Revisiting the relationship between income inequality and CO_2 emissions in the USA: new evidence from CS-ARDL model

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Abstract: Both theoretically and empirically, the association between income inequality and CO_2 emissions is ambiguous. Hence, considering the short- and long-term dynamics of income inequality on carbon emissions, as well as the heterogeneity of the emission distribution, this paper employed cross-sectional autoregressive distributed lag (CS-ARDL) approach over the period 1990–2018 and extended revisiting the effect of income inequality on carbon emissions across US states by considering human development index. The study finds that higher income inequality tends to exacerbate US carbon emissions in the long term. Additionally, the study validates the EKC hypothesis by demonstrating that carbon emissions rise with lower income levels and diminish with higher income levels. Population growth leads to increased carbon emissions in the short and long term, while human development index has a negative impact on carbon emissions in the short run. The findings are vigorous to various causality tests. Policy recommendations are further discussed.

Keywords: income inequality; carbon emissions; the US states; CS-ARDL; USA.

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1 Introduction

Rapid economic expansion has impacted not only the environment but has also led to significant socioeconomic issues, such as rising income inequality (Cheng et al., 2021; Kusumawardani and Dewi, 2020). Income inequality has risen dramatically in recent decades, which may have significant ramifications for climate change (Diffenbaugh and Burke, 2019). Mounting economic inequality is one of the social crises that most nations around the globe have been coping with, while the environmental crisis has manifested itself in a rapid increase in environmental challenges. Income disparity contributes to increased emissions by obstructing environmental regulations (Baloch et al., 2020a). Furthermore, it may result in less environmental protection and, as a result, increased emissions. Income inequality is claimed to raise emissions through ownership and voting channels (Grunewald et al., 2017). The United Nations (UN) in 2015 adopted the 2030 Sustainable Development Goals (SDGs) to resolve these and other global concerns, with the objective of holistically synchronise economic development, prosperity, and environmental conservation. The objectives are to eliminate poverty, improve long-term economic growth, promote social development, promote equality, preserve the environment, and combat climate change (Hundie, 2021).

The USA, as the world's largest economy and second-largest carbon emitter, has significant income inequality and is striving hard to reduce emissions. According to a statistical review of energy, the USA accounts for about 14% of global carbon emissions. On the other hand, according to the World Inequality Report 2021, the income share of the wealthiest 10% of population in the USA increased from 43.9% in 2000 to 47% in 2014, with a persistent upward trend. This suggests that the rich's share of wealth is increasing, and so income inequality is expanding. Rapid economic growth has been associated with increases in income disparity and environmental deterioration (Cheng et al., 2021; Fodha and Zaghdoud, 2010). The amount of carbon dioxide emitted varies by geography or region. When examining the association between income inequality and carbon emissions while taking individual variability into account, it can expose the effects of various regions of the total carbon emission distribution. Therefore, the following questions arise:

1 Does income inequality influence US carbon emissions?

2 Does income inequality have different short- and long-term effects on the US carbon emissions?

As a result, answering these questions can assist us in the extended level of re-examining the impact of income disparity on carbon emissions and give useful guidelines for policymakers.

This present study shows a peculiar divergence from the work of Jorgenson et al. (2017) that re-examines the relationship between income inequality and CO_2 emission in the USA in the following distinct ways. First, as per the studies of Jorgenson et al. (2017), they observe a significant and positive relationship between CO_2 emission and top 10% income share in the US states whereas an insignificant relationship is found between Gini coefficient and carbon emissions. However, we report a positive and significant links between income inequality (Gini) and CO_2 emission in the long run. Second, our paper focuses on an additional explanatory variable, human development index (HDI), which aims to enhance the work by Jorgenson et al. and the existing literature on socio-economic drivers of carbon emission. The human development index (HDI) represents a national average of outcomes in three key areas, including: health and long life, knowledge, and minimal standards of living. By adapting the HDI to pervasive levels of inequality in the aforementioned three dimensions, the HDI goes one step further. In other words, the distribution of the three underlying achievements within the population is also taken into account by the HDI. According to the United Nations Development Programme (UNDP), the HDI plays a crucial role in the economic development of a country (a state in this paper) not the growth of the economy alone. Although countries (states) may have the same or remarkably close gross domestic product per capita (GDPC), they may have different human development level thus the HDI enhances our model in this study. Third, based on the methodology, while their study uses the cross-sectional Prais-Winsten regression model with panel-corrected standard errors, this study extends analysis period and implements the CS-ARDL approach, allowing to account for the long-term effect in the case of cross-sectional dependency problem and providing more robust estimates compared to the other panel data methods. Chudik et al. (2015, p.2) states that "in the case of heterogenous slope specifications the CS-ARDL estimates of the long-run coefficients could also be sensitive to outlier estimates of the long-run effects for individual cross-section units". Fourth, this study extends data for the US state level over the period 1990–2018. All of these diversified findings have motivated us to explore the nexus of the income inequality and CO_2 emissions in the USA.

The main contribution of this paper is to show how income inequality affects carbon emissions in the short and long-run, as well as how long it takes to reach the long-run equilibrium if there is an exogenous shock in our model across the US states. Thus, this study undertakes to widen the existing literature by examining the new evidence of income inequality-carbon emissions nexus in the context of state-level analysis for the USA taking the HDI as an additional determinant of carbon emissions. In this work, we aimed to show how important HDI is to reduce carbon emission in the US states by enhancing the existing literature. As revisiting the study by Jorgenson et al. (2017) via applying a newer econometrics method, and enhancing that work with an additional explanatory variable, which is HDI, should be a fruitful addition to the existing literature. To sum up, answering these three questions above, this work proves a significant relationship between carbon emissions and income inequality in the US states, as well as how human development plays a critical role in reducing carbon emissions in the short run.

The rest of the paper is organised as follows. Section 2 highlights the relevant literature. Data, model, and methodology are described in Section 3. Section 4 presents results and discussions. Finally, we conclude in Section 5.

2 Related work

2.1 Economic growth and environmental quality

The environmental Kuznets curve (EKC) propounded by Grossman and Krueger (1995) is the fundamental theoretical paradigm that has been applied in most of the current research on the relationship between economic development and environmental degradation. The EKC hypothesis asserts that economic growth and CO_2 emissions have an inverted U-shaped relationship. The hypothesis indicates that economic growth adversely affects the environment at the initial stages of the development period, but it benefits the environment after exceeding the threshold level. Empirical studies aiming to test the EKC hypothesis have yielded inconclusive results concerning the relationship between economic growth and carbon emissions (Baloch et al., 2020a; Bhattacharya, 2019; Pata and Aydin, 2020; Sarkodie and Ozturk, 2020). Several empirical studies validate the EKC hypothesis (Baloch et al., 2020b; Dogan and Inglesi-Lotz, 2020; Hundie, 2021; Kusumawardani and Dewi, 2020; Pata and Aydin, 2020; Sarkodie and Ozturk, 2020; Sharif et al., 2020), others, however, have found no evidence to support the hypothesis (Dogan and Ozturk, 2017; Dogan and Turkekul, 2015). Some researchers have discovered a linear relationship between economic growth and CO_2 emissions (Gill et al., 2017), while others have explored a U-shaped relationship (Dogan and Ozturk, 2017; Dogan and Turkekul, 2015; Sohag et al., 2019), and yet, others have found an N-shaped association (Allard et al., 2018; Caravaggio, 2020; Lorente and Álvarez-herranz, 2016) and M-shaped (Bousquet and Favard, 2005; Terrell and Terrell, 2020). Many factors contribute to inconsistent or inconclusive findings, including the sample size, model and approach used, and variables used (Esteve and Tamarit, 2012; Zanin and Marra, 2012). Baek and Gweisah (2013) asserted that earlier studies in the EKC literature relied solely on per capita income to assess environmental degradation. In this regard, omitted variable bias became a concern in early research by ignoring variables that are major predictors of environmental issues (Iwata et al., 2010). Recent studies have shown that, in addition to per capita income, income distribution which has an immense social and economic impact, is another crucial factor influencing CO_2 emissions and environmental quality (Bai et al., 2020; Hailemariam et al., 2020; Mader, 2018). Hence, there is an increasing interest in examining the impact of national per capita income and its distribution on per capita carbon emissions and the global environment.

2.2 Income inequality and environmental quality

From a theoretical standpoint, there are three approaches in which income inequality can affect emissions levels. The first is the political economy approach (PEA), which concentrates on power dynamics that form environmental policy (Boyce, 1994; Torras and Boyce, 1998). In other words, income inequality has an indirect impact on pollution due to political power distribution. The second method focuses on household economic activity and marginal propensity to emit (MPE) (Ravallion et al., 2000; Heerink et al., 2001; Berthe and Elie, 2015). Finally, inequality and environmental phenomena have been used to establish Veblen's (1899) emulation theory (ET) (Jorgenson et al., 2017; Grunewald et al., 2017).

The first approach was propounded by Boyce (1994), who used a 'power-weighted social decision rule' to estimate the impact of income inequality on environmental pollution. According to Boyce's PEA approach, the effect of income inequality on environmental degradation is related to the attributes of winners and losers in economic ventures that cause environmental degradation. He asserts that environmental pollution is linked to the distribution of income and power in society's rich and poor segments. In a country with substantial income disparity, ruling classes will facilitate the approval of environmentally destructive projects and make auditing difficult, resulting in environmental damage (Boyce, 1994; Torras and Boyce, 1998). Since the income distribution is skewed toward the top, the elites have more influence over environmental decisions, resulting in higher pollution. The second approach is based on household consumption patterns and marginal propensity to emit (MPE). Hence, variations in household income distribution lead to a shift in emissions. According to this theoretical standpoint, the poor are commonly thought to have a much higher marginal propensity to emit than the affluent, owing to their inability to bear the high cost of low-carbon goods (Ravallion et al., 2000). Because of income equality, a substantial number of middle-class individuals live carbon-intensive lifestyles, resulting in increased carbon emissions. Furthermore, the poor are more likely than the rich to choose inefficient energy products. As a result, reducing inequality would increase the poor's income, resulting in an increase in carbon emissions. The third approach known as the ET of Veblen (1899) connects the effect of income inequality on environmental quality to individual economic activity. According to this theory, higher income inequality increases consumption intensity, which leads to increased energy consumption and CO_2 emissions. The Veblen effect, which suggests that income inequality stimulates status consumption, and the privileged consume luxurious and prestigious products and services to preserve their status, is attributed to the high level of consumption. Furthermore, income inequality causes an unusual increase in working hours, resulting in high energy usage and CO_2 emissions as a result of households' multiple consumption choices.

From an empirical viewpoint, the evidence on the association between income inequality and CO_2 emissions is mixed or inconclusive. Higher income inequality has been linked to lower CO_2 emissions in some studies or consistent with MPE theory (Demir et al., 2019; Huang and Duan, 2020; Hübler, 2017; Sager, 2019; Yang et al., 2020), while others have found a positive association between income inequality and carbon emission or support PEA theory (Bae, 2018; Baloch et al., 2020a; Hailemariam et al., 2020; Jorgenson et al., 2015; Liu et al., 2019a; Morse, 2018; Mushtaq et al., 2020; Padhan et al., 2019; Uzar and Eyuboglu, 2019), or income inequality exerts no effect on carbon emission (Borghesi, 2006; Wolde-Rufael and Idowu, 2017). Furthermore, some scholars claim that it is impossible to attribute the association between income inequality and environmental quality to one of the three theories entirely. This line of thought contends that income level and country-specific macroeconomic features are extremely important (Grunewald et al., 2017; Jorgenson et al., 2016; Kusumawardani and Dewi, 2020; Mittmann and de Mattos, 2020).

Table 1 presents a summary of the extant literature on the nexus of income inequality and carbon emission. Briefly, the above empirical studies yield mixed or inconclusive results. This merits further scrutiny to unravel how income inequality affects the environmental quality in the USA.

Table 1 Chronological summary of recent literature on income inequality and environmental quality

Study	*Country/region*	*Sample period*	*Technique*	*Relationship*
Ota (2017)	Asian developing countries	1990–2000	Trend analysis	Mixed
Knight et al. (2017)	26 countries	2000–2010	Fixed effect and CCEMG	Positive
Hübler (2017)	149 countries	1985–2012	Quantile regression and CCEMG	Negative
Jorgenson et al. (2017)	USA	1997–2012	Prais-Winsten regression	Non-significant
Wolde-Rufael and Idowu (2017)	China, India	1971–2010	Bound test technique	Non-significant
Grunewald et al. (2017)	158 countries	1980–2008	Fixed effect	Negative (low) Positive (high)
Mader (2018)	USA/ 26 countries	1997–2012/ 2000–2010	Fixed effect	Non-significant
Baloch et al. (2018)	Pakistan	1966–2011	ARDL bound test	Positive
Demir et al. (2019)	Turkey	1963–2011	ARDL bound test	Negative
Liu et al. (2019a)	50 states of USA	1997–2015	Panel quantile regression	Positive/mixed
Hailemariam et al. (2020)	17 OECD countries	1945–2010	CCEMG	Negative
Ridzuan (2019)	174 countries	1991–2010	OLS/random effect	Positive
Baloch et al. (2020a)	40 Sub-Saharan African countries	2010–2016	D&K regression	Positive
Bhattacharya (2020)	India	1981–2008	Various regression methods	Mixed
Bai et al. (2020)	China	2000–2015	Panel threshold model	Positive
Huang and Duan (2020)	92 countries	1991–2015	Dynamic panel threshold model	Negative
Yang et al. (2020)	47 countries	1980–2016	DSUR	Negative

Table 1 Chronological summary of recent literature on income inequality and environmental quality (continued)

Study	*Country/region*	*Sample period*	*Technique*	*Relationship*
Mushtaq et al. (2020)	China	1995–2015	FE, PCSE, N-W and FGLS	Positive
Uddin et al. (2020)	G7 countries	1870–2014	Non-parametric panel estimation	Mixed
Rojas-Vellejos and Lastuka (2020)	68 countries	1961–2010	Quantitative methods	Mixed
Hundie (2021)	Eithopia	1979–2014	ARDL and DOLS	Mixed
Ghazouani and Beldi (2021)	Seven Asian countries	1971–2014	Local linear dummy variable (LLDVE) approach	Mixed
Baloch and Danish (2022)	BRICS economies	1994–2018	DOLS and FMOLS	Positive
Alatas and Akin (2022)	28 OECD economies	1990–2018	DOLSMG, BA-OLS and CUP-FM	Positive
Ogede and Tiamiyu (2022)	Saharan Africa countries	2004–2019	Panel ARDL	Positive
Yang et al. (2022)	France and USA	1915–2019	Quantile-on-quantile regression	Mixed

Table 2 Chronological summary of recent literature on human development index and environmental quality

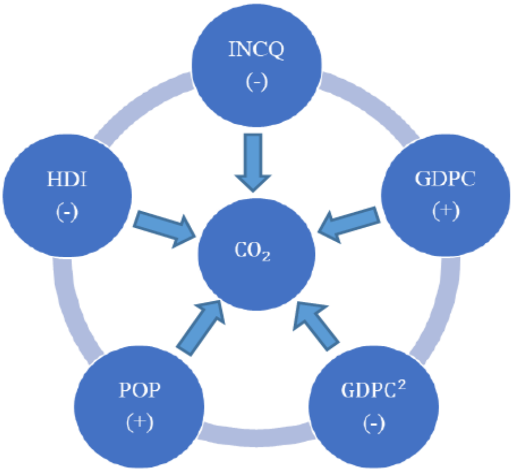
Study	*Country/region*	*Sample period*	*Technique*	*Relationship*
Bedir and Yilmaz (2016)	33 OECD countries	1992–2011	Granger causality	Mixed
Mohmmed et al. (2019)	Top ten emitting countries	2000–2013	LMDI	Positive
Ekasari and Suryanto (2020)	East Java	2012–2016	Panel data	Positive
Hussain and Dey (2021)	27 developed/ emerging/developing countries	1990–2016	Pooled-OLS, FE and FE with IV	Mixed
Dumor et al. (2022)	East African Community (EAC)	1980–2020	DARDL	Positive
Li et al. (2022)	189 countries	1990–2019	Decoupling Model	Mixed

2.3 Human development index and environmental quality

HDI as a socio-economic driver of carbon emission has not been widely used in the literature. There are only a few studies, which investigate this relationship. Among them, Asongu (2018) and Akbar et al. (2021) found evidence that more carbon emissions lead a decrease in inclusive human development and reduce human health and wealth which is similar to, but in opposite direction what we found in this study that shows a rise in HDI reduces carbon emissions in the short run since we have other economic drivers which affect carbon emissions in the long run strongly. Finally, this study is in line with Costa et al. (2011), which shows the importance of improving HDI to reduce carbon emissions. Table 2 summarised some important HDI-environmental quality related research studies.

In addition, the graphical representation of all the explanatory variables on CO_2 emissions is depicted in Figure 1.

Figure 1 Graphical representation of empirical findings (see online version for colours)



In addition, based on above discussions, the following hypotheses are proposed (see Table 3) in the study:

Table 3 Hypotheses proposed in the study

H_{1a}	GDP per capita will positively affect CO_2 emissions.
H_{1b}	The squared of GDP per capita will negatively affect CO_2 emissions.
H_2	Income inequality will negatively affect CO_2 emissions.
H_3	Human development index will negatively affect CO_2 emissions.

3 Data, model and methodology

3.1 Data

The dataset contains yearly observations of CO_2 emissions, Gini coefficient, GDP per capita (and square of it, GDPC and $GDPC^2$), human development index (HDI), and population size (POP) over the period from 1990 to 2018 for all states in the USA. The data for CO_2 emissions have been obtained from the US Energy Information Administration (EIA). Gini coefficient (INCQ), a proxy for income inequality, was downloaded from the US State-Level Income Inequality Data – Mark W. Frank. GDP per capita was taken from the US Bureau of Economic Analysis. Human Development Index was obtained from Global Data Lab., which Population data has been acquired from the

US Census Bureau, Population Division. CO_2 emissions, GDPC, and POP series are converted in their logarithmic forms to remove the potential heteroscedasticity problem and to have unbiased and efficient estimators, and others remain as they are. Table 4 lists the description of variables and units.

Table 4 Variable description

Acronym	*Variables*	*Unit*
CO_2	Carbon dioxide emissions	Measured as millions of metric tons
INCQ	Gini coefficient	Measured as Gini coefficient/index
GDPC	Gross domestic production per capita	Measured as GDP/population at constant 2010 US$
POP	Population size	Measured as number of persons
HDI	Human development index	Measured as the geometric average of health, education and income index (scores)

Table 5 Descriptive statistics

Variable		*Obs.*	*Mean*	*Std. dev.*	*Min*	*Max*
INCQ	Overall	N = 1,479	0.589	0.036	0.521	0.719
	Between	n = 51		0.025	0.551	0.652
	Within	T = 29		0.026	0.524	0.701
CO_2	Overall	N = 1,479	4.250	1.042	0.950	6.552
	Between	n = 51		1.047	1.288	6.465
	Within	T = 29		0.096	3.913	4.548
GDPC	Overall	N = 1,479	3.781	0.430	2.856	5.470
	Between	n = 51		0.336	3.350	5.194
	Within	T = 29		0.272	3.070	4.381
POP	Overall	N = 1,479	8.143	1.033	6.116	10.582
	Between	n = 51		1.038	6.251	10.461
	Within	T = 29		0.099	7.583	8.494
HDI	Overall	N = 1,479	0.892	0.027	0.809	0.956
	Between	n = 51		0.021	0.839	0.929
	Within	T = 29		0.018	0.844	0.935

Table 5 provides descriptive statistics of variables used in this study. According to Table 4, the average of INCQ and the $\ln CO_2$ are 0.589 and 4.250, respectively. The standard deviations of INCQ are 0.025 between and 0.026 for within, suggesting that income inequality fluctuated at a lower magnitude across states than within a state during the years in the sample. Additionally, the standard deviations of emissions are 1.047 between and 0.096 for within, which shows that emissions varied at a higher magnitude across states than within a state over the years in the sample. Results also show that the logarithmic mean of GDPC, $GDPC^2$, POP are 3.781, 14.487, and 8.143, respectively. The mean for HDI is 0.892 in the table. The standard deviations for these control variables are higher for cross states, explaining that the variables fluctuate more across the states when we compare to within a state from 1990 to 2018.

3.2 Empirical model

To discover the link between carbon emission and income inequality, this study specifies the following functional form, which is to be estimated empirically:

$$CO_{2_{i,t}} = f\left(INCQ_{i,t}, GDPC_{i,t}, GDPC_{i,t}^2, POP_{i,t}, HDI_{i,t}\right) \tag{1}$$

where the subscripts i is the number of states ($i = 1, \ldots, N$), t is the time period ($t = 1, \ldots, T$), CO_2 represents carbon emissions, INCQ denotes the GINI coefficient is used as a proxy for income inequality, GDP shows the per capita gross domestic product, $GDPC^2$ denotes the square of GDP per capita indicates the nonlinearity of the relationship between GDP and CO_2 emission, POP describes population size, and HDI refers to the human development index.

Based on the EKC hypothesis, which shows the environmental pollution and income per-capita relationships, this study investigates the relationship between income inequality and carbon emissions at the US state level where income inequality, per-capita income, HDI, and carbon emission are main determinants. Beyond the EKC hypothesis, this model links the inequality, HDI and carbon emissions. Since both theoretically and empirically, the association between income inequality and CO_2 emissions is ambiguous, this empirical model examines the relationship between inequality and carbon emissions. In addition, HDI is a fruitful extension to this study because it has not been widely studied in the existing literature.

Following the research studies of Shahbaz et al. (2017), Dong et al. (2018, 2019) and Wang et al. (2020), we take natural logarithm form of all the variables (except INCQ and HDI) to reduce the risk of autocorrelation and heteroscedasticity, and obtain more efficient and reliable estimators, then equation (1) can be expressed as:

$$\begin{aligned} \ln\left(CO_{2_{i,t}}\right) = \beta_0 + \beta_1\left(INCQ_{i,t}\right) + \beta_2 \ln\left(GDPC_{i,t}\right) + \beta_3 \ln\left(GDPC_{i,t}\right)^2 \\ +\beta_4 \ln\left(POP_{i,t}\right) + \beta_5\left(HDI_{i,t}\right) + \varepsilon_{it} \end{aligned} \tag{2}$$

where β_0 is the constant term, β_1–β_5 are the parameters to be estimated, and ε_{it} is the random error term.

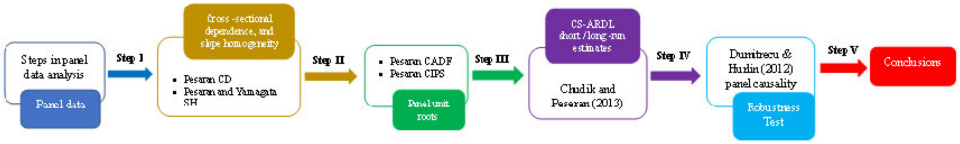
3.3 Estimation methodology

As similar to that of Li et al. (2020), Ali et al. (2020), Shen et al. (2021), Isiksal (2021), Safi et al. (2021), Mehmood (2022), Azam et al. (2022) and Noureen et al. (2022) this research work applies cross-sectionally augmented ARDL (CS-ARDL), popularised by Chudik and Pesaran (2013), approach to explore the relationship between income inequality and carbon emission in the case of the USA. The CS-ARDL model augments the traditional ARDL model, which predicts error correction coefficients associated with both the short- and long-run estimates and deals with the problems of potential endogeneity, serial correlation, endogenous covariates, and common-correlation bias in the panel data. Because there is more likely to have cross sectional dependence between US states since they are highly connected via technology, financial, trade and most importantly geopolitically integrated. Additionally, the data covers long term and is subject to unit root, and because of cross dependence issues and non-stationary issues, this work applies the CS-ARDL framework by Chudik and Pesaran (2013). Besides, this approach uses the method of pooled mean group (PMG) that provides more efficient estimators. Based on such assumptions, the equation for the CS-ARDL model is portrayed as below:

$$\begin{aligned}\Delta CO_{2_{it}} &= \mu_i + \phi_i\left(CO_{2_{it-1}} - \delta_i X_{it-1} - \varphi_{1i}\overline{CO_{2_{t-1}}} - \varphi_{2i}\overline{X}_{t-1}\right)\\ &\quad + \sum\nolimits_{j=1}^{p-1}\tau_{ij}\Delta CO_{2_{it-j}} + \sum\nolimits_{j=0}^{q-1}\varsigma_{ij}\Delta X_{it-j} + \eta_{1i}\Delta\overline{CO_2}_t + \eta_{2i}\Delta\overline{X}_t + \varepsilon_{it}\end{aligned} \tag{3}$$

where Δ is the first difference operator; $CO_{2_{it}}$ is the dependent variable; X_i is the set of explanatory variables such as income inequality, gross domestic product, the square of GDP per capita, population size, and human development index in the long-run; $\overline{CO_{2_{t-1}}}$ and $\Delta\overline{CO_{2_t}}$ are the mean of the dependent variable in the long run and short run, respectively; $\overline{X}_{t-1}$ is the mean of for all explanatory variables; ΔX_{it-j} is the independent variables in the short run; $\Delta\overline{X}_t$ is the mean of the explanatory variables in the short run; δ_i is the long-run coefficient of the explanatory variables; τ_{ij} is the short-run coefficient for the dependent variable [also known as error correction term (ECT)]; ς_{ij} is the short-run coefficients for the explanatory variables to be estimated; η_{1i} and η_{2i} denote the mean of dependent and explanatory variables in the short run, and ε_{it} is the error term. The precise view of the estimation process is given in Figure 2.

Figure 2 Estimation steps (see online version for colours)



4 Results and discussion

This section reports the findings obtained by applying different statistical approaches. Before proceeding with the analysis, one should check whether the panel time-series data is cross-sectionally independent and slope coefficients are homogenous. In addition, in the presence of cross-sectional dependence (CSD) and heterogeneity within the panel data, the second-generation panel unit root tests including the cross-sectional ADF (CADF) and cross-sectional augmented IPS (CIPS) frequently were preferred to the traditional panel unit root tests such as Im, Pesaran and Shin (IPS) and augmented Dickey-Fuller (ADF).

4.1 Preliminary analysis: cross-section dependence and slope homogeneity

In the existence of the CSD across the units, the produced estimators may be inconsistent and biased (Grossman and Krueger, 1995; Philips and Sul, 2003; Pesaran, 2004; Breitung, 2005; Chudik and Pesaran, 2013; Ullah et al., 2016). Having confirmed that the results of CSD and homogeneity of slope tests allow us to choose the right panel-unit root tests and cointegration method. Using this motivation, we use Pesaran's CSD test

(Pesaran, 2004) to address the potential CSD problem and Pesaran and Yamagata's test (Pesaran and Yamagata, 2008) for the slope of homogeneity (SHM).

Table 6 displays the CSD and SHM results. From the results, each variable in this study suffers from the cross-sectional dependence problem, leading us to apply a second-generation panel unit root test introduced by Pesaran (2007). In addition, as shown from Table 6, since the probability values are less than 0.05, we reject the null hypothesis of homogeneity in favor of the alternative hypothesis of heterogeneity and conclude that slope coefficients are not homogenous.

Table 6 Cross-sectional dependence and homogenous test

Cross-sectional dependence		*Homogenous tests*	
Variable	*Statistic*	*Test*	*Statistic*
CO_2	85.26***	$\bar{\Delta}$	29.695***
INCQ	126.69***	$\bar{\Delta}_{adj}$	34.093***
GDPC	187.72***		
$GDPC^2$	187.29***		
POP	178.89***		
HDI	190.42***		

Note: *** indicates significance at the 1% level.

4.2 Panel unit root test

Because of the non-stationary nature of time series data, another preliminary and necessary step is to check the degree of the integration of the variables before proceeding with the panel data models. Under the CSD, two types of second-generation panel unit root tests, which were advocated by Pesaran (2007), the CADF panel unit root test and the CIPS unit root test are applied in this empirical study. These tests, besides producing reliable and persuasive results in the presence of CD, determine whether there is any cross-sectional dependence and allow for residual serial correlation across the members of the panel. CADF test equation is given in equation (4).

$$y_{it} = \alpha_i + b_i y_{it-1} + c_i \bar{y}_{it-1} + d_i \Delta \bar{y}_t + \varepsilon_{it} \tag{4}$$

where y_{it} shows the series analysed, t expresses trend term, ε_{it} is error term, Δ is the difference operator, and p indicates the lag value that is obtained using BIC statistic. In addition, the calculation for CIPS test statistics is specified as:

$$\Delta W_{i,t} = \phi_i + \phi_i Z_{i,t-1} + \phi_i Z_{t-1} \sum\nolimits_{t=0}^{p} \phi_{il} \Delta \bar{W}_{t-1} + \sum\nolimits_{t=0}^{p} \phi_{il} \Delta \bar{W}_{i,t-1} + \mu_{it} \tag{5}$$

where $\bar{W}$ indicates the average cross-section and is represented as:

$$W^{i,t} = \phi^1 \overline{INCQ}^{i,t} + \phi^2 \overline{GDPC}^{i,t} + \phi^3 \overline{GDPC^2}^{i,t} + \phi^4 \overline{POP}^{i,t} + \phi^5 \overline{HDI}^{i,t} \tag{6}$$

The CIPS test statistics are given as

$$\widehat{CIPS} = N^{-1} \sum\nolimits_{i=1}^{n} CADF_i \tag{7}$$

Both the CADF and CIPS test results in Table 7 show that all series appear to include a unit root in their levels but become stationary at their first differences that indicate all variables are integrated at first differences, I(1). These findings allow us to investigate whether there exists a long run cointegration relationship among the selected variables.

Table 7 Results of CIPS and CADF panel unit root tests

Variable	*CIPS test statistic*		*CADF test statistic*	
	Level	*1st difference*	*Level*	*1st difference*
CO_2	–0.423	–2.175***	–0.886	–17.140***
INCQ	–1.845	–2.337***	–3.606	–10.430***
GDPC	–2.092	–3.467***	–1.197	–10.882***
$GDPC^2$	–0.611	–2.784***	–0.758	–10.856***
POP	–0.733	–2.883***	–5.145	–3.539***
HDI	–1.942	–3.507***	–0.818	–10.074***

Note: *** illustrates statistical significance at the 1% level.

4.3 CS-ARDL regression analysis

In this study, we estimate the three different CS-ARDL regression to evaluate both short- and long-term potential cross-sectional bias problems that are eliminated in the short run and long run. The CS-ARDL approach has been employed because there is cross-sectional dependence and non-stationary properties in the variables. In Table 8, we first focus on the common correlation bias both in the short and long run stated in the last column since there is cross-sectional dependence in all variables not only in the short run but also in the long run. Also, the coefficient of Error Correction Term (ECT) is found –0.402, which is statistically significant and negative that indicates the model converges 40.2% per year towards the long-run equilibrium if there is an exogenous shock in the short run. Thus, it takes about 2.5 years to eliminate the disequilibrium created at the beginning.

As expected from the literature, Boyce's (1994) PEA approach and ET of Veblen (1899) state that there is a positive relationship between income inequality and CO_2 emission (pollution) whereas a negative relationship by MPE theory. According to Table 7, there is a positive and significant relationship between income inequality and CO_2 emission in the long run. Thus, this result fits the theory in the literature as income inequality (or Gini coefficient) goes up, CO_2 emission goes up as well. Our empirical findings echo the findings by Bae (2018), Baloch et al. (2020a), Mushtaq et al. (2020) and Padhan et al. (2019) who state a positive relationship between carbon emissions and income inequality. GDPC coefficient affects carbon emission both positively and significantly not only in the short run but also in the long run. The coefficient of $GDPC^2$ has a negative and significant impact on emissions as well. Hence, our empirical findings for GDPC and $GDPC^2$ are in line with Boluk and Mert (2015), Pata (2018) and Sheldon (2019) the validity of the EKC hypothesis.

Table 8 Results from CS-ARDL analysis

Dependent variable: CO_2 emission use			
	CD in SR	*CD in LR*	*CD in SR and LR*
Error correction	–0.274*** (–8.24)	–0.335*** (–10.85)	–0.402*** (–9.45)
	Long-run estimates		
$INCQ_{t-1}$	–0.0059 (–0.04)	0.9394*** (4.26)	0.4082*** (3.58)
$GDPC_{t-1}$	1.8448*** (6.50)	1.8725*** (6.14)	–0.0977 (–0.56)
$GDPC^2_{t-1}$	–0.2231*** (–5.58)	–0.2304*** (–5.26)	0.0410* (1.81)
POP_{t-1}	0.5285*** (6.43)	0.5003*** (7.41)	0.6445*** (14.84)
HDI_{t-1}	–4.363*** (–9.52)	–2.2748 (–1.36)	0.9839 (1.01)
	Short-run estimates		
ΔINCQ	–0.2512 (–1.48)	0.3285*** (3.03)	–0.2402 (–1.50)
ΔGDPC	0.6319 (0.51)	–2.8003*** (–3.44)	–1.2801 (–1.27)
$\Delta GDPC^2$	–0.0397 (–0.26)	0.3709*** (3.46)	0.1947 (1.48)
ΔPOP	2.4787*** (3.74)	1.4175*** (4.49)	2.1608*** (3.61)
ΔHDI	–0.6196 (–0.25)	1.2643*** (2.05)	–0.4347 (–0.18)
Constant	–0.0183 (–0.54)	–7.9520*** (–10.87)	–1.0093*** (–9.45)
N	51	51	51
Observation	1,428	1,428	1,428

Notes: *** illustrates statistical significance at the 1% level.
t-values are in the parenthesis.

Not surprisingly, as the population goes up, CO_2 emissions rise significantly. Finally, there is a negative relationship between human development and CO_2 emission in the short run, which indicates that increasing human development reduces CO_2 emission. To the best of our knowledge, HDI has been considered less in terms of relationship with carbon emissions. Our finding of human development coefficient, in the short run, is consistent with Chen et al. (2020) and Hossain and Chen (2021) as they found a decoupling relationship between carbon emissions and HDI in Southwest China and Bangladesh, respectively.

4.4 Causality test

This study applies Dumitrescu-Hurlin panel causality tests developed by Dumitrescu and Hurlin (2012) for the causality test of the estimated findings. This test provides us the following advantages, such as considering heterogeneity causal relationship since our data is heterogeneous panel data, this causality test can be efficiently applied in cross-sectional dependence, and the average Wald statistics, which has standard normal asymptotic distribution, by Hurlin (2005) converge to normal distribution as time and state go to infinity. Additionally, homogeneity assumption problems by the Granger causality test (Engle and Granger, 1987) can be handled effectively as employing this test. Table 9 exhibits that all the independent variables significantly Granger causes the CO_2 emission in the US states. According to Table 9, it can be concluded that the CS-ARDL model results are robust and eliminate the common correlation and non-stationary bias problem.

Table 9 Results of Dumitrescu-Hurlin panel causality test

Hypothesis	*W-stat*	*Z-stat*	*Prob.*	*Result*	*Conclusion*
INCQ → CO_2	2.2348	6.2355	0.0000	Yes	INCQ causes CO_2
GDPC → CO_2	1.9742	4.9197	0.0000	Yes	GDPC causes CO_2
$GDPC^2$ → CO_2	1.9870	4.9840	0.0000	Yes	$GDPC^2$ causes CO_2
POP → CO_2	2.4087	7.1137	0.0000	Yes	POP causes CO_2
HDI → CO_2	3.0699	10.4524	0.0000	Yes	HDI causes CO_2

5 Conclusions and policy implications

Rapid economic expansion creates a plethora of environmental and socioeconomic problems, including rising income inequality and anthropogenic climate change allied to significant levels of carbon emissions. This study contributes to scientific research on the human aspects of climate change by examining the nexus between carbon emissions and income inequality at the state level in the USA. Though various forms of global and international inequalities have been intensively investigated, research on income inequality and CO_2 emissions is sparse, and it has primarily been undertaken at the nation-state level, emphasising how income inequality across nations affects national-level emissions. Cross-national studies, while potentially insightful, may overlook heterogeneity within countries, such as the link between income inequality and CO_2 emissions. Hence, the current study contributes to climate change research by examining whether and how income inequality is linked to emissions, and the study is performed at the sub-national level, providing a more nuanced considerate of these socio-environmental linkages. Thus, one of this study's goals is to enhance the existing literature by considering a new variable, which is the HDI, applying relatively fresh method for the US states.

This study aims to examine the recent link between CO_2 emission and income inequality in the case of US states over the period of 1990–2018 by applying cross-sectionally augmented ARDL (CS-ARDL). This study confirms the presence of common correlation across the states and over time. For the identification of cross-sectional dependence (CSD) and slope of homogeneity (SHM) within the panel data, the Pesaran's CSD test and Yamagata's SHM test, respectively, were utilised, which allow us to use second-generation panel unit root tests (e.g., CADF and CIPS). Results indicate that all analysed variables are integrated of order one. In terms of estimation, income inequality has a positive and statistically significant effect on CO_2 emission both in the long-run and short-run, which is consistent with the Boyce's PEA and Veblen's ET theory. The impact of GDPC and $GDPC^2$ on the levels of carbon emissions are significantly positive and negatives, respectively, which are aligned with the inverted U-shape EKC hypothesis as well. In addition to these, the coefficients of POP are positive and significant implying that CO_2 emissions go up as the population rises, whereas human development reduces emissions as it goes up only in the short run. Furthermore, Dumitrescu-Hurlin panel causality test results provide unidirectional causality between INCQ and CO_2, GDPC and CO_2, $GDPC^2$ and CO_2, POP, and CO_2, and HDI and CO_2.

Knowledge of both the theory and evidence reviewed in this study will help policymakers to offer some prominent policy implications. First, states with higher carbon emissions can impose environmental taxes to ensure a reduction in carbon emissions in parallel with income levels. Second, policy makers should encourage individuals to use clean energy sources by subsidising them based on their income levels, which are helpful in abating CO_2 emissions. Third, policymakers should focus on environment-friendly projects such as a green lifestyle to distribute income more equitably. Fourth, HDI should be considered seriously and sought ways to improve it since it reduces carbon emissions significantly. Fifth, states should subsidise firms when they use environmentally friendly technologies to reduce carbon emissions faster. Last, policymakers should consider putting more effort into human capital improvement and a better education system that ensures the use of more eco-friendly technologies.

Our study can be extended in a few ways. Since CO_2 emissions and income inequality are closely intertwined, one could explore the existence of a possible reverse causality by applying the instrumental variable (e.g., POP, HDI) to control unobservable heterogeneity, which may help to a better understanding of the relationship between CO_2 emissions and income inequality. In addition, one could focus on the subject by using the time series analysis for the USA in each state with more available variables such as renewable energy, natural gas, and biodiesel energy consumption for a wider research period if the relevant data is available. Finally, expanding this study connecting with the goals of the United Nations Development would make the study more interesting.

Author contributions

All authors have made significant contributions to this study.

- Batmaz, Oguzhan: conceptualisation, methodology, supervision, data curation, investigation, writing – review and editing.
- Çıtak, Ferhat: conceptualisation, methodology, analysis, software, writing – review and editing.
- Kamal, Muhammad Abdul: conceptualisation, literature review, writing – review and editing.

Data availability

This study used the secondary data. Thus, all the data information with details is available in the 'Data' section.

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