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Asymmetric effects of eco-innovation and human capital development in realizing environmental sustainability in China: evidence from quantile ARDL framework

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ABSTRACT

The present study investigates the dynamic and asymmetric impacts of eco-innovation and human capital development on ambient pollution by validating the Environment Kuznets Curve (EKC) hypothesis in China from 1988Q1 to 2018Q4. The findings confirm non-normality and structural breaks in data. Thus, Quantile Autoregressive Distributive Lag (QARDL) model and Granger Causality-in-Quantiles are applied to address non-linearity and structural breaks. The long-run results exhibit that eco-innovation and human capital have a significant negative relationship with carbon emissions, mainly from lower (0.05) to medium (0.5) quantiles and medium (0.50) to higher (0.95) emissions quantile. Moreover, economic growth contributes to higher emissions across all quantiles. In contrast, the square of economic growth has a significant negative association with emissions, confirming the validity of EKC from medium (0.40) to higher (0.95) quantiles. Lastly, Granger causality confirms a two-way causality between eco-innovation, human capital, and carbon emissions, and a one-way causality from human capital, economic growth to carbon emissions. These findings offer valuable policy recommendations.

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1. Introduction

Energy is a primary input in manufacturing, disseminating, and consuming nearly all goods and services worldwide (Sharif et al., 2019; Zhang et al., 2021). Energy is essential to increase economic growth and development, improve quality and standard of life, and offer many other benefits (Chiu & Lee, 2020). The increase in energy use for promoting industrialization causes global warming and greenhouse gases (GHGs) emissions in the atmosphere (Ozturk & Acaravci, 2013; Zhuang et al., 2021). Climatic

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change due to the greater concentration of GHG has been viewed as a key concern in the twenty-first century (Bano et al., 2018; Sharma et al., 2021). Global warming and the subsequent environmental concerns are extensively supposed to be the leading causes of future problems that will transact national borders (Sinha et al., 2020a, 2020b, 2020c; Yurdakul & Kazan, 2020). Likewise, GHG emissions of GHGs raise atmospheric temperature globally, which becomes a severe threat for both developing and developed nations (Saleem & Shujah-Ur-Rahman, 2019; Sinha & Rastogi, 2017). Gu and Wang (2018) investigated that research and development (R&D) investment at the company level becomes a necessary tool for reducing GHGs emissions. Expenditure in R&D in the companies is reflected as an operative instrument to improve environmental tactics that frequently allow sustainable products and services (Frondel et al., 2007; Lee & Min, 2015; Nasiritousi, 2017; Porter & Van der Linde, 1995). Expenditure in physical assets, investment in R&D, and human capital training require a long-term commitment by implementing the idea of eco-innovation (Cucchiella et al., 2017; Fernández et al., 2018).

The notion of eco-innovation has been reflected as a root for anticipating environmental damages due to GHGs and is expected to decrease the quantity of waste, material resource usage, and air pollution (Hojnik & Ruzzier, 2016; Sun et al., 2021; Yurdakul & Kazan, 2020). Eco-innovation is defined as new ideas for improving processes and products and reducing environmental burden (Dangelico & Pujari, 2010; Fussler & James, 1996; Garcia-Granero et al., 2018; Mensah et al., 2018). According to Serrat (2009), organizations can improve their product quality with the help of product innovation, and its cost can be reduced with the help of process innovation. Eco-product innovation can be achieved by improving existing or new products by reducing environmental concerns (Reid & Miedzinski, 2008). Likewise, eco-process innovation necessitates an amendment in existing business processes and systems by R&D investment, cutting resource costs and technological investment, and reducing greenhouse gas emissions (Cheng et al., 2014; Fethi & Rahuma, 2020; Mensah et al., 2018; Rennings, 2000). Eco-innovation could be a key pointer for executing a sound environmental tactic and help improve operational efficiency, future sustainability, and environmental performance (Fethi & Rahuma, 2020; Lopez-Gamero et al., 2010).

Human capital (HC) is deliberated as a substantial constituent that plays an imperative part in plummeting energy ingestion through improving energy efficiency (Bano et al., 2018). HC is one of the essential parameters for innovation, add value during the production process, plays an essential role in economic growth, and permitting developments in energy depletion competence and reduction in carbon emissions (CE) (Armstrong, 2016; Fang & Chang, 2016; Huang et al., 2021; Razzaq et al., 2021a). As an imperative cause of knowledge aggregation and technological revolution, HC is a significant component in improving green production through energy conservation, emission reduction, and environmental regulation (An et al., 2021). Pablo-Romero and Sánchez-Braza (2015) have found that more educated laborers can act as a substitute for energy, as enhancement in HC maintains technological advancement, which moreover decreases the implementation cost of these technologies, whereas utilizing such technologies leads to more ecologically friendly production (Dasgupta et al., 2000; Kim & Lee, 2011). Some prior studies propose that technological advancement can supplant labor and capital speculation while, on the other hand, it increments the request energy as well (Jiao et al., 2018; Yang & Li, 2017). Accordingly, the progressive outcome of technological innovation on the environment can be found merely in nations with a greater mix of renewable energy.

On the contrary, some other studies suggested that environmental-related technologies (low carbon) can play a substantial part in diminishing CE (De Jesus et al., 2018; Lee & Min, 2015). Moreover, De Jesus et al. (2018) also highlighted that eco-innovation could achieve environmental sustainability. Becker (2009) divides HC venture into different practices such as health care, quality of life, social setting, school-level education, and work-related training. There are many benefits by investing in HC, such as HC adds to greater labor productivity, economic growth, and is concomitant with a variation of societal externalities likewise less inequalities, abidance of government rules, better health, and deterioration in crime ratios (Rist, 2019; Romer, 1990; Schultz, 1961; Sianesi & Reenen, 2003). Desha et al. (2015) determined that improvement in HC with the help of knowledge, awareness, and education leads to increases renewable energy consumption. HC can be classified into three forms: first, the general HC, which is also known as HC stock and it is the amalgamation of education and general experience; the second one is called as firm-specific HC, which is the combination of skills, knowledge, and firm-level education; and third, task-specific HC, representing job-related training, knowledge, and skills (Au et al., 2008; Kwon, 2009).

Most of the prior studies used the Environmental Kuznets Curve (EKC) phenomena to analyze the relationship between economic growth and environmental change. The concept of EKC was presented by Kuznets (1955). The EKC demonstrates that at the early economic growth, increases in the atmosphere due to greater use of economic resources in the production process, but when a certain level of threshold of economic development is achieved, it will improve the environment. Shafik and Bandyopadhyay (1992) first analyze the association between economic growth and CE under EKC phenomena, and the results showed an increasing trend. A detailed review of this association is provided by Shahbaz and Sinha (2019).

Likewise, Choi et al. (2012) investigated the association between economic growth and CE under KEC hypothesis in developed economies. The study's findings revealed a positive relationship between and CE at an early stage of economic development, but later as the economic growth increases, the CE decreases. So, it implies that when economic growth is in the early stages, the natural resources are in plentitude with limited waste generation, but amid industrialization and advancement, the consumption of natural resources upsurges which come about in a significant positive relationship between economic growth and CE. As the nation gets in the developed stage of improved technology, it lessens the consumption of resources and results in an enhanced environment (Panayotou, 2016). The findings are also supported by some prior studies Dinda and Coondoo (2006), Grossman and Krueger (1995), Stern (2004), and Sinha and Shahbaz (2018).

China is one of the developing countries which shown tremendous economic growth over the last few decades; this growth is the result of increasing the consumption of fuel energy which will ultimately cause an increase in CE (Lapinskienė et al., 2017; Nguyen & Le, 2018; Tian et al., 2017). The government of China is taking Proactive initiatives to enhance energy efficiency and trying to develop renewable energy. Regardless of these incentives, CE in China is still high compared to other developed countries (Tan et al., 2011). The government of China commits at the Paris Climate Conference 2015 to reduce CE in a range between 60% and 65% till 2030 and try to incorporate this target in their long-term national projects respectively (Nguyen & Le, 2018).

From the above discussion, it can be said that eco-innovation and HC are important components for reducing CE. The silent feature of eco-innovation is that it helps in reducing environmental burden by giving new ideas for improving process and product manufacturing. HC ascertained to be a substantial component in improving green production through energy conservation and emission reduction. The said study analyzed the impact of eco-innovation and HC on environmental degradation by using QARDL approach. The motivation behind utilizing the QARDL is to test the long-term relationship over the quantiles of dependent variables, i.e., DJCM and DJIM, besides the conceivable asymmetric association with the exogenous variables in thought. Examination of asymmetries is the most advantage of QARDL over the linear ARDL approach (Xiao, 2009). Asymmetric association among the variables is due to the nonlinear relationship, which shows the changing impacts of regressors beneath various regressands (Cheng et al., 2021; Godil et al., 2020; Mishra et al., 2019; Shahbaz et al., 2018a, 2019a). In this study, asymmetries in relationship with eco-innovation and HC are analyzed regarding the aforementioned environmental degradation. The QADRL approach handles the long- and short-run association of eco-innovation and HC with environmental degradation and locating asymmetries under various quantiles.

The remaining paper is organized as takes after: The outline of the previous studies is created in the literature review section. The inquire about the research approach and data analysis techniques are debated in the methodology section. Data investigation and its discussion appear in result and interpretation, while the conclusion and policy implication appears in the conclusion segment.

2. Literature review

Eco-innovation has been recorded as an effective approach to addressing environmental problems (Lingyan et al., 2021; Zhang et al., 2017). Yurdakul and Kazan (2020) examined the effect of eco-innovation on CE and firm financial performance on a sample of 219 Turkish manufacturing firms. The results from the SEM revealed that eco-innovation is significantly positively related to resource-saving, recycling, and pollution prevention. Razzaq et al. (2021b) argued that eco-innovation has important implications for the environment. Sun et al. (2021) investigated the role of eco-innovation and globalization in mitigating CE in the case of the USA. The study used QARDL approach to estimate the long-run and the short-run association between selected variables. The findings of the study revealed that eco-innovation acts as a mitigating factor of CE. The study also supports the existence of EKC for the USA. Ding et al. (2021) determined the impact of eco-innovation, international trade, and energy on CE for G7 countries from 1990 to 2018. The findings from the panel causality test suggested that eco-innovation, trade, and energy are the primary factors of consumption-based CE in the G7 countries.

Erdoğan et al. (2020) analyzed the importance of environmental innovation in reducing CE in G20 countries. The author found that environmental innovation in the industrial sector reduces CE. Ji et al. (2021) used data from seven highly fiscally decentralized countries, Australia, Austria, Belgium, Canada, Germany, Spain, and Switzerland, from 1990 to 2018. The findings from econometric analysis revealed that eco-innovation reduces CE. This study recommends that any policy that targets green growth will affect CE. Yang and Li (2017) supported the role of eco-innovation to achieve the low-carbon emissions target. The author found that eco-innovation is helpful in reducing CE by improving carbon emission efficiency. Ali et al. (2021) examined the role of environmental innovation, trade, and renewable energy consumption in the nexus between trade and CE for the top 10 carbon emitter countries. The results of the Westerlund cointegration method suggest a long-term equilibrium relationship between environmental innovation, trade, and renewable energy consumption and CE.

Hojnik and Ruzzier (2016) concluded that eco-innovation in the form of greener technology has a long-term capacity to improve environmental quality. Wang et al. (2020) explored the effect of eco-innovation and export diversification on CE on panel data of G7 countries from 1990 to 2017. The result of the study shows that eco-innovation help in reducing CE in G7countries. Mensah et al. (2018) explore the impact of eco-innovation on environmental degradation in 28 OCED nations at an individual level for the time period 1990–2014. The study used three models based on the economic-EKC development model, the STIRPAT model, and the innovation-EKC model. This research showed that innovation plays a noteworthy part in alleviating CE in most OECD nations.

Fethi and Rahuma (2020) use the Porter hypothesis in the short run and long run to consider the dynamic influence of three eco-innovation indicators, namely HC training, investment, and R&D on CE in selected petroleum firms. The study applied second-generation panel regression on quarterly data over the period 2005–2016. The results demonstrate that investment as one of the gauges of eco-innovation altogether diminishes CE in the long-run, while R&D and HC make substantial reductions in CE in the short run. Garrone and Grilli (2010), discovered the association between R&D and CE for thirteen advanced countries. The study used annual data over the period 1980–2004. The OLS regression and GMM difference estimator findings revealed that R&D spending is not adequate to stimulate innovation in energy. To extend the argument, Yii and Geetha (2017) examined the relationship between technological innovation and CE for the Malaysian economy from 1971 to 2013. The results from ARDL approach and Granger causality test revealed a negative relationship between technological innovation and CE in the short run, while no such association is observed in the long run in the said economy.

Ramanathan et al. (2017) scrutinized the relationship between eco-innovation, sustainable benefits in terms of pollution reduction, environmental regulations, and CE impact on 9 case studies of Chines and British companies. They perceived that corporations that depend on their assets and capabilities move their commitments towards sustainability through decreases in pollution and enhanced performance. Zhang et al. (2017) examined the impact of eco-innovation on CE in China. The study utilized panel data of 30 provinces of China for the period 2000–2013. Empirical results from GMM estimation technique revealed that eco-innovation reduces CE in China effectively. Alam et al. (2019) studied the impact of R&D investment on the environment in G6 countries from 2004 to 2016. The findings of study revealed a significant positive association between R&D investment and CE reductions.

Huang et al. (2021) found the impact of HC on carbon emissions in 30 provinces in China from 1998 to 2017. The overall results from the quantile regression model and spatial panel lag model revealed that primary, knowledgeable, skilled, and institutional HC would offer assistance in decreasing carbon emissions in various selected regions. Shahbaz et al. (2019b) found that HC plays a noticeable part in controlling energy consumption. HC also helps to increase renewable energy consumption because of education, awareness, and knowledge about energy security (Desha et al., 2015). HC promotes technology advancement and decreases the execution cost of these technologies (Kim & Lee, 2011). Ahmed and Wang (2019) scrutinized the impact of HC on the ecological footprint in India over the period 1971–2014. It appears from the research findings that higher HC mitigates the ecological footprint in the long-run and short-run. Bano et al. (2018) examined HC's short- and long-term impact on CE in Pakistan from 1971 to 2014 by employing an autoregressive distributed lag model and the vector error correction model. The study's finding shows a long-term association between HC and CE. It also shows a two-way causal relationship between HC and CE in the long run. Li and Ouyang (2019) found the long-run cointegration linkage between HC and CE in China from 1978 to 2015 by using the ARDL approach. Mehrara et al. (2015) expressed that HC measured by tertiary education is imperative for renewable energy consumption and maintains renewable energy through information sharing, skilled labor, and financial-economic development. Yao et al. (2020) found the relationship between HC and CE for 20 OECD countries from 1870 to 2014. The result from cross-sectional dependence and structural breaks proposed that HC is related to a diminishment in CE. Furthermore, a higher level of human capital might also promote enterprises to strictly follow related environmental standards, which will also help reduce CO2 emission intensity (Li & Ouyang, 2019).

Yuan and Zhang (2017) suggested that HC, as an essential source of knowledge accumulation and technological innovation, can promote green production through energy-saving and technological innovation. Iqbal et al. (2021) examined the impact of trade openness, urbanization, and HC on environmental degradation using the panel data of 126 economies for the years 1971–2020. The study also extends the analysis for four sub-panels, namely, high-income economies (HIC), upper-middle-income economies (UMIC), lower-middle-income economies (LMIC), and low-income economies (LIC) by using fully modified least squares (FMOLS), dynamic ordinary least squares (DOLS), fixed effects (FEM), random effects (REM), and system GMM. The results show that enhancement in HC will lessen emissions in all economies. Therefore, economies should invest in human capital to combat emissions.

Besides, Yao et al. (2019) centered on determinants of renewable energy consumption (REC) and non-renewable energy consumption (NREC) for high-income part nations by utilizing data from 1965 to 2014. They have found a negative relationship between HC and NREC, though a positive relationship between HC and REC. Adom (2015) analyzed the asymmetric impact of the elements affecting energy intensity within the case of Nigeria from 1971 to 2011 and has found that HC improvement upgrades energy consumption in the case of Nigeria. Lin et al. (2021) examined the effect of innovative HCl on CE in China. The provincial panel data of 30 Chinese provinces from 2003 to 2017 was analyzed utilizing the fixed effect, OLS, and the system GMM. The analysis revealed that innovative HC alleviates environmental deterioration in China. The outcomes unfold the presence of the EKC considering innovative HC in the model. Wang and Xu (2021) observationally analyze the relationship between internet usage, HC, and CE beneath the diverse level of financial development by using system GMM and a threshold regression model on the panel data of 70 nations from 1995 to 2018. The outcomes appear internet usage and HC are basic drivers of low-carbon economy development, and HC can inversely regulate the impact of internet usage on CE.

3. Material and methods

3.1. Quantile ARDL approach

To investigate the asymmetric and dynamic association between eco-innovation, human capital, economic growth, and CE in China, the current study utilized Quantile Auto Regressive Distributed Lag (QARDL) approach, which was developed by Cho et al. (2015). The QARDL approach is an extension of ARDL approach, and this strategy permits testing the asymmetries and long-term equilibrium relationship between eco-innovation (EI), human capital (HC), economic growth (GDP), square economic growth (SQGDP), and carbon emissions (CE). The study moreover utilized the Wald test to decide the cointegration affiliated among the said factors. The test permits checking the steadiness of integration coefficients through a range of quantiles. The equation for ARDL model is as follows:

$$CE_t = \mu + \sum_{i=1}^{p} \varphi i \; CE_{t-i} + \sum_{i=0}^{q} \gamma i EI_{t-i} + \sum_{i=0}^{r} \omega i HC_{t-1} + \sum_{i=0}^{s} \gamma i GDP_{t-i} + \sum_{i=0}^{u} \omega i SQGDP_{t-i} + \varepsilon_t \quad (1)$$

where ε_t is the error term, EI_t, and HC_t, GDP_t and $SQGDP_t$ refer to the eco-innovation, human capital, ECO_GRO, and square economic growth individually, whereas CO_2 signifies CE. Cho et al. (2015) extended the model in Eq. (1) to a quantile setting and presented the following basic form of the QARDL (p, q, r, s, u) model:

$$QCE_t = \mu(\tau) + \sum_{i=1}^{p} \varphi i(\tau)CE_{t-i} + \sum_{i=0}^{q} \gamma_i(\tau)EI_{t-i} + \sum_{i=0}^{r} \omega_i(\tau)HC_{t-1} + \sum_{i=0}^{s} \psi_i(\tau)GDP_{t-i} + \sum_{i=0}^{u} \phi_i(\tau)SQGDP_{t-1} + \varepsilon_t(\tau) \quad (2)$$

where, $\varepsilon_t(\tau) = CO_{2t} - Q_{CE_t(\tau v_{t-1})}$ and $0 > (\tau) < 1$ illustrate quantile (Kim & White, 2003). Owing to the chance of a sequential relationship, the QADRL demonstrate appeared in Eq. (2) is generalized as takes after:

$$Q_{\Delta CE_t} = \mu + \rho CE_{t-1} + \partial_{EI}EI_{t-1} + \partial_{HC}HC_{t-1} + \partial_{GDP}GDP_{t-1} + \partial_{SQGDP}SQGDP_{t-1} + \sum_{i=1}^{p-1} \varphi i \ \Delta CE_{t-1} + \sum_{i=1}^{q-1} \gamma i\Delta EI_{t-1} + \sum_{i=1}^{r-1} \omega i\Delta HC_{t-1} + \sum_{i=1}^{s-1} \gamma i\Delta GDP_{t-1} + \sum_{i=1}^{u-1} \omega i\Delta SQGDP_{t-1} + \varepsilon_t(\tau) \quad (3)$$

The parameters in Eq. (3) degree the short-term dynamics, whereas the long-term connections between eco-innovation, human capital, and carbon dioxide spread emanation can be captured by reformulating adaptation of Eq. (3) moreover to avoid the serial correlation of ε, we generalize the QARDL as takes after:

$$Q_{\Delta CE_t} = \mu + \rho CE_{t-1} + \beta_{ECOI}EI_{t-1} + \beta_{HC}HC_{t-1} + \sum_{i=1}^{p-1} \varphi i \ \Delta CE_{t-1} + \sum_{i=0}^{q-1} \gamma i\Delta EI_{t-i} + \sum_{i=0}^{r-1} \omega i\Delta HC_{t-\mathrm{i}} + \sum_{i=0}^{s-1} \gamma i\Delta GDP_{t-i} + \sum_{i=0}^{u-1} \omega i\Delta SQGDP_{t-i} + \varepsilon_t(\tau) \quad (4)$$

By utilizing the delta strategy, the aggregate short-run effect of previous carbon dioxide outflow on present carbon dioxide emanations is decided by:

$$\partial_* = \sum_{i-1}^{p-1} \partial\partial_j,$$

Whereas the aggregate short term effect of the past and current levels of EI, HC, GDP, and SQGDP are determined by

$$\theta_* = \sum_{i-1}^{q-1} \partial\partial_j \text{ and } \Psi_* = \sum_{i-1}^{r-1} \partial\Psi_j \text{ , respectively.}$$

The factor associated to long-run for eco-innovation, human capital, economic growth, and square economic growth is calculated as:

$$\beta_{CE^*} = -\frac{\beta_{CE}}{\rho}, \beta_{EI^*} = \frac{\beta_{EI}}{\rho}, \text{and} \beta_{HC^*} = \frac{\beta_{HC}}{\rho}, \beta_{GDP^*} = \frac{\beta_{GDP}}{\rho}, \text{and}, \beta_{SQGDP^*} = \frac{\beta_{SQGDP}}{\rho}.$$

It might be noted that the ECM parameter ρ out to be essentially negative. Wald test is applied to look at the validity of short and long-run asymmetric impact of parameters.

$$H_\circ \ : \ \rho_* \ (0.05) = \ \rho_* \ (0.1) = \ \rho_* \ (0.2) = \ \ldots. \ \ldots. = \ \rho_* \ (0.95)$$

opposite to an alternative one

$$H_i : \ \exists_i \neq j/\rho^{(i)} \ \neq \ \rho^j$$

3.2. Data and variables

This research contains five variables, Carbon emissions (CE), Eco-innovation (EI), Human capital (HC), economic growth (GDP), and square economic growth (SQGRP). Table 1 shows the detail of variables along with measurement, source, and empirical justifications.

By virtue of limited data, the annual data was further transformed into quarterly observations by using the quadratic match sum method used by Aziz et al. (2020a), Godil et al. (2020), and Shahbaz et al. (2018b). The match sum quadratic method is very effective as this method converts the data from low frequency into high frequency. This method allows amendments for seasonal deviations by dropping end-to-end data deviation (Godil et al., 2020; Mishra et al., 2020). The graphical trend of carbon emissions, Eco-innovation, Human capital in China from 1988 to 2018 is provided in Figure 1.

Table 1. Detail and justification of variables.

Variable name	Measurement	Source	Justification of variables
Carbon emissions (CE)	Metric tons per capita	World Development Indicator (WDI)	Chen and Lei (2018); Godil et al. (2020); Shahbaz et al. (2013); Shoaib et al. (2020); Tamazian et al. (2009)
Eco-innovation (EI)	% of total technological innovation	OECD (2019)	Ali et al. (2021); Ding et al. (2021); Ji et al. (2021)
Human capital index (HC)	Human capital index	Penn World Table (PWT)	Hassan et al. (2019); Lederman et al. (2017); Saleem & Shujah-Ur-Rahman (2019)
Economic growth (GDP)	GDP per capita growth (annual %)	World Development Indicator (WDI)	Godil et al. (2020); Shoaib et al. (2020); Tamazian et al. (2009)

Source: authors' calculations.

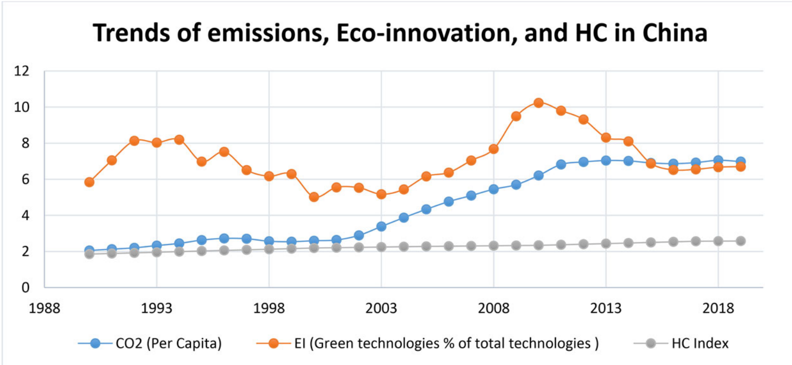

Figure 1. Trends of carbon emissions, eco-innovation, and HC in China.
Source: WDI, OECD, and PWT.

Table 2. Descriptive statistics.

Description	CE	EI	HC	GDP	SQGDP
Mean	4.461	7.107	2.252	3.423	6.846
Median	4.110	6.704	2.274	3.414	6.827
Maximum	7.060	10.286	2.581	3.895	7.789
Minimum	2.030	4.918	1.847	2.855	5.710
Std. Dev.	1.962	1.375	0.208	0.322	0.643
Skewness	0.194	0.611	−0.178	−0.098	−0.098
Kurtosis	1.317	2.633	2.107	1.729	1.729
Jarque-Bera	14.917	8.147	4.620	8.267	8.267
Probability	0.001	0.017	0.099	0.016	0.016
Observations	120	120	120	120	120

Source: authors' calculations.

3.3. Descriptive statistics

Measures of central tendency are represented by mean value, median value, minimum value, and maximum value. Table 2 shows the summary statistics of all the variables used in the study, the minimum value, mean value, and the maximum value of selected variables shows positive numbers i.e., CE (M = 2.030, Min= 4.461, Max = 7.060), EI (M = 4.918, Min = 7.107, Max = 10.286), HC (M = 1.847, Min = 2.252, Max = 2.581), GDP (M = 2.855, Min = 3.423, Max = 3.895), SQGDP (M = 5.710, Min = 6.846, Max = 7.789). In order to validate the normality of the data, this research study used the Jarque-Bera test. The test outcome showed that all the null hypotheses of data linearity were rejected, which instigated us to apply the QADRL approach (Batool et al., 2019; Godil et al., 2020; Sinha et al., 2021; Troster et al., 2018). The quantile distribution of data for each variable is presented in Figure 2.

4. Results and discussion

4.1. Unit root test

The unit root test was used to find the stationarity of the data. For QADRL approach, it is necessary to confirm the order on integration in a given data set. According to Li and Ouyang (2019), all the regressors used in the QADRL approach must be integrated at level I (0) or at the first difference I (1). therefore, this research study

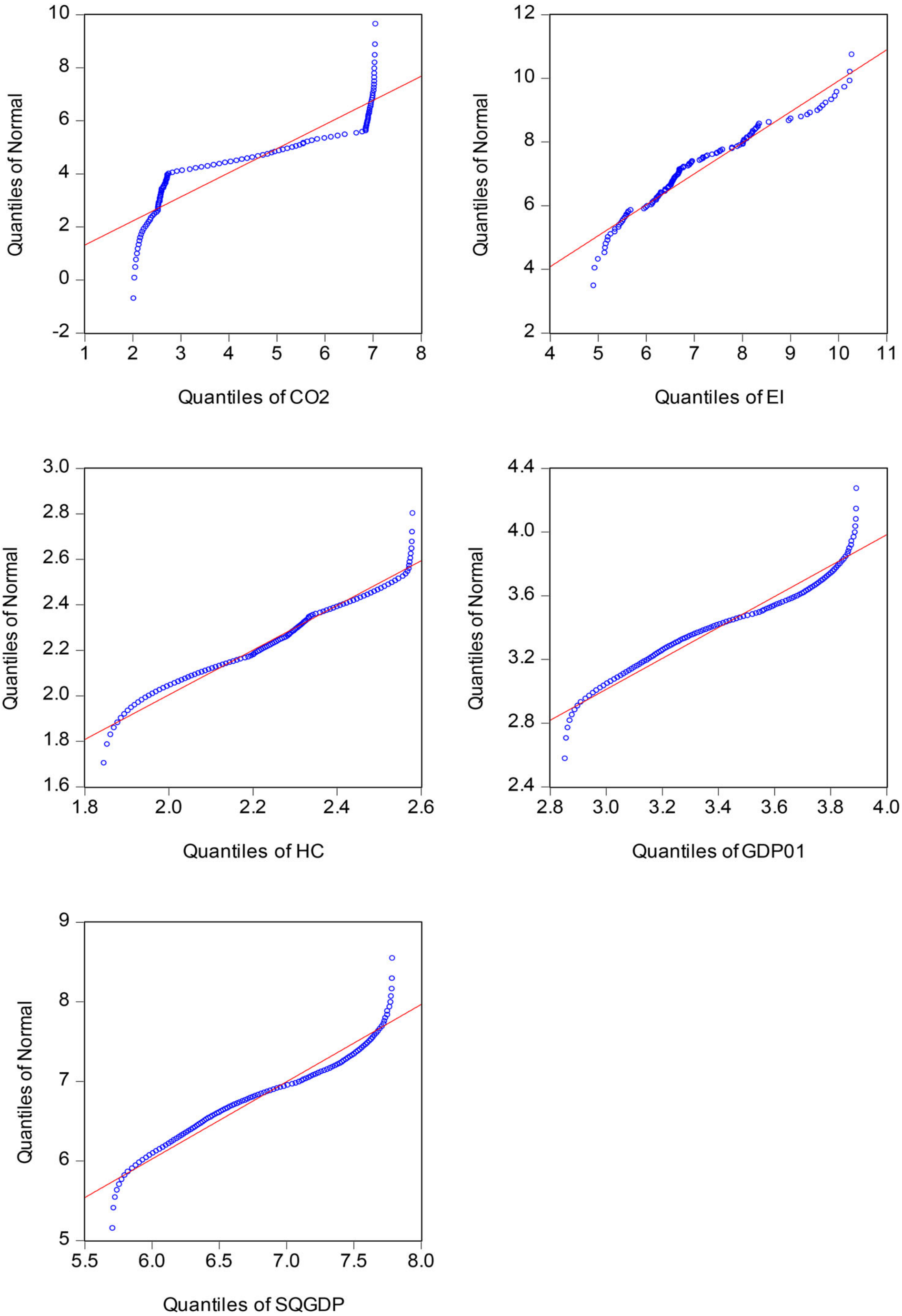

Figure 2. Quantile distribution of data.
Source: authors' calculations.

applied two unit root tests, the first one is the Zivot and Andrews (2002) unit root test (ZA), and the second one is Augmented Dickey-Fuller unit root test (ADF). The ZA test is essential as this test help to determine the structural breaks in the given

Table 3. Unit root test.

Variable	CE	EI	HC	GDP
ADF (Level)	−1.145	−2.829	−1.567	−2.354
ADF (Δ)	−2.725**	−2.889*	−2.886**	−2.695**
ZA (Level)	−3.968	−3.908	−4.582*	−2.960
Year	2001Q1	2008 Q1	2010 Q1	2001Q1
ZA (Δ)	−3.842***	−3.681**	−4.193**	−4.193**
Year	2011 Q1	2010 Q1	2017Q1	2018 Q1

Note. *, **, and *** indicate a level of significance at 10 %, 5% and 1%, respectively.
Source: authors' calculations.

data. Table 3 shows the results of the ZA unit root test and ADF unit root test. The findings showed that all the selected time series variables are I (1) and stationary either at a 5% or 10% level of significance, except HC, which is found to be I (0) as well as I(1). The results revealed that all the variables have unique order of integration I (1). Hence, it is confirmed that the QADRL approach is an appropriate method that elaborates structural breaks, dynamic trends, and non-linearity in the data (Aziz et al., 2020b Sharif et al., 2020a,2020b; Razzaq et al., 2021).

Table 4 reports the outcomes of QARDL approach. The finding shows that the estimated parameter of dependency ρ is highly significant with a negative sign in all 11 quantiles (0.05–0.95). It shows the long-run equilibrium relationship between eco-innovation, human capital, economic growth, square economic growth, and CE. Eco-innovation βEI shows a significant negative relationship with CE at lower (0.05) to medium (0.50) levels of quantiles. These findings are supported by some prior studies (Ding et al., 2021; Ji et al., 2021; Sun et al., 2021; Wang et al., 2020) and inconsistent with (Ahmad et al., 2021; Ozcan & Apergis, 2018). The study considers that eco-innovation shall be helpful in support of environmental quality. The author contended that energy efficiency technologies accommodate swapping the financial structure to more sustainable energy sources, renewable energies. Likewise, human capital βHC indicates a significant negative relationship with CE at medium (0.50) to highest (0.95) level of quantiles. The findings showed the presence of long-run asymmetric relationship between HC and CE for China. The findings of this study are consistent with some prior studies (Bano et al., 2018; Bastola & Sapkota, 2015; Chengliang et al., 2017; Huang et al., 2021; Iqbal et al., 2021; Lin et al., 2021). As a fundamental source of information aggregation and technological innovation, human capital can advance green production through energy-saving and technological innovation. Economic growth βGDP, the results show a significant positive relationship with CE at lower (0.20) to highest (0.95) level of quantiles, and the results are supported by Alkhathlan and Javid (2013), Begum et al. (2015), Hussain et al. (2012), Ji et al. (2021) and Sun et al. (2021). In contrast, the square of economic growth βSQGDP specifies a significant negative relationship with CE in lower (0.40) to highest (0.95) level of quantile. The βSQGDP indicate the EKC hypothesis, justified through the negative coefficient value at only lower (0.40) to highest (0.95) level of quantiles in the long run. These findings are echoed by recent literature (Lin et al., 2021; Saleem & Shujah-Ur-Rahman, 2019; Sun et al., 2021; Xuefeng et al., 2021).

The short-run relationship among the selected variables for QARDL approach is also presented in Table 3. The study's findings show that the fluctuations in the

Table 4. Results of quantile autoregressive distributed lag.

	constant	Long-run coefficients					Short-run coefficients				
Quantiles (τ)	α	ρ	βEI	βHC	β_{GDP}	β_{SQGDP}	φ_1 (C)	ω_0 (EI)	λ_0 (HC)	θ_0 (GDP)	δ_0 (SQGDP)
0.05	1.019	−0.353*	−0.319**	−0.069	0.239	−0.001	0.527***	−0.027	0.072	0.217	−0.099
0.10	0.526	−0.410**	−0.493***	−0.073	0.137	−0.019	0.550***	−0.026	0.073	0.308	−0.018
0.20	1.238*	−0.402**	−0.639***	−0.056	1.333***	−0.017	0.469***	−0.026	−0.014	0.431**	−0.010
0.30	1.222**	−0.408**	−0.540***	−0.035	1.203***	−0.013	0.442***	−0.028	−0.002	0.341***	−0.012
0.40	1.287**	−0.405**	−0.285**	−0.028	1.073***	−0.160*	0.590***	−0.065*	−0.011	0.466***	−0.015
0.50	1.134**	−0.405**	−0.274**	−0.129*	1.181***	−0.166**	0.481***	−0.069*	−0.024	0.533***	−0.012
0.60	0.854	−0.395**	−0.049	−0.156**	1.060***	−0.128**	0.502***	−0.075**	−0.057	0.475***	−0.012
0.70	0.713	−0.379**	−0.028	−0.127**	1.612***	−0.125**	0.531***	−0.091**	−0.107**	0.417***	−0.010
0.80	0.703	−0.390**	−0.032	−0.149**	0.975***	−0.174**	0.614***	−0.020	−0.087*	0.418***	−0.024
0.90	1.834*	−0.323*	−0.050	−0.151**	0.972***	−0.186**	0.629***	−0.021	−0.089*	0.261*	−0.029
0.95	1.901**	−0.254*	−0.045	−0.150**	0.876***	−0.131**	0.604***	−0.010	−0.083*	0.217*	−0.099

Note. The table reports the quantile estimation results. The standard errors and *t* values are not reported for the sake of brevity. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.
Source: authors' calculations.

Table 5. Results of the Wald test for the constancy of parameters.

Variables	Wald-statistics [*p*-value]
Long-run parameters	
ρ	3.824*** [0.000]
βEI	5.643*** [0.000]
βHC	3.712*** [0.000]
β_{GDP}	5.410*** [0.000]
β_{SQGDP}	4.672*** [0.000]
Short-run parameters	
φ_1	7.109*** [0.000]
ω_0	2.892** [0.040]
λ_0	3.001** [0.000]
θ_0	3.628*** [0.000]
δ_0	1.720 [0.692]

Note. Null hypotheses: Parameters are constant.
Source: authors' calculations.

current CE are significantly positively influenced by their own past at the grid of all quantiles from lower (0.05) to highest (0.95). In the short-run, eco-innovation (EI) indicates a significant negative relationship with CE at lower (0.40) to higher (0.70) level of quantiles and insignificant at the rest of the quantiles. Likewise, human capital (HC) also shows a significant negative relationship with CE at the grid of higher (0.70) to highest (0.95) level of quantiles. For economic growth, GDP shows a significant positive association with CE at lower (0.20) to highest (0.95) level of quantiles. Lastly, the findings for square economic growth (SQGDP) show an insignificant relationship with CE in the long run, indicating that the KEC hypothesis does not validate in the short run. Overall, the study's findings showed a long-run quantile integration relationship between EI, HC, GDP, SQGDP, and CE in China.

The findings of the Wald test are presented in Table 5. The Wald test results confirm that the consistency parameters and the linearity of the speed of adjustment parameters are not accepted, so that it will reject the null hypothesis. In addition, the consistency parameter hypothesis at all the 11 quantiles for the selected variables, i.e., βEI, βHC, βGDP, and βSQGDP are not accepted. These results indicate the presence of asymmetry as the results show that the parameters for all the variables used in this study are varied across qualities. Similarly, the outcomes of short-term dynamics are also presented in Table 4. The results rejected the null hypothesis of parameter consistency around the lattice of all the 11 quantiles. For the short-run impact, the Wald test rejects the null hypothesis of parameter consistency and indicates an asymmetric relationship for EI on CE, HC on CE, and GDP on CE. The Wald test failed to reject the null hypothesis of parameter consistency for SQGDP impact on CE, demonstrating the symmetric collective short-run impact of SQGDP on CE.

Table 6. Test results of granger causality in quantile.

Quantiles	[0.05–0.95]	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95
ΔEI_t to CE_t	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ΔCE_t to ΔEI_t	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ΔHC_t to CE_t	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ΔCE_t to ΔHC_t	0.452	0.450	0.520	0.402	0.402	0.503	0.560	0.560	0.568	0.710	0.695	0.650
ΔGDP_t to CE_t	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ΔCE_t to ΔGDP_t	0.337	0.682	0.614	0.764	0.736	1.032	0.544	0.456	0.995	0.910	0.832	0.902
ΔEI_t to HC_t	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ΔHC_t to ΔEI_t	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note. Null hypothesis: No Casual associations exist.
Source: authors' calculations.

Table 6 presented the result of the Granger-causality test. The given probability values at various quantiles confirm the casual link at a particular quantile. For eco-innovation and CE, the findings show two-way causality running from EI to CE and from CE to EI, respectively, across all the given quantiles at a 1 percent level of significance. This finding justified that eco-innovation causes CE, and as a result, CE also causes eco-innovation. Shabani and Shahnazi (2019) support these findings, identifying two-way causality between eco-innovation and CE in China. Similar findings are endorsed by Razzaq et al. (2021) in the BRICS sample. On the contrary, contrarily et al. (2018) find one-way causality running from eco-innovation to CE. Likewise, for the relationship between human capital and CE, it is confirmed that a one-way causality exists between human capital and CE for all quantiles at a 1 percent level of significance. For ECO_GRO, one-way causality was observed running from economic growth to CE. These findings are consistent with Ben Jebli and Hadhri (2018). Whereas the results are contradicted with Zhang and Gao (2016), indicating two-way causality between economic growth and CE. Lastly, two-way causality is observed for eco-innovation and human capital at a 1 percent level of significance. The overall findings of the Granger causality test result show the presence of causality at all the quantiles, respectively.

5. Conclusion and policy implications

The key objective of this study is to ascertain the long-run and the short-run association among eco-innovation, human capital, and carbon emissions by concurrently determining the presence of EKC hypothesis in China. We applied Quantile ARDL and Granger causality test to estimate dynamic and asymmetric association among model variables using quarterly data from 1988Q1 to 2018Q4. In the long run, the findings indicate that eco-innovation (EI) and human capital (HC) significantly mitigate the level of carbon emissions (CE) at lower (0.05) to medium (0.50) levels of quantiles and medium (0.50) to highest (00.95) level of quantiles respectively. Economic growth (GDP) directs a positive asymmetric impact on CE at the lower (0.50) to highest (0.95) level of quantiles. Likewise, the square of economic growth (SQGDP) exerts a negative influence on CE at lower (0.40) to highest (0.95) level of quantiles, validating the existence of EKC hypothesis in the long run. Likewise, in the short run, EI and HC possess significant emissions mitigating effects mainly at lower (0.40) to higher (0.70) quantiles and higher (0.70) to highest (0.95) level of quantiles, respectively. While GDP indicates a significant positive impact on CE at lower (0.20) to highest (0.95) level of quantiles. Granger causality results confirm the presence of two-way causality between EI, HC, and CE at 1 percent significance level, while a one-way causality runs from HC to CE and GDP to CE at 1 percent level of significance, respectively.

These results imply that human capital development is the foundation of sustainable growth. It encourages innovation and increases overall productivity for firms/ countries. Although several human capital development initiatives are already undertaken in China, it is reiterated to embark on another wave to develop human capital by introducing an integrated policy where an innovation-driven model is promoted at the firms and national level. Moreover, the Chinese government should revitalize the national innovation plan to encourage households and firms to adopt sustainable technologies by proposing lower interest rates for energy-efficient acquisitions like electric cars, vitality-efficient housing construction, solar system purchase, installation, etc. Moreover, the government should offer credits at a lower interest rate to private, commercial, and industrial clients for introducing solar energy, as this will quicken the move from non-renewable energy to renewable energy consumption. Policy practitioners ought to plan arrangements to contribute to environmental friendly technologies. In expansion, the government should start new ventures and encourage research and development in environmentally friendly technologies. It is imperative to energize unique and diverse sources of renewable energy at the household and commercial levels to manage the issues of environmental degradation. Lastly, China should be heightening endeavors to intensify efforts to foster innovative human capital. The Chinese central and regional government must do some strategic planning to nurture innovative human capital. In this respect, introducing different training programs for human capital and centering on expanding R&D staff by offering some subsidies and benefits on R&D in different economy divisions can provide assistance to foster innovative human capital.

Disclosure statement

No potential conflict of interest was reported by the authors.

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