginning, and the pollutant emissions were gradually reduced, so the environmental quality was also improved. On the basis of the proven validity of EKC hypothesis, we can conduct the following nonlinear empirical model analysis.

**Table 4**  
Cross-sectional dependency test results.

	CD	P-value
lnCO2	139.555	0.000
lnren	148.067	0.000
lngini	156.940	0.000
ln10%	156.937	0.000
lnurb	156.964	0.000
lngdp	80.386	0.000
lnind	156.861	0.000
lnopen	156.804	0.000

**Table 5**  
Unit root test result.

variables	first-order difference data		raw data	
	CIPS*	significance level	CIPS*	significance level
lnCO2	-3.758	1%	-2.382	did not pass the significance test
lnren	-4.134	1%	-2.452	
lngini	-4.391	1%	-2.965	
ln10%	-4.623	1%	-3.462	
lnurb	-2.383	1%	-2.737	
lngdp	-3.007	1%	-1.673	
lnind	-3.458	1%	-2.135	
lnopen	-3.446	1%	-2.263	

**Table 6**  
AMG regression results.

	Coefficients	Std. Err.	z value	P > z
lnren	-0.35124***	0.060756	-5.78	0
lnurb	1.990314	1.890343	1.05	0.292
lngdp	5.253307**	2.191502	2.4	0.017
lngdp <sup>2</sup>	-2.49819*	1.489564	-1.68	0.094
lnind	0.154067	0.116765	1.32	0.187
lnopen	0.00114	0.035287	0.03	0.974
c_d_p	0.884467	0.170635	5.18	0
_cons	-4.86052	3.569129	-1.36	0.173

Note: \*\*\*, \*\*, and \* denote the level of significance at 1%, 5%, and 10%.

4.3. Panel threshold effect test results

Before conducting specific analysis, it is necessary to check the existence of threshold effect and the specific number of thresholds. First, a single threshold test is proceeded. The null hypothesis is no threshold value. If the null hypothesis is rejected, a double threshold test is performed. The original assumption is that the threshold value does not exist. If the  $H_0$  is rejected, the triple threshold test is performed, and so on. Having checked for smoothness, we proceed to test for the existence of a threshold effect of economic development on carbon emissions in our selected countries.

It can be seen from Table 7 that there is a threshold effect with income inequality as the threshold variable. The model adopted the single threshold test and the double threshold test, and in the triple threshold test, the F value is 14.77, and its P value is 0.1600, showing that the null hypothesis that the model has two threshold values cannot be rejected. Therefore, the test results show that there are two thresholds of income inequality in the sample.

Then, the truth check of the threshold estimates was performed. The likelihood ratio trend plot is shown in Fig. 2. This plot allows to determine each threshold value and the corresponding confidence interval to further test whether the threshold estimates are true values, as shown in Table 7, and the two threshold values are obtained as 0.0051 and 0.0061, respectively, and the corresponding 95% confidence intervals are (0.0039, 0.0061) and (0.0054, 0.0064), respectively, and the LR statistics of the two threshold values are less than the critical values at the 95% significance level, indicating the existence of a double threshold in the model. The results of a series of tests indicate that there is a threshold effect of economic development level on carbon emissions

**Table 7**  
Panel threshold effect test results.

	F-value	P-value	10%	5%	1%
Single	13.10**	0.0233	7.6150	9.4682	14.8025
Double	16.13***	0.0067	8.5526	9.9670	14.1550
Triple	14.77	0.1600	22.5200	28.6430	40.3975

Note: \*\*\*, \*\*, and \* denote the level of significance at 1%, 5%, and 10%.

with income inequality as the threshold variable.

	value	confidence interval
first threshold	0.0051	(0.0039, 0.0061)
second threshold	0.0061	(0.0054, 0.0064)

4.4. Panel threshold estimator results

The results of panel threshold estimator are displayed on Table 8. Table 8 shows that among the selected sample data from 56 countries the influence of economic growth on carbon emissions has a double-threshold effect of income inequality, that is, the impact of economic growth on per capita carbon emissions is non-linear. The sign of the elasticity coefficient of per capita GDP indicates that economic growth has different effects on carbon emissions in different income inequality ranges.

An interesting finding is that the relationship between these two factors in the countries studied has an “N”-shaped curve under the influence of the threshold effect of income inequality. From the empirical results during our research period, in the stage of low income inequality, economic growth has a significant promoting impact on carbon emissions. With the deepening of income inequality, economic growth in turn inhibits the growth of carbon emissions. However, in the stage of high income inequality, the effect of economic growth on carbon emissions once again becomes a positive promotion.

We use income inequality as the threshold variable to obtain two threshold values of 0.0051 and 0.0061, respectively. The appearance of the threshold means that income inequality is an essential factor that influences the relationship between them. The threshold values of 0.0051 and 0.0061 divide these data into three different regions. When the income inequality is at a low level (that is, lngini is lower than the threshold value of 0.0051), the coefficient of economic growth to carbon emissions is 0.6005, and it has passed the 1% significance level check, this suggests that at lower income inequality, economic growth has a significant positive contribution to per capita carbon emissions, and GDP growth causes growth in per capita carbon emissions. When income inequality is in the middle stage (that is, lngini is higher than 0.0051 and lower than 0.0061), the coefficient of economic growth to per capita carbon emissions is -2.1056, but it does not pass the significance test, which means that when income inequality enters the middle stage, GDP increase does not bring an increasing of carbon emissions, instead, GDP growth inhibits the growth of carbon emissions. When the degree of income inequality is high (i.e. lngini is higher than 0.0061), the coefficient of economic growth to carbon emissions is 0.6272 significant at the 1% level, that is, GDP growth in the context of high income inequality significantly increases per capita carbon emissions.

The potential cause is that when these selected sample countries are in the stage of low income inequality, usually one country is in the early period of industrialization, the income level is low, and the social groups at this time rarely generate demand for environmental quality, economic growth is mainly achieved by resource-intensive and labor-intensive sectors which are characterized by high energy consumption and high carbon emissions, and the economic structure has changed from agriculture to energy-intensive heavy industry, which increases pollution emissions (Zhao et al., 2017). Therefore, in the stage of low income inequality, economic development is accompanied by a significant increase in carbon emissions.

With the deepening of income inequality, economic development in turn inhibits the increase of carbon emissions. This may be because with the continuous progress of society and the upgrade of the level of economic development, the income gap has begun to widen, and the degree of income inequality has gradually increased. This process can bring about higher economic growth efficiency and a cleaner energy structure. This largely reduces the dependence on carbon-based energy consumption and the impact on increased carbon emissions (Huang and

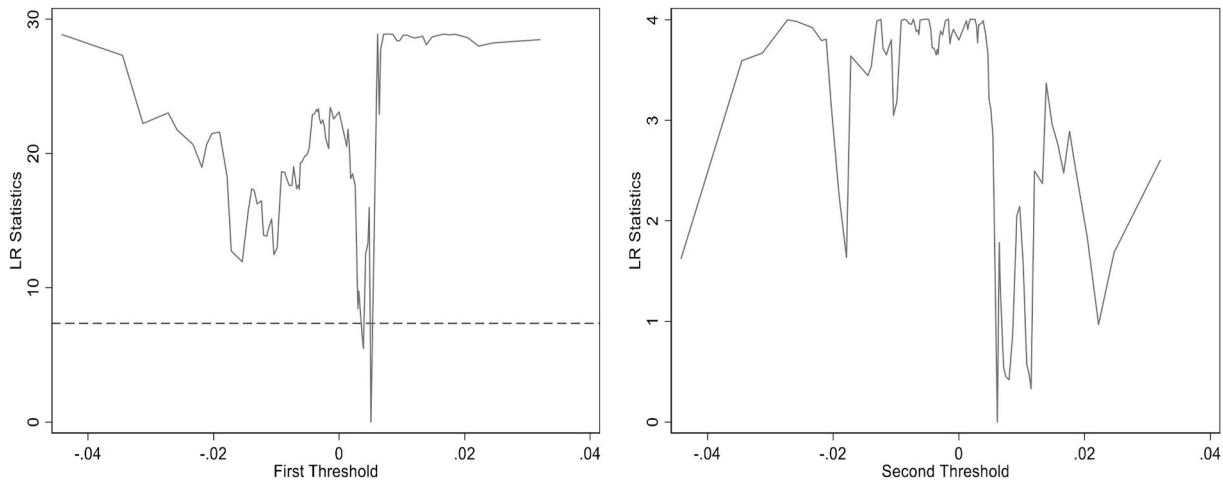


Fig. 2. Likelihood ratio trend plot.

**Table 8**  
Panel threshold regression results.

	Coefficients	t value	P value
lngdp (Ingni $\leq$ first threshold)	0.6005***	6.97	0.000
lngdp	- 2.1056	-	0.101
(first threshold < Ingni $\leq$ second threshold)		1.67	
lngdp (Ingni > second threshold)	0.6272***	7.39	0.000
lnurb	0.8925	1.48	0.144
lnren	- 0.1638***	-	0.006
		2.84	
lnopen	0.1144***	4.67	0.000
lnind	- 0.0625	-	0.348
		0.95	
cons	-0.0063***	-	0.001
		3.44	
R <sup>2</sup>	0.2969		
Observations	840		

Note: \*\*\*, \*\*, and \* denote the level of significance at 1%, 5%, and 10%.

Duan, 2020; Wang et al., 2022a). Churchill et al. argue that the higher the income inequality, the more the R&D spending in OECD countries, and the increase in R&D spending will contribute to the reduction of carbon emissions(Awaworyi Churchill et al., 2019), and the emergence of this stage also corroborates the findings of Churchill et al. and Wan et al. (2022).

Finally, in countries with higher income inequality, income is more concentrated at the top of the distribution, leading to increased competition in consumption and longer working hours, which in turn increases energy consumption and emissions (Bagwell and Bernheim, 1996; Bowles and Park, 2005; Fitzgerald et al., 2015). In addition, rising income inequality has an obvious negative effect on renewable energy consumption (Tan and Uprasen, 2021) and slows development of green innovation. Reduced consumption of clean energy also could increase carbon emissions. A series of research evidence shows that when income inequality in these countries is high, the growth of GDP significantly increases per capita carbon emissions (Bai et al., 2020; Jorgenson et al., 2017).

Results from a threshold regression model with panel data from 56 countries confirms an N-shaped relationship between them, and our findings are consistent with those of Martinez Zarzoso, Amin Haghnejad, Chien-Chiang Lee, Allard et al. (Allard et al., 2018; Haghnejad and Dehnavi, 2012; Lee et al., 2009; Martínez-Zarzoso and Bengochea-Morancho, 2004). At the same time, the addition of the income inequality variable also expands the nonlinear link between the two under a unified analytical framework, providing new evidence for an N-shaped link between them. Previous studies have pointed out that

economic mechanisms affect the direction or extent of the effect of income inequality on carbon dioxide emissions(Wan et al., 2022). This paper shows that income inequality also affects the direction and extent of the effect of economic growth on per capita carbon emissions. Our findings echo the former conclusion. In addition, some studies have explored the factors affecting China’s economic growth and carbon emissions, and found that there is a threshold effect with population structure, energy structure, technological level and government investment in the environment as threshold variables (Song, 2021). Compared to this study, the sample size of our study survey was 56 countries from different income groups, and the sample covered a wider range of studies. Our study is unique from previous studies in that it explores at an international level rather than a specific country, shows that the impact of economic growth on carbon emissions is dependent, to some extent, on the degree of income inequality, and complements the former.

From Table 8, we can know that in terms of other control variables, the impact of urbanization and industrial structure on carbon emissions is not significant. Renewable energy consumption and trade openness are closely related to carbon emissions. Their corresponding coefficients are -0.1638 and 0.1144 respectively. This shows that the consumption of renewable energy reduces carbon emissions, and the opening of trade will promote the growth of carbon emissions. This is because carbon emissions are mainly due to the large use of non-renewable energy such as fossil fuels. The increase of renewable energy consumption will reduce the consumption of non-renewable energy, and the environmental quality will be improved to some extent. Trade opening is accompanied by more frequent economic activities, and carbon emissions are also increasing.

4.5. Robustness check

Because different samples have different sensitivities to the obtained results, sub-sample regression is often performed during robustness testing. At the same time, considering that the Gini coefficient is more sensitive to changes in the distribution center than to extreme cases, we use Income share held by highest 10% to measure income inequality instead of the Gini coefficient as a threshold variable when performing robustness tests. According to the difference in income level and referring to the classification standard of the World Bank database, we divided the samples into high-income group, middle-high-income group and middle-low-income group, grouped regression and established an econometric model to analyze the link between income inequality, economic growth and per capita. The results of the robustness check are presented in Table 9 and Fig. 3.

The results of the high-income group show that there is a threshold effect with income inequality as the threshold variable. The model has

**Table 9**  
Robustness test results Panel threshold effect test results section.

	Threshold Effect	F-value	P-value	10%	5%	1%
high income group	Single	9.53*	0.0600	7.9631	10.1317	15.3269
	Double	21.82***	0.0000	8.2558	11.0092	19.3478
Upper middle income group	Single	3.36	0.5300	7.4356	8.9786	10.7424
	Double	27.24***	0.0000	7.0969	8.7520	10.4363
low-middle income group	Single	9.72***	0.0067	4.8286	6.2207	8.2849

Note: \*\*\*, \*\*, and \* denote the level of significance at 1%, 5%, and 10%.

passed both single and double threshold tests. Therefore, the test results show that there are two thresholds of income inequality in the sample of countries in the high-income group,  $-0.0206$  and  $-0.0216$ , respectively. The results show that the relationship between the two variables in these countries in the high-income group is an “N”-shaped curve under the influence of the threshold effect of income inequality. The elasticity coefficient of economic growth is positive when degree of income inequality is below the first threshold or above the second threshold, but negative when the threshold variable is between  $-0.0206$  and  $-0.0216$ . Although the elasticity coefficient in the high-income group model is different from that in global model in absolute value, the effect direction is the same, and it has passed the significance test, which shows robustness of our results.

The results of the upper-middle-income group also show that the influence of economic growth on carbon emissions has a double-threshold effect of income inequality. However, no matter which interval the threshold variable is in, the influence of economic growth on per capita carbon emissions is always positive, this is in agreement with the findings of Michael Kaku Minlah et al. (Minlah and Zhang, 2021). The results of the lower-middle-income groups show that the impact of economic growth on per capita carbon emissions has a single threshold effect of income inequality. The value and number of static panel thresholds are based solely on the sample data, and there are fewer observations in the upper-middle-income group and the lower-middle-income group, so the regression results of these two groups are different from the regression results of all samples. Due to differences in regions and economic development, the relationship between economic growth and carbon emissions is diverse (Yang et al., 2015). Because the existing carbon emissions literature often finds that EKC is applicable to developed countries, but generally not to developing economies (Hasanov et al., 2019; Wang et al., 2022d). In this regard, most of the upper-middle-income and lower-middle-income groups are developing or emerging economies that have just entered the market economy or have recently developed. Therefore, there is a far way to go yet for countries in the upper-middle and lower-middle-income groups to reach the level of economic, institutional and environmental development where income levels are negatively related to carbon dioxide.

		value	confidence interval
high income group	first threshold	$-0.0206$	$(-0.0245, -0.0199)$
	second threshold	$-0.0216$	$(-0.0245, -0.0199)$
Upper middle income group	first threshold	$0.0063$	$(0.0062, 0.0072)$
	second threshold	$0.0072$	$(0.0066, 0.0076)$
low-middle income group	first threshold	$-0.0081$	$(-0.0146, -0.0075)$

Panel threshold regression results section.

		Coefficients	t value	P value	
high income group	lngdp (lngini $\leq$ first threshold)	0.9358**	2.58	0.015	
	lngdp	-0.1511	-0.15	0.885	
	lngdp (lngini $<$ lngini $\leq$ second threshold)	0.4127***	5.55	0.000	
	lnurb	0.1371	0.15	0.884	
	lnren	-0.1620**	-2.60	0.014	
	lnopen	0.1903***	3.84	0.001	
	lnind	-0.1153*	-1.85	0.075	
	cons	-0.0075***	-3.46	0.002	
	R <sup>2</sup>	0.2473			
	Observations	465.0000			
	Upper middle income group	lngdp (lngini $\leq$ first threshold)	0.5901***	5.34	0.000
		lngdp	3.6664***	3.23	0.005
		lngdp (lngini $>$ second threshold)	0.6972***	5.37	0.000
		lnurb	1.3178*	1.84	0.082
lnren		-0.2335***	-4.86	0.000	
lnopen		0.0613	1.65	0.116	
lnind		0.1164	1.24	0.230	
cons		-0.00573**	-2.37	0.029	
R <sup>2</sup>		0.4404			
Observations		285			
low-middle income group		lngdp (lngini $\leq$ threshold)	1.6188***	4.5700	0.0060
		lngdp (lngini $>$ threshold)	0.5378	1.7400	0.1410
		lnurb	3.3512	0.7900	0.4660
		lnren	-0.3258**	-2.8000	0.0380
	lnopen	0.0440	0.7300	0.4980	
	lnind	-0.3226	-1.9200	0.1120	
	cons	-0.17598	-1.23	0.272	
	R <sup>2</sup>	0.4094			
	Observations	90			

Note: \*\*\*, \*\*, and \* denote the level of significance at 1%, 5%, and 10%.

**5. Conclusion**

On the one hand, the relationship between economic growth and environmental pollution has always been a hot topic of concern, and the environmental Kuznets curve hypothesis is important to the formulation of climate change countermeasures and development strategies. Although there has been a lot of research over the decades. These studies did not reach consistent conclusions about the validity of the EKC hypothesis at different stages of development in different regions due to differences in methodological techniques and selected datasets. On the other hand, the COVID-19 pandemic has exacerbated already high income inequality worldwide. This study revisits the EKC hypothesis from the perspective of income inequality by incorporating this social factor into the EKC framework. We collected data from 56 countries in the high, upper middle and lower middle income groups from 2003 to 2018, and used income inequality as a threshold variable, and focused on exploring the nonlinear relationship between economic growth and carbon emissions. Meanwhile, macro variables such as urbanization degree, renewable energy consumption, trade openness and industrial structure are also included in the model, and the threshold effect of economic growth on carbon emissions is examined from the perspective of income inequality. We find that income inequality redefines the EKC hypothesis. First, the results indicate, the impact of economic growth on carbon emissions is non-linear. The impact of economic growth on carbon emissions has a double-threshold effect of income inequality. This also means, economic growth has different impacts on carbon emissions in various income inequality ranges. An interesting finding is that the relationship between economic growth and per capita carbon emissions in the countries studied has an “N”-shaped curve, rather than the traditional inverted U-shaped curve, under the influence of the

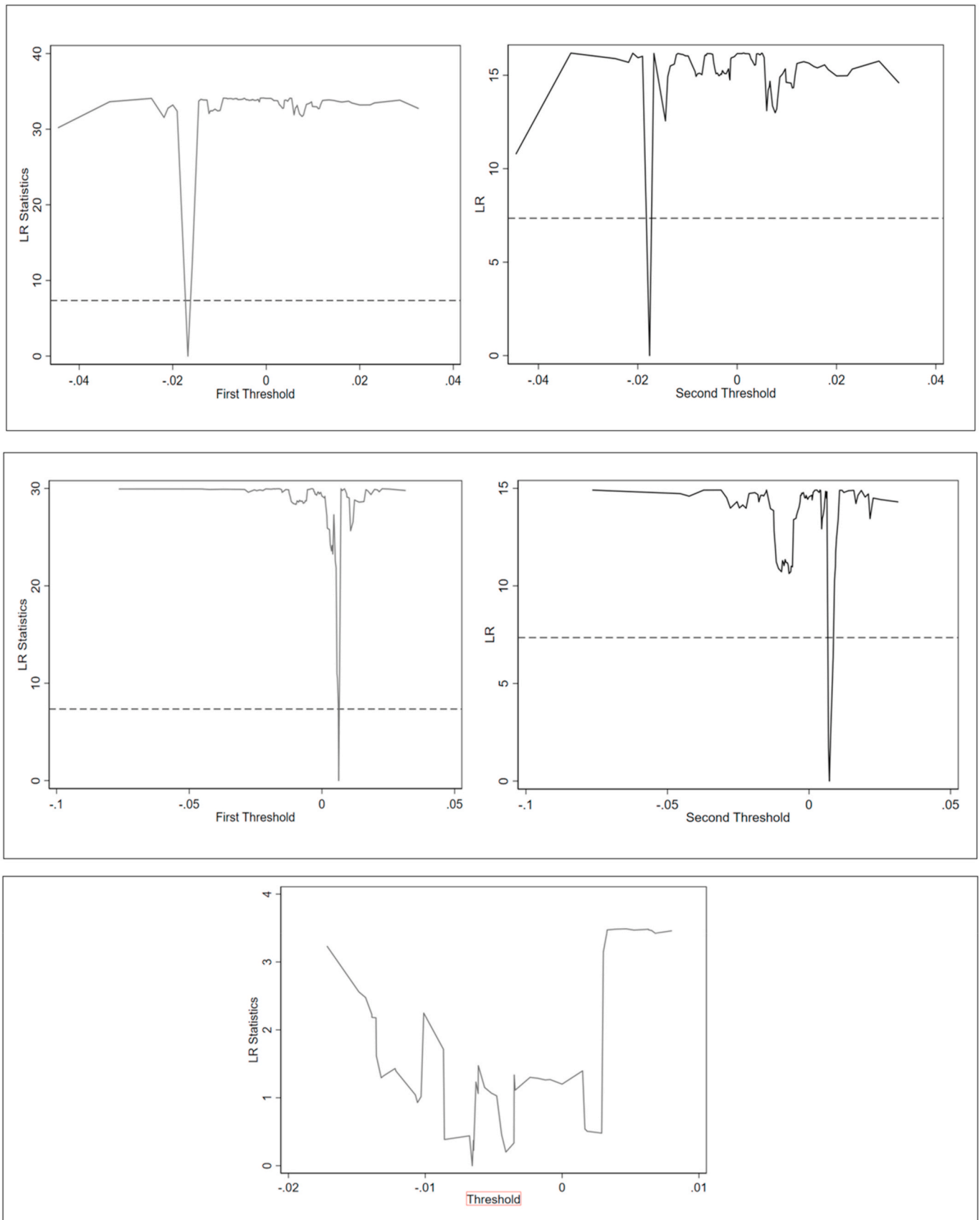


Fig. 3. High income group likelihood ratio trend plot, upper middle income group likelihood ratio trend plot and lower middle income group likelihood ratio trend plot.

threshold effect of level of income inequality. Second, from the empirical results during our research period, in the stage of low-income inequality, economic growth has an obvious facilitation on carbon emissions. As income inequality deepens, economic growth, in turn, dampens the increase in carbon emissions. However, in the stage of high income inequality, the impact of economic growth on carbon emissions once again becomes a positive promotion. Finally, the robustness test results show that countries in the high income group and the upper middle income group are more suitable for this research conclusion. The relationship between economic growth and per capita carbon emissions in the high-income group is an "N"-shaped curve under the threshold effect of income inequality. However, in the upper-middle-income groups, regardless of the range of the threshold variable, the impact of economic growth on per capita carbon emissions is always positive. However, the test results for the lower-middle-income group were not significant. In this regard, most of the upper-middle and lower-middle-income groups are developing or emerging economies that have just entered the market economy or have recently developed. Countries in the upper-middle and lower-middle-income groups still have a far journey to go through to reach the level of economic, institutional and environmental development where income levels are negatively related to carbon dioxide.

According to our research conclusions, when the income inequality of a country or region is in different ranges, the impact of economic growth on carbon emissions is different, in the low income inequality range or the high income inequality range, economic growth significantly promotes the rise of carbon emissions, only when the income inequality is in the middle range, economic growth inhibits the growth of carbon emissions. This shows that the objective of "sustainable social development" and the objective of "reasonable income distribution" have a crucial connection. Achieving trade-offs between income distribution, economic development and carbon emission reduction is worthy of further consideration. The trade-off between economic growth and sustainable development requires consideration of income distribution. When income inequality is at a higher or lower level, the issue of carbon emissions during economic growth becomes more acute. In fact, being in a moderate income inequality range can subtly ease the contradiction between the two. On the one hand, for countries with high income inequality, we suggest taking some measures to control income inequality within a moderate range to promote carbon reduction. On the other hand, according to the mechanism of this threshold effect, we suggest that the government should advocate more renewable energy

and clean energy in terms of energy consumption, fully support the development of green innovative technologies, and create an institutional environment that facilitates the exploitation of new energy sources and low-carbon techniques to enhance the efficiency of R&D. Equal income distribution or a huge wealth gap is not conducive to the realization of the dual goals of economic development and carbon emission reduction. Under almost absolute egalitarianism, more economic growth leads to more carbon emission growth. Similarly, with a huge wealth gap, because of the vicious competition brought about by the fact that income is almost all concentrated at the top, economic growth promotes the growth of carbon emissions. Therefore, when achieving the dual goals of economic development and carbon emission reduction, policy makers should consider the income distribution policy, And the government can neither adopt an almost egalitarian income distribution policy, nor do not take measures to intervene in the continuously widening income gap. Policy makers should give play to the leading role of the government, and keep the income gap within a reasonable range.

#### Author contribution statement

Qiang Wang: Conceptualization, Methodology, Data curation, Investigation Writing- Original draft, Writing- Reviewing. Ting Yang: Methodology, Software, Data curation, Investigation Writing- Original draft, Writing- Reviewing and Editing. Rongrong Li: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Supervision, Writing- Reviewing and Editing.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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## Appendix 1

high income group	upper middle income group	lower middle income group
Austria	Argentina	Bolivia
Belgium	Armenia	Honduras
Canada	Bulgaria	Indonesia
Switzerland	Belarus	Kyrgyz Republic
Cyprus	Brazil	El Salvador
Czech Republic	China	Ukraine
Germany	Colombia	
Denmark	Costa Rica	
Spain	Dominican Republic	
Estonia	Ecuador	
Finland	Georgia	
France	Kazakhstan	
United Kingdom	Moldova	
Greece	Panama	
Hungary	Peru	
Ireland	Paraguay	
Iceland	Russian Federation	
Italy	Thailand	
Lithuania	Turkey	
Luxembourg		

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(continued)

high income group	upper middle income group	lower middle income group
Latvia		
Malta		
Netherlands		
Norway		
Poland		
Portugal		
Slovak Republic		
Slovenia		
Sweden		
Uruguay		
United States		

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