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Income inequality, innovation and carbon emission: Perspectives on sustainable growth

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ABSTRACT

The present study aims to investigate the impact of income inequality and economic growth on carbon dioxide (CO2) emission through the moderating role of innovation in China at national and regional levels. To test the hypothesised relationships, this study took the data from 1995 to 2015 and employed panel estimation. Findings of the whole analysis show that income inequality and economic growth influence CO2 emission in China. Moreover, technological innovation moderates the proposed link. However, the findings at the regional level are mixed, thus confirming the existence of regional differences. Policy implications are also discussed.

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1. Introduction

Carbon dioxide (CO2) emission is a major threat to environmental quality and to the sustainable economic growth of numerous countries. This threat has placed countries under pressure to become low-carbon economies (Liu, Xiao, Zikhali, & Lv, 2014). As a result, a series of agreements, including the United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol and Paris Agreement, has been made among different countries to control the global CO2 emission. In addition, various developed and industrialised countries have devised and implemented their own policies to reduce this emission (Shi, Sun, Lin, & Zhao, 2019; Zhao, Zhang, & Shao, 2016). This action highlights that decreasing the level of CO2 emission has become an important strategy for sustainable development in recent years (Wei, Li, Wu, & Li, 2019). Structural transformation in industries, for example, is conducive to curb CO2 emission. This effect cannot be significant unless the structure of energy consumption significantly changes (Mi, Pan, Yu, & Wei, 2015). However, technology, consumption

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structure of energy, industrial structure and urbanisation may help to control the level of CO_2 emission. Economic and environmental issues are becoming more critical, and researchers are more interested in examining the effects of technological innovation on CO_2 emission (Yang, Yu & Du, 2019). Furthermore, the impact of innovation on carbon emission depends on the economic development stage of the economy (Fan, Liu, Wu, & Wei, 2006). Several studies have found that technological innovation may result in the decline of CO_2 emission (Guo, 2017). The relationship of carbon emission to income inequality and innovation on the regional perspectives has yet to be investigated. Therefore, this study aims to investigate the relationship between income inequality and carbon emission when a country focuses on innovation. Moreover, this study considers income inequality based on regions to link it with innovation that influences carbon emission.

Fast growing economies, such as Brazil, Russia, India, China and South Africa (BRICS), have entered into a new paradigm (i.e. innovation-oriented economy), which also has changed the pace and the factors of economic growth (Yu & Du, 2019). Moreover, China is one of the second-largest economies and one of the largest CO_2 producers worldwide; it has emitted 9.12 billion tons of carbon in 2016—27.3% of the total global carbon emission (Shi et al., 2019). Considering this amount, China has aimed to become a low-carbon and sustainable economy (Luo, Dubey, Papadopoulos, Hazen, & Roubaud, 2018). The major challenge in this transition process is keeping the economic growth rate high whilst significantly reducing carbon emission in China (Qi, Peng, & Tan, 2019). Therefore, the effects of income inequality (Shi et al., 2019; Zhang & Zhao, 2014) and economic growth (Wang, Li, Fang, & Zhou, 2016) on carbon emission are extensively studied, particularly with reference to environmental Kuznets curve (EKC) hypothesis (Kaika & Zervas, 2013). However, past studies have barely examined the role of technological innovation in these relationships. To become a low-carbon economy, China has shifted the economic growth from high-speed growth to medium-to-high growth and factor-driven growth to innovation-driven growth, which poses new challenges to the linkages between the economy and the environment (Yu & Du, 2019). This type of shift requires new insights into an old problem. Therefore, revisiting the effects of income inequality and economic growth on CO_2 emission by considering the role of technological innovation in China is imperative. Similarly, during the rapid economic growth in China, income inequality has risen, which increases the quantity of carbon emission in the country (Hao, Chen, & Zhang, 2016). Liu, Wang, Zhang, Li, and Kong (2019) have found an inverted U-shaped relationship between income and CO_2 emission by using EKC hypothesis, thus confirming that high-income inequality leads to environmental deterioration.

The present study contributes to the literature in two ways: Firstly, this study contributes to the literature of income inequality and carbon emission in the regional context. Secondly, this study examines the effect of income inequality on CO_2 emission by exploring the moderating role of technological innovation, which has attracted little attention in past research. Thus, this study also contributes to EKC hypothesis. Third, considering regional disparities, this study has covered more regions than previous studies (Zhang & Zhao, 2014). Therefore, the present study contributes to regional economies that focus on innovation.

The remainder of this paper is organised as follows. Section 2 provides a literature review. Section 3 presents the methodology in detail. Section 4 describes the analysis and results. Section 5 covers the discussion, conclusion and policy implications.

2. Literature review

Reducing income inequality and carbon emission whilst maintaining high economic growth under the policy of technological innovation is challenging for China. As a major producer of CO2, China is under huge pressure to control carbon emission. Therefore, numerous scholars have become increasingly interested in identifying the key drivers of CO2 and the conditions that can increase or decrease the quantity of carbon in the environment. Since the introduction of impact, population, affluence and technology (IPAT), several studies have separately studied the impact of income inequality and economic growth on CO2 emission in China (Zhang & Zhao, 2014; Liu et al. 2019).

Scholars have used different theoretical approaches to understand the nature of the relationship between income inequality and carbon emission. Firstly, Boyce (1994) has provided a political economic perspective on this relationship. According to this perspective, environmental pollution may depend on the distribution of income and power among the rich and the poor. Unlike the poor, rich people, though they have a larger share in carbon emission, have more ability to protect themselves from the detrimental effects of environmental degradation; conversely, this burden is borne by the poor (Laurent, 2015). The second perspective relies on the marginal propensity to emit, in which CO2 fluctuates with the variation in income distribution (Borghesi, 2006). When income inequality increases, the carbon emission tends to decrease (Ravallion, Heil, & Jalan, 2000). The third approach is based on the assumption that higher inequality leads to higher energy consumption, thus increasing carbon emission (Borghesi, 2006; Ravallion et al., 2000). Although these three perspectives have different standpoints, they confirm that income inequality and carbon emission have a strong link. To verify this relationship, scholars have conducted a range of empirical studies and found interesting results.

For example, one group of researchers highlights that a well-established positive relationship exists between income inequality and carbon emission. Zhang and Zhao (2014) have stated that income inequality causes an increase in carbon emission and varies from region to region. Liu et al. (2019) have also found that in China, income growth increases carbon emission and supports the EKC. Further, Golley and Meng (2012) have used the input–output (IO) method to calculate direct and indirect emission consumption from the survey Urban Household Income and Expenditure Survey (UHIES) conducted by the National Bureau of Statistics (NBS) of China. Their study results show that carbon emission varies from household to household with different income levels. Golley and Meng (2012) have further found that a household with a high income causes more emission than a low-income household. Moreover, Baek and Gweisah (2013) have used time series data and the autoregressive distributed lag (ARDL) model and examined that impartial income distribution can improve environmental quality both in the short and long run.

Contrary to the first group, the second group highlights a negative relationship between income inequality and carbon emission. Jun, Zhong-Kui, and Peng-Fei (2011) have explored a significant adverse relationship between income inequality and carbon emission. Grunewald, Klasen, Martínez-Zarzoso, and Muris (2017) have also found that low- and middle-income countries contribute to high carbon emission. Furthermore, Hübler (2017) has employed quantile regression and found that high inequality leads to a decrease in carbon emission. Moreover, Heerink, Mulatu, and Bulte (2001) has found that nations with a higher income inequality produce less carbon emission. Likewise, Borghesi (2006) has used the Gini coefficient, measured income inequality for 35 nations and analysed income inequality effects per capita carbon emission. The findings further explored that income inequality can help to reduce carbon emission in underdeveloped countries.

Other researchers have examined inequality–carbon emission links from a short- and long-term perspective. For example, using panel data from 1997 to 2015, Liu et al. (2019) have examined the effect of income inequality on carbon emission and found that in the short run, high income inequality increases carbon emission, whereas in the long run, high income inequality reduces carbon emission in the US. Baek and Gweisah (2013) have investigated the short- and the long-term effects of income inequality in the US; they have found that more equal income distribution results in better environmental quality in both the short and long run. In another study, Akbostanci, Türüt-Aşik, and Tunç (2009) have studied the association between income inequality and carbon emission in Turkey and revealed the existence of a unique relationship between these two variables in the long run. They have also reported that a monotonously increasing relationship exists between carbon emission and inequality.

Given the above discussion, empirical evidence also confirms that income inequality and carbon emission are closely linked in China. However, findings show the lack of consensus on the type of relationship because researchers have found different relationships, such as linear (positive) relationship (Zhang & Zhao, 2014), U-shaped relationship (Zhao et al., 2016), inverted U-shaped relationship (Liu et al., 2019) and no relationship (Wolde-Rufael & Idowu, 2017).

Numerous other studies have tested the growth–carbon emission nexus using the popular EKC hypothesis (Grossman & Krueger, 1991). EKC suggests that an inverted U-shaped relationship exists between economic growth and emission. In the early stage of economic growth, the carbon emission level rises. Once the growth reaches the threshold point and the income level increases, the environmental quality also starts improving. To confirm this hypothesis, a range of studies has been undertaken. However, the results are mixed. For example, some studies (i.e. Apergis & Ozturk, 2015; Dong, Sun, Jiang, & Zeng, 2018) have empirically found the existence of EKC, whereas other studies (i.e., Akbostanci et al., 2009; Mikayilov, Galeotti, & Hasanov, 2018; Nasir & Rehman, 2011) have failed to find any support for the existence of this hypothesis. However, other studies have found an N-shaped and an inverted N-shaped EKC (Martínez-Zarzoso & Bengochea-Morancho, 2004; Özokcu & Özdemir, 2017). However, Moomaw and Unruh (1997) have reported that neither the N-shaped nor the U-shaped connection between carbon emission and economic growth exists.

These contradictory results have led to a number of scholarly criticisms regarding EKC. For example, Yang, Sun, Wang, and Li (2015) have argued that the link built on the EKC hypothesis using a limited data set cannot be appropriate to develop a particular model because such models are applied worldwide. Another criticism of the EKC is the heterogeneity problem that can be easily recognised across the regions and countries through panel estimation and can be solved by using cointegration and unit-root tests (Apergis, 2016; Liu et al., 2019) However, models like the EKC fail to deal with such problems due to the nonlinearity (Gonzalez, Battles, Collins, Robards, & Saah, 2015).

Several other studies have found the relationship between economic growth and CO2 emission using EKC (Gonzalez et al., 2015). Using provincial data in China, Du, Zhou, Pan, Sun, and Wu (2019) have found that the economic development of most of the provinces is positively related with CO2. Similarly, Esso and Keho (2016) have reported that economic development positively relates to carbon emission in Sub-Saharan nations. In a recent study, Nie and Xing (2019) have examined economic development in relation to carbon emission in different regions of China and concluded that economic growth influences carbon emission. Taking this observation into account, the present study expects that economic growth and CO2 emission are closely linked.

The use of technological innovation as a vital factor can reduce income gap and carbon emission. Innovation refers to 'creative destructions' (Hong, 2018). By recognising the value of innovation in its National Middle to Long Term Plan for Science and Technology Development 2006–2020 (MLP, 2006), China has set itself to become the largest innovative country in the world (Liu, Serger, Tagscherer, & Chang, 2017). Therefore, heavy investment in activities to improve the innovative performance and growth of the country has become a vital internal strategy in the country. China's competitive advantage mainly rests on cheap labour, and with the rising income level, long-term sustainable growth will not only rely on cheap labour. Instead, China must accelerate technological innovation to continue the momentum of income growth (Liu et al., 2017). Existing literature has indicated that technological innovation decreases income inequality (Thewissen & Rueda, 2019). For example, people who work in innovative firms earn more than those who work in less innovative firms (Liu et al., 2017). In sum, workers with jobs that require advanced technical skills are highly paid (Breau, Kogler, & Bolton, 2014). In addition, innovative regions attract creative and highly skilled workers by offering them competitive wages; however, innovative cites have high inequalities (Depalo & Di Addario 2014; Fan et al., 2006). Liu and Lawell (2015) have found a U-shaped relationship, which means that minor innovations reduce inequality and breakthrough innovations; however, these innovations can increase income inequalities in Chinese provinces. Other studies, such as that of Domenico and Di Addario (2014) have observed that innovation decreases overall income inequality and increases top income share. Such observation entails that innovation can decrease income inequality in a way that individuals with fewer technological skills may learn from those with more advanced skills. Thus, individuals who improve their skills can also earn more. Thereby, the income gap between workers tends to decrease.

Likewise, innovation is connected to CO2 emission. However, the findings are mixed. For example, energy-related R&D expenses increase carbon emission in 19 high-income OECD nations (Koçak & Ulucak, 2019). Using the STIRPAT model in different nations, Fan et al. (2006) have found that technological innovation and CO2 are connected but are different across the nations. Similarly, Kumar and Managi (2009) have found that technological innovation mitigates carbon emission in developed countries, but it increases CO2 emission in developing economies. In addition, Dauda, Long, Mensah, and Salman (2019) have explored the impact of economic development and innovation on carbon emission across 18 developed and developing economies and found that innovation causes a reduction in carbon emission in G6 economies; however, innovation leads to a surge in emission in BRICS and MENA nations. Numerous other studies (i.e. Kumar & Managi, 2009; Liang, Zhao, He, Xu, & Ma, 2019; Wang, Chen, & Zou, 2005) have found a negative relationship between technological innovation and income inequality. Thus, innovation reduces carbon emission and improves environmental quality (Yu & Du, 2019; Zhao, Ma, & Yang, 2013). Technology helps to introduce energy-efficient innovation, which reduces environmental degradation (Balsalobre-Lorente, Shahbaz, Roubaud, & Farhani, 2018; Samargandi, 2017). Hence, technology plays an undoubtedly important role in mitigating carbon emission. However, this effect can differ across various regions based on the regional properties, policies and infrastructures. Considering the discussion, technological innovation in a country can be vital in curbing income inequality and carbon emission.

Despite the voluminous previous research that has explored the relationship of income inequality, economic growth, technological innovation and CO2 emission with practical implications, further research from various aspects is needed. Firstly, previous studies have examined the direct impact of income inequality, economic growth and technological innovation on CO2 emission, whereas less research has focused on the indirect effects (moderating) role of innovation. Similarly, many studies have overlooked to test direct and indirect relationships between study variables across different regions of China. Whereas, considering regional differences, studying these relationships in different regions can reveal some interesting findings, which can help the policymakers to develop the national as well as regional policies accordingly. Therefore, this study intends to avoid these limitations and analyses the relationship between variables of studies at a national and regional level. In doing so, this study follows IPAT model (Di, Rui, & Hai-Ying, 2011). Researchers have widely used this model when they examined the role of technology with reference to CO2 emission (Hailemariam, Dzhumashev, & Shahbaz, 2019; Zhou & Song, 2016).

3. Methodology

Our theoretical framework encompasses the EKC hypothesis, which demonstrates the relationship between environmental degradation and income levels (Grossman & Krueger, 1991). Some recent studies (i.e. Ellabban, Abu-Rub, & Blaabjerg, 2014; Golley & Meng, 2012) have focused increased attention on environmental degradation influenced by the distribution of income. Jun et al. (2011) have stated that income distribution can be used as a descriptive variable. Usually, when discussing the association between environmental quality and economic growth, the researcher tends to examine a range of variables, including GDP, income per capita and energy consumption. However, income inequality tends to be limited in terms of variables especially when examining the regional differences at the income level. The regression models FE, PSCE, N-W and FGLS are employed.

$$lnCO2 = \beta_0 + \beta_1 * ln(RGDP) + \beta_2 * ln(RGDP_sq) + \beta_3 * ln(GINI) + \beta_4 * ln(Innovation) + \beta_5 * ln(EI) + \beta_6 * ln(indStr) + \beta_7 * ln(URB) + \varepsilon_{ij,} \tag{1}$$

where *lnC02* is the total carbon emission, an indicator of environmental degradation. *lnRGDP* is the total regional *GDP*. *lnGINI* is a coefficient of inequality measurement. *lnInnovation* is the technology innovation calculated by the total patent applications accepted. *lnEI* indicates energy intensity measured by the total consumption ratio to the *GDP*. *lnURB* is urbanisation. *lnindstr* is the industry structure, which is measured by the primary industry ratio to the *GDP*.

For the *GINI* coefficient, this study adopts the data collected by Tian (2012) from 1995 to 2010. For the following five years (2011 to 2015), we calculated the data through the formula that Tian (2012) applied:

$$GINI = Pc\frac{\mu_c}{\mu}G_c + Pr\frac{\mu_r}{\mu}G_r + PuPr\left|\frac{\mu_c - \mu_u}{\mu}\right|,$$

where *GINI* is the Gini coefficient of the population. *Gc* and *Gr* are the Gini coefficients of the rural population and the urban population, respectively. In addition, P_c indicates the proportion of the urban population. P_r denotes the rural population proportion, where μ_u and μ_c show the income per capita of urban residents and rural residents, respectively. μ denotes the income per capita for the whole region.

3.1. Data source and description

We use a panel dataset of 27 provinces of China from 1995 to 2015 and divide the sample into six regions. The data of carbon emission was calculated by the Intergovernmental Panel Data of Climate Change in 2006. The data of regional GDP and primary industry value added were collected by the NBS of China. Data on energy consumption were collected by the City Statistical Yearbook. Data on urbanisation were collected by the China Compendium and the China Statistical Yearbook. Table 1 describes the descriptive statistics of the study. For CO2, we obtain the 20500.99 mean, which is close to the maximum value. Meanwhile, the Gini coefficient mean is 0.349. For innovation, the mean value is 14592.3 (Table 2).

Table 1. Variables description.

Variables	Definition
Carbon emission (C02)	Total carbon emission
GDP (Rgdp)	Log of Total regional GDP
GINI	Measure the difference in income distribution
Energy intensity (EI)	Total energy consumption divided by GDP
Urbanization (URB)	Urban population divided by total population
Industry structure (IndStr)	Primary value-added divide GDP
Technology innovation	Number of Domestic Patents Application Granted(item)

Source: The Authors.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
CO2	567	20500.99	16238.61	1148.358	94582.98
GINI	567	0.349	0.100	0.1068	0.5665
URB	567	0.440	0.207	0	0.962
IndStr	567	0.139	0.074	0.0043	0.357
Innovation	565	14643.95	35225.63	43	269944
EI	567	1.708	2.478	0.181	55.3
RGDP	567	22641.9	21293.15	1826	107960

Source: The Authors.

4. Empirical analysis and discussion

4.1. Income inequality, innovation and carbon emission

The aim of this study is to investigate the relationship between income inequality, innovation and carbon emission. At the country level, the high-income inequality, improving innovation and high energy intensity are responsible for CO2 emission. The results of the panel estimation whole sample are presented in Table 3. The coefficient of lnGINI is significant at a 10% level of significance and has a positive relationship with carbon emission. Thus, with higher income inequality, CO2 emission increases. Similarly, the coefficient of innovation (lninovation) is positive and significant at level 1% (0.206). Hence, innovation also degrades the environment at the national level.

The lnGDP (lnRGDP_sq) coefficient is positive (negative) and statistically significant at a 1% level, which shows a non-monotonic relationship. Findings confirm the existence of an inverted U-shaped EKC in China. This finding illustrates that deteriorated environmental quality results from the massive consumption of energy resource benefits to economic growth, thereby boosting carbon emission. Therefore, this finding implies that CO2 emission is increasing in China. Moreover, the coefficient on energy intensity (lnEI) is (0.069) positive and significant at 5%. This finding indicates that a rise of 1 unit in the energy intensity causes of 0.69% increase in CO2 emission. The coefficient of industry structure (IndStr) is negatively related to carbon emission. Therefore, a unit increase in the industry structure causes a 3.7% reduction in environmental degradation.

We estimate other models, such as PCSE, N-W and FGLS for the robustness test, as shown in Columns 2, 3 and 4 in Table 3. The coefficients of lnGINI, lnInnovation, lnRGDP and lnEI are positive and statistically significant. Moreover, the results indicate that CO2 follows an inverted U-shaped trend and supports EKC. Also, the industry structure discourages environmental degradation.

Table 3. Whole sample analysis.

VARIABLES	sign	FE (1)	PCSE (2)	N-W (3)	FGLS (4)
lnGINI	+	0.0630*	0.200***	0.200***	0.175***
		(0.0339)	(0.0482)	(0.0588)	(0.0381)
lnInnovation	–	0.206***	0.350***	0.350***	0.288***
		(0.0254)	(0.0369)	(0.0557)	(0.0259)
lnRGDP	+	2.33e-05***	7.84e-05***	7.84e-05***	9.38e-05***
		(4.56e-06)	(1.12e-05)	(1.02e-05)	(5.92e-06)
lnRGDP_sq	–	−2.71e-10***	−9.83e-10***	−9.83e-10***	−1.17e-09***
		(5.73e-11)	(1.77e-10)	(1.44e-10)	(9.05e-11)
lnEI	?	0.0693**	0.555***	0.555***	0.604***
		(0.0332)	(0.0741)	(0.171)	(0.0376)
lnURB	?	−0.0352	−0.144***	−0.144***	−0.171***
		(0.0295)	(0.0399)	(0.0418)	(0.0321)
lndStr	?	−3.669***	1.281***	1.281***	1.082***
		(0.342)	(0.296)	(0.283)	(0.209)
Constant		8.327***	6.025***	6.025***	6.398***
		(0.217)	(0.317)	(0.494)	(0.211)
Observations		565	565	565	565
R-squared		0.825	0.698		
N		27	27	27	27

Standard errors in parentheses
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.
Source: The Authors.

The empirical findings reveal a positive and significant association between income inequality and carbon emission in China at the national level. These results are similar to several previous studies (Baek & Gweisah, 2013; Hao et al., 2016; Liu et al., 2019; Zhang & Zhao, 2014). Rapid economic growth is characterised by the rising income levels as high carbon emission in the environment. Rapid economic growth, industrialisation and urbanisation are the main reasons for the high level of carbon emission in the second-largest economy of the world (Zhang & Zhao, 2014). The excessive population of China relies on a higher value-added share of the manufacturing sectors than Pakistan (Imran, Husen, Kaleem, Bangash, & Ud Din, 2020). Therefore, China uses heavy manufacturing capital and has a significantly low ratio of clean capital to dirty capital (Yoon & Yoon, 2018). This finding implies that when inequality decreases, the income level of the poor increases. As a result, the use of energy-intensive goods in the economy also rises, thus emitting more CO2 to the environment (Hailemariam et al., 2019). Similar results have also been found in Turkey (Uzar & Eyuboglu, 2019), confirming that the increase in inequality damages the environmental quality in the country.

4.2. Income inequality and regional carbon emission

China is among the countries with the largest area. The country is divided into different regions: North, Northwest, Eastern, Central and South, Southwest and Northwest. Therefore, we analyse the regional level to determine the impacts of income inequality and innovation on carbon emission in these regions.

The results of the six regions are presented in Tables 4 and 5. In Table 4, Column 1 estimates the results for the North region. The coefficients of lnGINI, lnRGDP and LnEI are significant and have a positive relationship to CO2. These results are similar to the result of the whole country, but the coefficients are higher than those of the country

Table 4. Regional analysis of CO2 emission.

		North region				Central and South Region				Northeast Region			
VARIABLES	Sign	FE (1)	PCSE (2)	N-W (3)	FGLS (4)	FE (5)	PCSE (6)	N-W (7)	FGLS (8)	FE (9)	PCSE (10)	N-W (11)	FGLS (12)
lnGINI	+	0.199***	0.129	0.129**	0.107***	−0.191**	−0.0530	−0.0530	−0.0697	−0.0132	−0.0233	−0.0233	0.00878
		(0.0463)	(0.102)	(0.0574)	(0.0383)	(0.0750)	(0.111)	(0.0604)	(0.0568)	(0.133)	(0.0875)	(0.0604)	(0.0591)
lnInnovation	–	−0.321***	−0.195***	−0.195***	−0.228***	−0.171*	−0.108	−0.108	−0.154**	−0.153	−0.114***	−0.114***	−0.100***
		(0.0835)	(0.0504)	(0.0422)	(0.0298)	(0.103)	(0.160)	(0.0853)	(0.0743)	(0.101)	(0.0374)	(0.0301)	(0.0165)
lnRGDP	+	1.512***	0.428	0.428	0.511***	1.981***	0.852	0.852	0.555	0.454	−0.739	−0.739	−1.107***
		(0.344)	(0.501)	(0.268)	(0.191)	(0.688)	(0.948)	(0.558)	(0.552)	(0.895)	(0.828)	(0.465)	(0.315)
lnRGDP_sq	–	−0.0139	0.0460	0.0460***	0.0413***	−0.0378	−0.000328	−0.000328	0.0221	0.0629	0.116***	0.116***	0.136***
		(0.0181)	(0.0290)	(0.0149)	(0.0108)	(0.0363)	(0.0543)	(0.0313)	(0.0313)	(0.0411)	(0.0441)	(0.0279)	(0.0169)
lnEI	?	0.877***	0.992***	0.992***	0.937***	0.111**	0.169**	0.169	0.425***	1.326***	1.115***	1.115***	1.124***
		(0.0620)	(0.0769)	(0.0612)	(0.0355)	(0.0460)	(0.0703)	(0.130)	(0.0629)	(0.203)	(0.205)	(0.146)	(0.0644)
lnURB	?	0.00686	−0.0895	−0.0895**	−0.0986**	−0.216**	−0.408***	−0.408***	−0.327***	−0.375	−0.714**	−0.714***	−0.794***
		(0.0608)	(0.0757)	(0.0443)	(0.0428)	(0.101)	(0.121)	(0.0866)	(0.0708)	(0.328)	(0.307)	(0.157)	(0.126)
lndStr	?	−0.224	−0.519	−0.519	−0.562*	2.718**	−0.153	−0.153	−0.575	2.007	−0.202	−0.202	−0.845
		(0.810)	(0.630)	(0.406)	(0.315)	(1.287)	(1.731)	(1.016)	(0.927)	(2.179)	(1.326)	(0.616)	(0.597)
Constant		0.458	4.072**	4.072***	3.977***	−4.327	2.722	2.722	4.065	1.376	7.537*	7.537***	9.224***
		(1.371)	(2.058)	(1.057)	(0.791)	(3.642)	(4.974)	(3.005)	(2.902)	(4.640)	(4.065)	(1.942)	(1.577)
Observations		84	84	84	84	105	105	105	105	63	63	63	63
R-squared		0.990	0.986			0.859	0.907			0.922	0.955		
Number of years		21	21		21	21	21	21	21	21	21		21

Note: lnRGDP_sq is square of regional GDP. Standard errors in parentheses
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.
Source: The Authors.

Table 5. Regional analysis of CO2 emission.

		Eastern region				Southwest region				Northwest Region			
VARIABLES	Sign	FE (1)	PCSE (2)	N-W (3)	FGLS (4)	FE (5)	PCSE (6)	N-W (7)	FGLS (8)	FE (9)	PCSE (10)	N-W (11)	FGLS (12)
lnGINI	+	0.0871	0.0902	0.0902*	0.0453	0.161	−0.0350	−0.0350	−0.0220	−0.0453	−0.0520	−0.0520	−0.0399
		(0.0945)	(0.0689)	(0.0528)	(0.0507)	(0.101)	(0.102)	(0.0650)	(0.0498)	(0.120)	(0.0921)	(0.0652)	(0.100)
lnInnovation	–	−0.0540	−0.0652	−0.0652*	−0.0604*	0.0790	−0.134	−0.134**	−0.190***	0.751***	0.894***	0.894***	0.820***
		(0.0559)	(0.0941)	(0.0333)	(0.0344)	(0.0780)	(0.0818)	(0.0585)	(0.0440)	(0.274)	(0.337)	(0.191)	(0.188)
lnRGDP	+	1.316***	1.241	1.241***	1.683***	0.679	0.843	0.843*	1.102***	0.0321	0.0110	0.0110	0.0159
		(0.497)	(0.892)	(0.372)	(0.406)	(0.513)	(0.921)	(0.423)	(0.401)	(0.0218)	(0.0239)	(0.0149)	(0.0146)
lnRGDP_sq	–	−0.0110	−0.0064	−0.00641	−0.0277	−0.0064	0.00813	0.00813	−0.00281	1.577***	1.365***	1.365***	1.380***
		(0.0288)	(0.0510)	(0.0198)	(0.0227)	(0.0281)	(0.0537)	(0.0239)	(0.0236)	(0.150)	(0.246)	(0.117)	(0.0716)
lnEI	?	0.575***	0.590***	0.590***	0.635***	0.936***	1.060***	1.060***	1.096***	−0.0819	−0.167**	−0.167***	−0.152***
		(0.0555)	(0.108)	(0.0618)	(0.0421)	(0.148)	(0.154)	(0.0873)	(0.0705)	(0.0784)	(0.0704)	(0.0360)	(0.0314)
lnURB	?	0.0533	0.0395	0.0395	−0.0352	−0.143	0.0254	0.0254	0.0987	0.104**	0.140**	0.140***	0.142***
		(0.0516)	(0.0470)	(0.0503)	(0.0342)	(0.0984)	(0.149)	(0.0863)	(0.0717)	(0.0412)	(0.0643)	(0.0244)	(0.0169)
IndStr	?	1.969***	1.911*	1.911***	2.269***	−1.974	−3.158***	−3.158***	−3.646***	−0.825	1.089	1.089**	1.115***
		(0.496)	(1.021)	(0.392)	(0.360)	(1.197)	(1.178)	(0.566)	(0.494)	(1.123)	(1.104)	(0.522)	(0.315)
Constant		−0.763	−0.358	−0.358	−2.801	3.680*	3.115	3.115	2.344	−0.316	−0.637	−0.637	−0.352
		(2.536)	(4.461)	(1.932)	(2.021)	(2.188)	(4.032)	(1.885)	(1.781)	(0.986)	(1.194)	(0.614)	(0.633)
Observations		126	126	126	126	82	82	82	82	105	105	105	105
R-squared		0.899	0.948			0.843	0.900			0.930	0.954		
Number of years		21	21		21	21	21		21	21	21		21

Note: lnRGDP_sq is square of regional GDP. Standard errors in parentheses.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.
Source: The Authors.

level. Moreover, the Gini coefficient (0.199) is higher than that of other regions. However, the coefficient of lninnovation is negative and significant, which is different from the results of the whole country. The result shows that this region encourages more service-based technological innovation, which cannot cause CO2 emission. The coefficient of lnURB is insignificant. Therefore, the urbanisation neither supports nor discourages CO2 emission. These results are robust with other regression models, that is, N-W and FGLS but not PCSE, as shown in Columns 2, 3 and 4 (Table 4).

In Table 4, Column 5 presents the results for the Central and South regions. The coefficients of lnGINI, lnInnovation and lnURB have a significant and negative relationship with CO2 emission. Therefore, income inequality, innovation and urbanisation decrease CO2 emission. The coefficient of lnInnovation is significant at a 10% level and has a negative association with CO2 emission. However, the coefficients of IndStr, and lnEI are significant and have a positive association to CO2 emission. Therefore, the results are partially similar to those of the whole country. These results are consistent with prior literature (Yoon & Yoon, 2018). Similarly, the coefficients of lnRGDP and lnGDP_sq do not support the EKC in this region. We estimate PECSE, N-W and FGLS for the Central and South regions, as shown in Columns 6, 7 and 8.

The Northeast region is quite different from the entire country, shown in Table 4. In Column 9, lnEI is significant and has a positive relationship with the emission of CO2, the remaining variables are insignificant. However, the lnRGDP (lnGDP_sq) is negative (positive) relationship with CO2 emission and is statistically significant, which confirms that it follows a U-shaped EKC to some extent, as shown in Column 12 of Table 4.

Table 5 presents the result of CO2 emission in the Eastern region (Columns 1-4), Southwest region (Columns 5-8) and Northwest region (9-12) of China. In Table 5, Columns 1-4 present the results for the Eastern region. The coefficient on GINI is insignificant. The coefficient of lnInnovation is negative and significant at a 10% level, shown in Columns 3 and 4. Thus, innovation discourages CO2 emission in the Northeast region. The coefficients of lnRGDP, lnEI and lnStr are statistically significant and positively associated to CO2 emission (Columns 1, 2 and 4). However, the coefficient of GDP square (lnRGDP_sq) is insignificant. Thus, the EKC does not exist in the Eastern region of China.

The Southwest region is also not much different from the Northeast region, as shown in Table 5, Columns 5-8. In Column 5, only lnEI is significant and positively related to CO2. The coefficients on IndStr have a negative association to CO2 and significant at a 1% confidence interval. The results are not the same as the whole country.

Table 5 shows the results of the panel estimation of the Northwest region. The coefficients of lnGINI and lnRGDP are insignificant, whereas the coefficient of lnInnovation, lnEI, and lnURB are statistically significant and are positively association with CO2. Moreover, lnRGDP is insignificant, but the coefficients of lnRGDP_sq are positive and significant at a 1% level of confidence (Columns 10-12). Therefore, the Northwest is at the early stages of the EKC.

The findings are mixed at the regional level. For example, this relationship has been found to be positive in North China and the Eastern region, negatively significant in the Central and South region and insignificant in the rest of three regions.

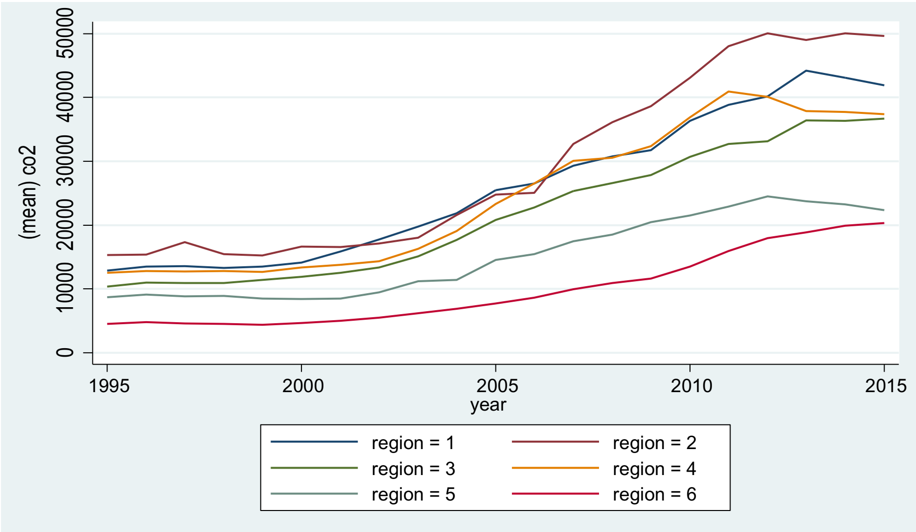

Figure 1. Trend of mean CO2 emission of six regions of china including region 1 is norther, region 2 is Northeast, region 3 is Eastern, region 4 is Central and South, region 5 Southwest, region 6 is Northwest. *Source:* The Authors.

These findings are consistent with previous similar studies (Clarke-Sather, Qu, Wang, Zeng, & Li, 2011; Wolde-Rufael & Idowu, 2017) that have also found interregional differences in inequality and carbon emission (i.e. Figures 1 and 2). The possible research for these regional differences can focus on the differences in economic growth, human capital, urbanisation, industrial concentration and income level across regions.

4.3. Innovation as a moderating variable

This study measures whether innovation moderates the relationship between income inequality and CO2. In Column 1 of Table 6, the coefficient of the interaction term (lnGINI $\times$ Innovation) is positive and is significant and positively related to CO2. The results indicate that higher income inequality and innovation increases the emission of CO2. This result indicates that innovation and inequality can cause carbon emission. However, this relationship can either be stagnant or become stronger if the country's carbon emission policy remains the same. lnRGDP is positive and significant, implying that economic growth increases the emission of CO2. In addition, the coefficient of lnRGDP_sq is significant and has a negative relationship with CO2, thus showing the relationship of EKC with carbon emission.

The results show that innovation is one of the key factors for reducing the income gap and increasing the carbon emission in China (Figure 3). In the process of 'economic catch-up', the Chinese government has heavily concentrated on investing in R&D activities in the country, which has definitely reduced the income gap in the country (Liu et al., 2017). Consistent with previous studies (Fan et al., 2006; Koçak & Ulucak, 2019), technological innovation is a source of high carbon emission. In a

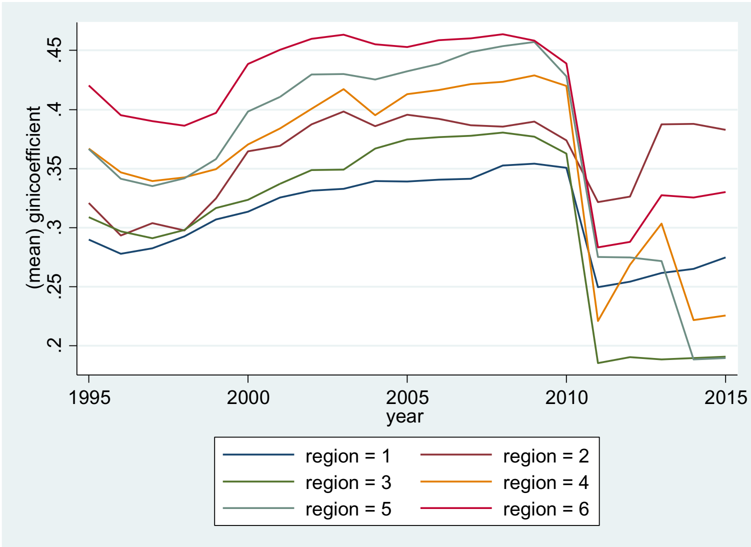

Figure 2. Trend of mean income inequality of six regions of china including region 1 is norther, region 2 is Northeast, region 3 is Eastern, region 4 is Central and South, region 5 Southwest, region 6 is Northwest. *Source:* The Authors.

Table 6. Moderation effect of technology innovation on income.

VARIABLES	sign	FE (1)	PCSE (2)	N-W (3)	FGLS (4)
lnGINI	+	−0.653***	−1.379**	−1.379***	−1.113***
		(0.193)	(0.584)	(0.344)	(0.268)
lnInnovation	–	0.275***	0.475***	0.475***	0.404***
		(0.0310)	(0.0533)	(0.0669)	(0.0357)
lnGINI × lnInnovation	?	0.0758***	0.166***	0.166***	0.135***
		(0.0201)	(0.0603)	(0.0364)	(0.0281)
lnRGDP	+	2.32e-05***	8.12e-05***	8.12e-05***	9.61e-05***
		(4.50e-06)	(1.15e-05)	(1.02e-05)	(5.83e-06)
lnRGDP_sq	–	−2.12e-10***	−8.92e-10***	−8.92e-10***	−1.12e-09***
		(5.87e-11)	(1.68e-10)	(1.41e-10)	(9.49e-11)
lnEI	?	0.0436	0.506***	0.506***	0.604***
		(0.0335)	(0.0738)	(0.172)	(0.0389)
lnURB	?	−0.0315	−0.134***	−0.134***	−0.180***
		(0.0292)	(0.0399)	(0.0423)	(0.0320)
lndStr	?	−3.730***	1.044***	1.044***	0.883***
		(0.338)	(0.311)	(0.277)	(0.223)
Constant		7.691***	4.817***	4.817***	5.280***
		(0.272)	(0.556)	(0.608)	(0.316)
Observations		565	565	565	565
R-squared		0.829	0.709		
N		27	27	27	27

Note: lnRGDP_sq is square of regional GDP. Standard errors in parentheses.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.
Source: The Authors.

recent study, Sheng, Miao, Song, and Shen (2019) have observed that innovation plays a moderating role in the relationship between urbanisation and CO2 emission. Although previous research has scantly used innovation as a moderator between the relationship of innovation and CO2 emission, our study has found that technological innovation is an important moderator in this link. This finding highlights that

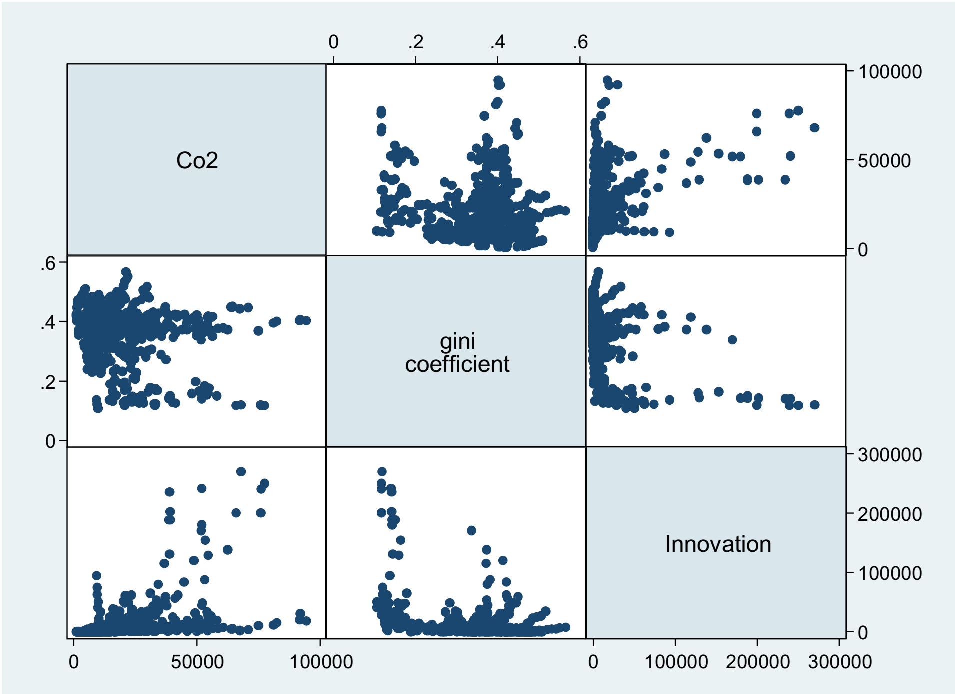

Figure 3. Income inequality, innovation and carbon emission. *Source:* The Authors.

innovation can help to reduce the inequality level and decrease the level of carbon emission by introducing energy-efficient innovations.

5. Conclusion

The present research has aimed to examine the relationship between income inequality and carbon dioxide emission through the moderating role of technological innovation in China. This study has employed the panel model, covering the period from 1995 to 2015, and reported interesting empirical findings.

Our findings demonstrate that (i) carbon emission increases as the income gap widens. (ii) Empirical results also confirm that innovation not only has a direct positive impact on the CO2 emission but also moderates the relationship of income inequality and carbon emission at the national and the regional level. (iii) The parameters of GDP and GDP square are positive and negative, respectively, which means that the relationship between economic development and carbon emission is nonlinear. This observation confirms the existence of an EKC in China. Hence, the energy intensity of the share of energy consumption to GDP is positive and significant, thus showing that an increase in energy consumption results in an increase of carbon emission at the national level.

Based on the above findings, this study provides the following policy implications. Considering the potential of economic growth, along with current carbon emission policies, China must focus on more efficient policies to decarbonise the economy. Moreover, technological innovation in the Chinese context, particularly those that are energy efficient, not only reduces the income gap but also helps to improve environmental quality. Thus, policymakers particularly focus on the growth of R&D activities in the country. Environmental taxes and incentives for the use of clean energy can improve the success of this process. The study results show that fair income inequality can reduce CO2 emission. Therefore, the Chinese government's policies with regards to the distribution of income can be used to safeguard the environment from carbon from. Moreover, a mechanism that reduces the income gap between the rich and the poor must be present, and the poor should not pay the cost of carbon emitted by the rich. In addition, a mechanism must be present so that China can escape from the middle-income trap.

Moreover, considering regional differences, the government must pay attention to the quality of economic growth in all regions so that the residents' income grows consistently. In this way, the government can reduce the regional differences and ensure that all segments of the country across every region can enjoy almost the same benefits. Regions with high carbon emission should contribute more to the welfare of the poor segment of the country, which not only helps to reduce the detrimental effects of CO2 emission but also reduces income disparities.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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