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Clean energy transition and load capacity factors: Environmental sustainability assessment through advanced statistical methods

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Clean energy transition and load capacity factors: Environmental sustainability assessment through advanced statistical methods

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Weather index insurance for transition to sustainable cotton production under climate change in Xinjiang, China

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Assessing climate-induced reductions in cotton yields is critical to developing weather insurance for sustainable agricultural development. Climatic factors such as frost, hail, and drought severely constrain the sustainable development of cotton production in Xinjiang. In this study, based on cotton production and meteorological data from 1988 to 2019 in Aksu, Xinjiang, the H-P filtering method, correlation test, and regression analysis were used to develop a weather index model of cotton yield reduction rate and key meteorological factors. The results showed that the trend yield separated by the H-P filtering method was more stable. The correlation analysis between cotton fertility and meteorological factors concluded that there was a strong positive correlation between precipitation and cotton yield, i.e., the more rainfall, the more unfavorable environment for cotton growth and development. The results of the empirical analysis to determine the net premium rate under different disaster registrations based on the logistic probability distribution model showed that the highest probability of meteorological disasters in the Aksu region was 22.36%, the premium rate was 1.79%, and the net premium was 34.01 RMB per mu. It is found that climate change is closely related to the environment, and human production activities are compatible with the carrying capacity of the environment, otherwise, climate change leads to frequent meteorological disasters, which is not conducive to the sustainable development of agricultural production. It is expected that these research results can provide a relevant basis for the implementation of cotton policy weather insurance in Aksu and other regions and promote the sustainable development of cotton production.

KEYWORDS

climate change, precipitation, cotton, weather index insurance, environmental sustain ability, China

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1 Introduction

Current topical issues include global warming, greenhouse gas emission reduction, and how to adapt to climate change (Martina, 2016). Agricultural production is extremely dependent on climatic conditions, and this vulnerability makes agriculture one of the most sensitive and significant sectors to climate change impacts (Lobell et al., 2011). Climate change, through variations in temperature and precipitation, causes changes in environmental elements for crop growth such as sunlight, moisture, and soil, which subsequently affects crop phenological periods, growth potential, cropping systems, pest control, farm management, and ultimately crop yield (Liu et al., 2013). Meanwhile, related studies have shown that the warming trend in northwest China is higher than the national average during climate change (Diarra et al., 2017). Therefore, climate warming may shorten cotton ferity, reduce seed cotton yield, and increase evapotranspiration intensity and irrigation water use, thus increasing the risk of sustainable cotton production in Xinjiang (Yang et al., 2014; Saseendran et al., 2016; Wang et al., 2018).

Cotton is one of the most labor-intensive cash crops in the world and is an important strategic material for the country's livelihood. Since it joined the World Trade Organization, cotton imports have accounted for about a quarter of the world's total imports (Liu, 2020; Mi and Cheng, 2020). In China, cotton is the second largest crop after grain, with an annual planted area of about 5.53 million ha, accounting for about 15% of the world's planted area (Yu et al., 2015). Meanwhile, as an important textile raw material, cotton has provided a strong impetus for the development of the Chinese textile industry and has become a key factor for the green and sustainable development of the industry (Li et al., 2021). Xinjiang is the largest cotton-producing area in China. Xinjiang's total cotton production, yield, planted area, and commodity sales have ranked first in the country for more than 20 consecutive years (Xinhua News Agency, 2021). Among them, in 2021, the total cotton production in Xinjiang reached 5.129 million tons, accounting for nearly 90% of the national cotton production (Xinjiang Uygur Autonomous Region Bureau of Statistics, 2022). However, cotton cultivation in Xinjiang is typical of oasis agriculture, prone to natural disasters, with a weak agricultural production base that is heavily influenced by climate change, a relatively fragile natural environment, and scarce water resources. Various disasters such as floods, droughts, high winds, sand, and dust have caused huge economic losses to cotton farmers and become a major factor limiting the green and sustainable development of cotton production in Xinjiang (Tao et al., 2022).

Agricultural insurance is an important measure to guarantee the security of cotton production and farmers' income. Among them, cotton insurance supported by the Chinese government is an important way to ensure the security of cotton production (Stoeffler et al., 2016). Since 2007, the policy of cotton insurance implemented in Xinjiang has experienced problems such as moral hazard, adverse selection, high underwriting, and loss assessment costs (Xu, 2021), which affect the sustainable development of cotton insurance industry. However, weather index insurance refers to the study of the relationship between weather data and crop losses, and the design of insurance contracts relies on local weather and crop growth data, which can effectively spread agricultural risks and overcome the drawbacks of traditional agricultural insurance (McIntosh et al., 2013). After piloting in some countries and regions, it is now widely accepted by farmers and insurance companies (Xu, 2021).

The existing literature on weather index insurance has focused on the following aspects. Firstly, whether insurance premium pricing models are adopted for research on the practical experience of weather insurance in developing countries (Collier et al., 2009; Chen, 2011; Yin, 2014; Conradt et al., 2015; Ma, 2019). For example, early scholars mainly used the Pearson coefficient method, principal component analysis, entropy weighting method, multiple stepwise regression model, stepwise adjustment outpu, and detrending to construct weather indicator insurance models and determine insurance rates (Wu et al., 2010; Yang et al., 2015; Shao, 2016; Liang and Zhou, 2019; Yu, 2020; Yu and Wang, 2021). Secondly, most of the studies on the design of weather index insurance contracts have been conducted with food crops as the target. Examples, maize drought weather index insurance, medium rice high-temperature heat damage weather index insurance, millet comprehensive weather index insurance, and winter wheat drought weather index insurance (Qu et al., 2018; Liu et al., 2017; Wang et al., 2019; Cao et al., 2019). Thirdly, the literature on cotton weather index insurance and its rate setting is relatively limited, and only a few studies deal with cotton agricultural insurance to cope with climate change. For example, Wang et al. (2014) and Wu (2017) and Chao et al. (2017) proposed yield and cotton futures prices as the main components of agricultural insurance for income insurance price index to cope with climate change. In addition, Weber et al. (2015) designed different weather insurance products based on the put option of cumulative precipitation index, and weather insurance with meso-level index can significantly reduce the risk. Chu and Cao (2014) and Sun et al. (2016) proposed the impact of cotton precipitation index insurance and low-temperature index insurance on the sustainable development of cotton production in the northern Xinjiang Corps region.

In general, the current literature is relatively rich in discussing weather index insurance, but there are still the following shortcomings. First, Chinese agricultural production has obvious regional differences, and crops in different regions face the influence of different meteorological environmental factors, and the corresponding weather insurance index should be designed according to local conditions. Second, many weather factors affect crop growth. Most studies have

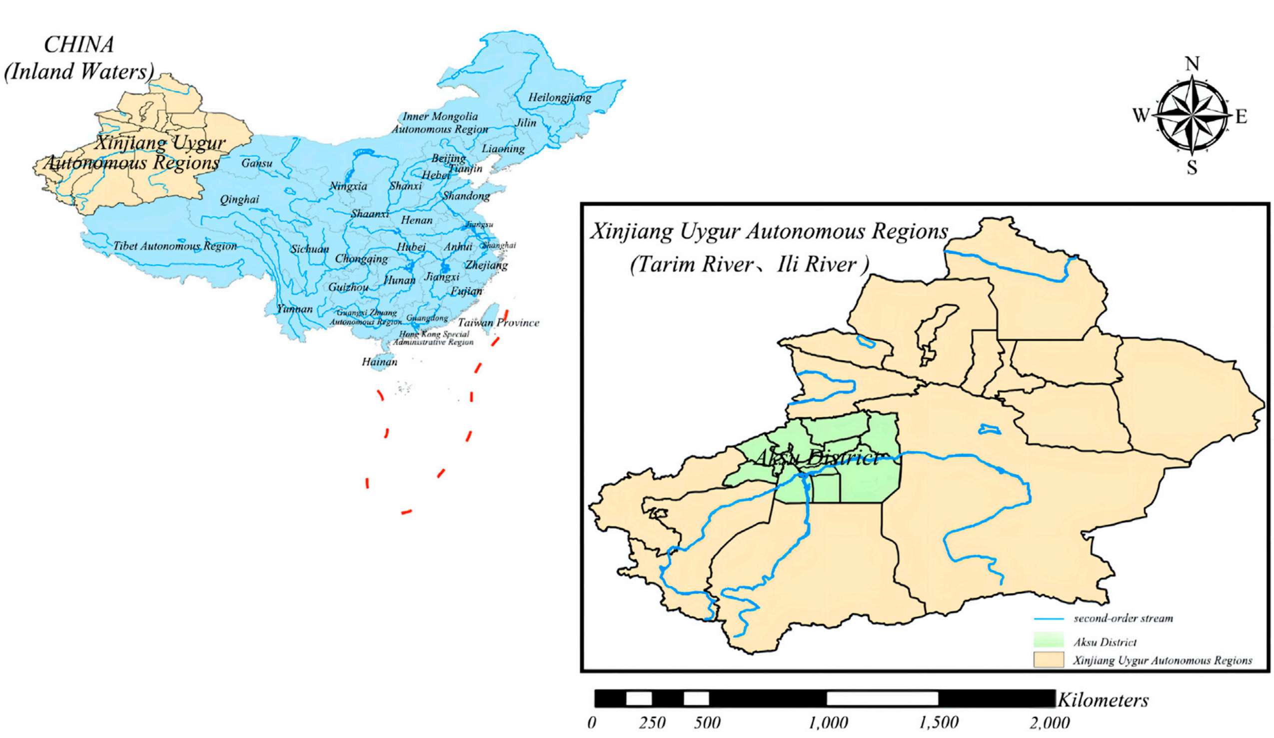

FIGURE 1
The geographical location of the study area.

selected the impact of specific weather factors on crop yield while ignoring the relationship between weather factors. There are limitations in the design of weather index insurance, resulting in insurance products that cannot effectively hedge against the risk of facing weather hazards. Third, previous studies may have measurement errors and did not consider the effects of different weather factors throughout the growth period of crops. Therefore, this study endeavors to collect available information on weather factors such as temperature, rainfall, sunshine, and crop yield from the Xinjiang Meteorological Bureau and the National Bureau of Statistics to better understand the vulnerability caused by weather factors and the design of agro-weather insurance for risk mitigation.

To construct a more comprehensive framework, this study proposes to achieve five key objectives: 1) To isolate meteorological yields and trend yields and determine yield reduction rates using the H-P filtering method. 2) To select key agro-weather insurance index factors based on the correlation test between yield reduction rate and each meteorological factor. 3) A regression model of cotton yield reduction rate and meteorological factors was established based on the relationship between cotton fertility and key meteorological factors. 4) Combining the distribution of yield reduction rate, determine the pure rate of insurance under different disaster registration. 5) Analyze the determinants affecting the design of weather index insurance. The results of this study, on the one hand, provide decision-makers with the design of effective weather insurance rate payout criteria to better protect farmers from weather shocks; on the other hand, provide a reference basis for the establishment of weather index insurance for other crops subsequently.

2 Materials and methods

2.1 Study area and sampling frame

Located in northwestern China (Figure 1), the Aksu region is the largest cotton-producing region and high-quality cotton production base in Xinjiang. 2021, the total cotton cultivation area in the Aksu region is 7.147 million mu, and cotton production accounts for about 80% of the total production in Xinjiang. The steady growth of cotton revenue plays a vital role in local economic development and national cotton production, on the one hand. On the other hand, meteorological conditions determine the growth and development of cotton to a large extent. Among them, the amount and spatial distribution of precipitation directly affect boll quality and ultimately cotton yield. Too much precipitation leads to late maturity and more rotten boll; while insufficient precipitation limits the elongation

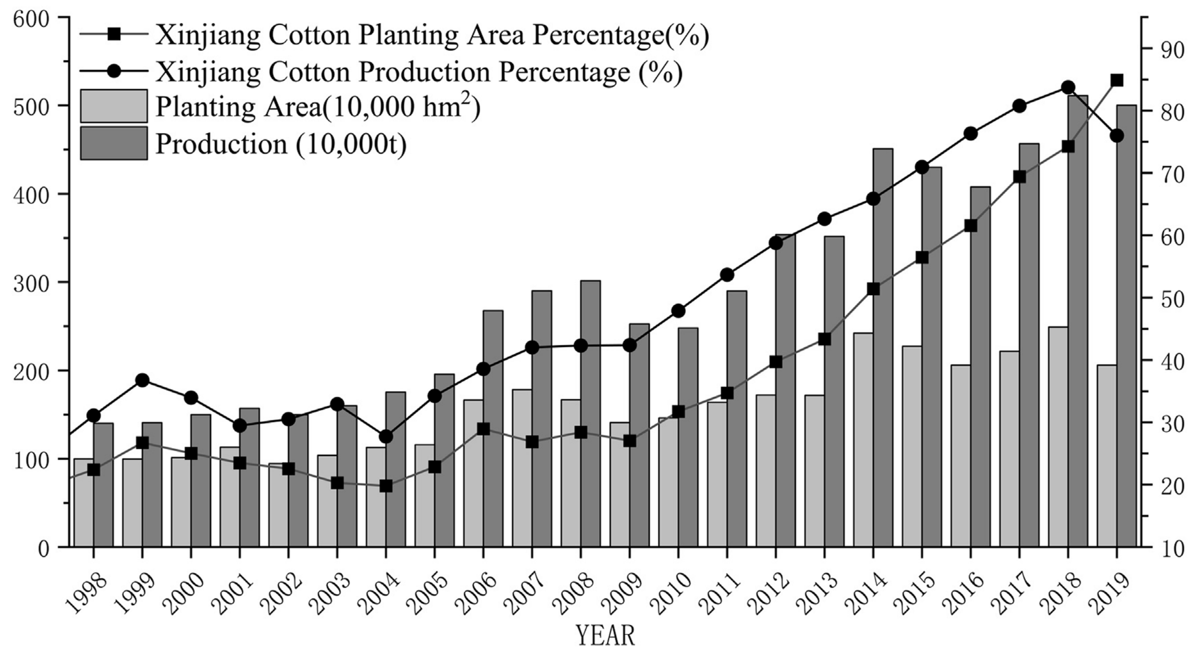

FIGURE 2
Cotton production and planting area in Xinjiang, 1998–2020.

of cotton fiber, leading to early boll splitting and lower boll weight, resulting in reduced cotton production or even no harvest. In addition, temperature and sunshine duration affect the evaporation of water. For example, daily maximum temperatures above 34°C or daily average temperatures above 32°C may be detrimental to cotton growth. Therefore, in this paper, we will choose Xinjiang, China as the study area and use precipitation, temperature, and insolation as key meteorological indicators, thus providing a suitable case for sustainable cotton production.

From 1998 to 2019, cotton production and planting area in Xinjiang showed a significant upward trend, and the proportion of cotton planting area in the country rose from 22.40% in 1998 to 84.90% in 2019, with an average annual increase of 4.82 $hm^2 \times 10{,}000\ hm^2$, and in 2019, Xinjiang's cotton planting area was 38,107,500 mu, up 2% from 2018, accounting for 76% of the national planting area (Figure 2). In the same year, Xinjiang's cotton production continued to be the highest in the country, reaching 5.002 million tons, accounting for an increase of 1.1 percentage points year-on-year to 84.9% of the total national production.

2.2 Data collection

The data sources for this study consisted of two main sources: 1) the weather phenology data from the National Meteorological Science Data Center and the China Weather Network, including monthly sunshine hours, monthly average temperature, and monthly total precipitation in the Aksu region; and 2) cotton planting data, including cotton yields, from the statistical yearbook of the National Bureau of Statistics, with a sample interval of 1988–2019. The cotton growing period in Xinjiang is about 180 d. Sowing usually starts in early April and growth stops in late October, so based on the cotton fertility period the data collected in this study are from April to October (Gu, 2016). Cotton fertility and cotton yield have a direct impact, in general, cotton fertility refers to a year from April sowing to October harvest, the fertility period by the impact of climate change and lead to yield changes.

2.3 Variables definition and measurement

The objective of this study was to design a weather insurance index pricing model. By extending the traditional insurance model, the weather yield was separated by the H-P filtering method to calculate the yield reduction rate, and the key weather factors affecting cotton yield were further screened based on the correlation analysis method for the whole reproductive period of cotton production. Finally, the insurance rates were determined by empirical analysis, and the pure insurance rates of insurance products were calculated.

2.4 Separation of meteorological yields and reduction rate calculation

In 1980 Hodrick and Presccot proposed the H-P filter method, one of the main methods used to analyze long-term trends in time series, which has been widely used to separate long-term trends and volatility factors of economic variables. The method can fit well the trend term of output growth in weather index insurance design. The basic principle is to minimize the loss function in the following Eq. 1:

$$\min\left\{\sum_{t=1}^{n}\left(Z_t - Z_t^T\right)^2 + \mu\sum_{t=1}^{n}\left[\left(Z_{t+1}^T - Z_t^T\right) - \left(Z_t - Z_{t-1}^T\right)\right]^2\right\} \quad (1)$$

In the formula: the first square means the change in the fluctuation factor, and the second square means the change in the long-term trend component. Z_t denotes the time series, Z_t^T denotes the trend output, and n denotes the sample size. The smoothing parameter μ indicates the weight of the long-term trend component of output in the model, and the larger the value, the smoother the series curve, which will be close to a straight line When μ tends to positive infinity.

When designing weather index insurance, the actual crop yield is changing under the combined influence of various factors, and the yield change is not completely linear in time. The H-P filter method precisely separates the series with a certain trend from the time series of the actual crop yield, takes this part as the trend yield Z_t, and considers the remaining part as the meteorological yield (Z_w) caused by the change in weather conditions. The trend yield Z_t and the random disturbance term ϵ_t outside of the meteorological yield Z_w are expressed, and the final actual yield Z, an equation can be expressed as:

$$Z = Z_t + Z_W + \epsilon_t \quad (2)$$

According to Eq. 2, The difference between the actual yield Z and the trend yield Z_t separated by the H-P filter method is used to obtain the meteorological yield Z_w, and then the ratio of meteorological yield to trend yield is used as the relative meteorological yield Z_w^t, where the negative relative meteorological yield (Z_w^t) data can represent the relative reduction of crop yield caused by meteorological factors, which is the yield reduction rate. When the relative weather yield $Z_W^t < 0$, the absolute value is defined as the yield reduction rate (YLR).

$$Z_W = Z - Z_t \quad (3)$$

$$Z_w^t = \frac{Z_W}{Z_t} \quad (4)$$

2.5 Correlation analysis

Correlation analysis is a method of statistical evaluation used to study the strength of a relationship between two, numerically measured, continuous variables. This particular type of analysis is useful in identifying possible connections among variables. If a correlation exists between two variables, it means that when there is a systematic change in one variable, there is also a systematic change in the other, or the variables alter together over a certain period (Kendall and Gibbons, 1990). In terms of the strength of the relationship, the value of the correlation coefficient varies between +1 and −1. A value of ±1 indicates a perfect degree of association between the two variables. As the absolute value of the correlation coefficient value goes towards 0, the relationship between the two variables is weak. The direction of the relationship is indicated by the sign of the coefficient, where a + sign indicates a positive relationship and a − sign indicates a negative relationship. Usually, in statistics, four types of correlations are measured: Pearson correlation, Kendall rank correction, Spearman correction, and the Point-Biserial correction (Draper and Smith, 1998). The following formula is used to calculate the Pearson correlation:

$$r = \frac{N\sum xy - \sum x\sum y}{\sqrt{\left[N\sum x^2 - \left(\sum x\right)^2\right]\left[N\sum y^2 - \left(\sum y\right)^2\right]}} \quad (5)$$

where r is the Pearson correlation coefficient; N represents several observations; and x, y represents two variables.

To select the suitable weather factor in this study, Pearson correlation will be used to test the degree of correlation between the dependent and independent variables. A high degree of autocorrelation between independent variables will affect the impact of independent variables on dependent variables.

2.6 Determining pure insurance rates

To determination pure insurance rates is a process of pricing insurance products based on the estimation of expected losses and the probability of loss occurrence of the insured (Zhang et al., 2015), therefore, insurance rates are mainly determined by a combination of the probability of disasters and the expected loss method of agricultural insurance. Combined with the data characteristics of this study, a parametric method is mainly used to fit the distribution of crop yield risk to calculate the probability of meteorological disaster occurrence. The commonly fitted distributions mainly include (Gallagher, 1987): Normal distribution, Lognormal distribution, Weibull distribution, Gamma distribution, and Logistic distribution, and the specific parameters and functions are shown in (Table 1).

2.6.1 Probability of disaster events

First, the model parameters were estimated by fitting the meteorological yield distribution model with the maximum likelihood estimation method to determine the fitting effect of each distribution probability density function on the histogram of yield reduction rate. Secondly, the Anderson-Darling (AD) test

TABLE 1 Common distribution function table.

Distribution	Parameter	Density function
Normal distribution	$X \sim N(\mu, \sigma^2)$	$f(x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$
Logarithmic normal distribution	$\ln X \sim N(\mu, \sigma^2)$	$f(x; \mu, \sigma) = \begin{cases} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}, x > 0 \\ 0, x \le 0 \end{cases}$
Weibull distribution	$X \sim Weibull(\lambda, k)$	$f(x; \lambda, k) = \begin{cases} \left\{\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}, x \ge 0 \\ 0, x < 0 \end{cases}$
Gamma distribution	$X \sim Gamma(\beta, \alpha)$	$f(x; \beta, \alpha) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}, x > 0$
Logistic distribution	$X \sim Logistic(\mu, \gamma)$	$f(x; \mu, \gamma) = \frac{e^{-\frac{x-\mu}{\gamma}}}{\gamma(1+e^{-\frac{x-\mu}{\gamma}})^2}$

was applied to test the distribution of the sample, and the smaller the AD value, the better the distribution fit. Finally, the optimal distribution fitting model is determined, and the probability density function of the optimal fitting model is integrated to calculate the probability of occurrence of each level of disaster (Weber et al., 2015).

2.6.2 Insurance pure rate

The pure insurance rate is the expected value of agricultural insurance losses. The product of the yield reduction rate caused by each disaster class under different meteorological conditions and the probability of each meteorological disaster class is the basis for determining the pure insurance rate, and its expression is

$$R_i = \frac{E(loss)}{\lambda \cdot \eta} = \sum P_i \times X_i \tag{6}$$

In Eq. 6, R_i represents the pure rate of insurance; $E(loss)$ is the expected value of crop loss (insured loss); λ represents the coverage percentage of insurance and takes the value of 100%; η represents the expected yield and takes the value of 100%; P_i is the yield reduction rate of each meteorological hazard class; X_i is the probability of an event (%) of each meteorological hazard class.

Based on the results of regression analysis, fitted distribution, and changes in meteorological indices, the magnitude of the yield reduction rate is determined, and the amount payable by the insurance is calculated.

3 Results and discussion

3.1 Meteorological yield separation

Figure 3 shows the trend of cotton yield changes in the Aksu region of Xinjiang from 1988 to 2019, and there is a clear trend effect of cotton yield with increasing years. Cotton yields increased from 630 kg/hm^2 in 1988 to 1762 kg/hm^2 in 2019, with an average annual growth rate of 46.4%. The substantial increase in yields reflects significant changes in variety renewal, planting techniques, and production inputs, which provide technical support for the sustainable development of cotton production.

Based on the data from China Statistical Yearbook, the yield per unit area of cotton (kg/hm^2) was selected as the actual yield Z, the trend yield was separated by the H-P filtering method, and the results of the separation were shown in Figure 4. In Figure 4, the solid line shows the total yield before the trend yield Z_t separation, which is volatile and the series is not smooth. The dashed line shows the trend yield after filtering the actual yield by the H-P filter method, which is smoother than the actual yield and shows an obvious upward trend in cotton yields with the development of the market and technology level before 2004. With the gradual stabilization of the market, a more stable trend between 2004 and 2008, the cotton market was more volatile in 2012, and the income from cotton cultivation was significantly affected by market fluctuations, and there was a slow upward trend in cotton yields after 2014, and the trend change in actual yields is more clearly reflected by the dashed line trend in Figure 4.

Meteorological yield changes of cotton in the Aksu region from 1988 to 2019 (Figure 5). As can be seen from Figure 5, compared with the actual yield Z, after separating the trend yield Z_t, the meteorological yield Z_w series eliminates the trend effect and the series behaves smoothly relative to the total yield. According to Eq. 4, the relative meteorological yield can be calculated Z_w^t. When the relative meteorological yield is less than 0, the absolute value of relative meteorological yield is the yield reduction rate (YLR), which indicates the reduction of cotton yield caused by the change in meteorological conditions.

Figure 6 shows the changes in the yield reduction rate of cotton in the Aksu region due to changes in meteorological

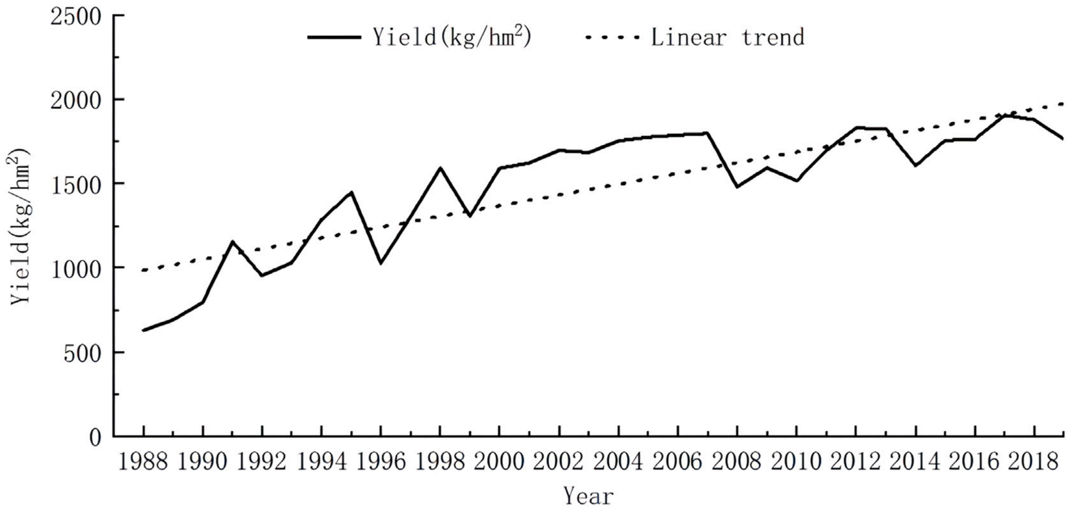

FIGURE 3
Changes in cotton yields in Aksu from 1988 to 2019.

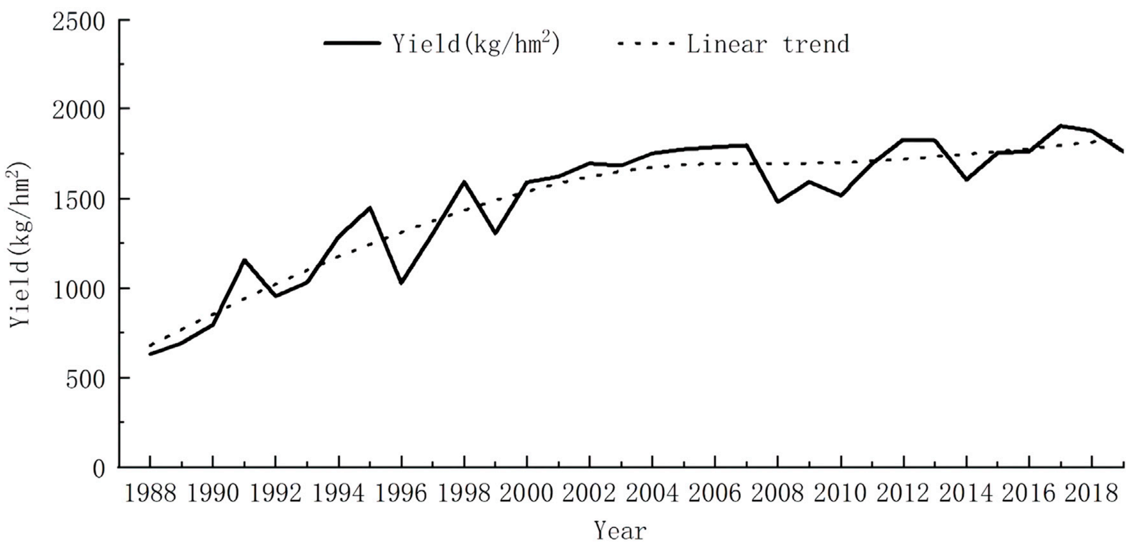

FIGURE 4
1988–2019 Separation diagram of actual yield and trend yield.

conditions over the last 30 years. Overall, it can be seen that the fluctuation of meteorological yield is large, and the highest rate of cotton yield reduction in the Aksu region was 28% in 1996, with a total yield reduction of about 283 kg per hectare. By reviewing the information, we know that several cotton varieties were introduced from the Yellow River Basin in the Aksu region in that year, which caused a large yield reduction because they were not adapted to the local climate (Wang and Zhang, 2010). With the improvement of varieties and changes in planting techniques, the situation of yield reduction has improved. The most recent large yield reduction was in 2007 and 2008, according to the analysis and forecast of the production situation of grain and cotton in China by the Chinese Academy of Sciences in 2008, China's agricultural meteorological conditions in 2007 were

FIGURE 5
Time series of cotton meteorological yields in Aksu from 1988 to 2019.

TABLE 2 Correlation between YLR and meteorological factors throughout the growth period.

Weather factor	Monthly average sunshine hours (H)	Average monthly precipitation (MM)	Monthly average temperature (°C)
Correlation coefficient	−0.44	0.66	0.39

worse than normal and suffered the most severe drought in 10 years, which caused crop yield reduction in different degrees in some areas.

3.2 Correlation analysis

To accurately calculate the magnitude of the effect of meteorological factors on cotton yield, this study divided the entire cotton reproductive period into five stages, namely sowing emergence (T1), seedling stage (T2), bud stage (T3), boll stage (T4), and spat stage (T5), based on the results of previous studies, when the absolute value of yield reduction rate is lower than 5%, it can be considered that the occurrence of meteorological disasters has no significant effect on crop yield, and or caused by unstable factors other than meteorology; when the absolute value is higher than 5%, it is defined as crop yield reduction caused by meteorology (Shirsath et al., 2019). Further, the correlation between meteorological factors affecting cotton yield and cotton yield reduction rate at each stage was analyzed in Table 2.

The results in Table 2 show that: 1) The variation of cotton yield reduction rate was strongly and positively correlated with the average monthly precipitation, and the more precipitation, the higher the yield reduction rate was. This is because excessive precipitation is detrimental to the growth of cotton. 2) There was a weak negative correlation between yield reduction rate and monthly average sunshine hours. The increase in cotton yield was strongly correlated with long monthly sunshine hours, which is consistent with previous studies (Abdukrim, 2007). 3) There was a weak positive correlation between increased temperature and cotton yield reduction. In other words, excessive temperately hinders the growth of cotton to some extent and thus affects the yield of cotton.

The correlations between yield reduction rate and meteorological factors (sunshine hours, precipitation, and temperature) at each fertility stage are shown in Table 3. Our results showed that: 1) Sunshine hours during the growing period were negatively correlated with yield reduction rate, and the correlation coefficients of each stage were less different, which implies that light helps to improve cotton yield. 2) Precipitation had a large correlation with yield reduction rate at different stages

TABLE 3 Correlation between yield reduction rate and meteorological factors in each growing period.

Growth period/meteorological factors	Monthly average sunshine hours (h)	Average monthly precipitation (mm)	Monthly average temperature (°C)
T1	−0.43	0.31	−0.56
T2	−0.22	−0.07	0.03
T3	−0.28	0.49	−0.23
T4	−0.40	0.90	−0.19
T5	−0.46	0.06	0.05

of cotton growth. Precipitation was only weakly negatively correlated with yield reduction at the seedling stage (T2), implying that an appropriate increase in precipitation during this period may help to increase cotton yield. Precipitation affected cotton yield for most of the period, with the highest correlation with yield reduction at the boll stage (T4), which was highly positively correlated, i.e., the more precipitation there was, the greater the yield reduction and the more serious the cotton loss. 3) Average temperature had the strongest correlation at the sowing stage (T1) and the weakest correlation with yield reduction in the rest of the growing season, with correlations not exceeding 0.1.

From the point of view of natural conditions, cotton, as a warm and light-loving short-day crop, can be affected by natural disasters such as rain and flooding, excessive drought, and pest damage during the growing period (Xu, 2021). Drought during the cotton seedling stage (T1) affects seedling emergence, while excessive rainfall tends to cause soil consolidation, which is detrimental to plant root respiration. During the boll stage (T4), the rapid growth of cotton consumes a lot of water, and the high temperature during this time can easily cause water imbalance and metabolic disruption in the plant, resulting in boll loss. Into the flocculation maturity (T5), water needs gradually reduced, at this time needs to maintain clear weather to benefit the cotton flocculation, if met with continuous cloudy weather prone to rotten boll, resulting in yield reduction.

Combining the results of Tables 2, 3, and the above analysis, precipitation was selected as the main meteorological factor to construct the Weather Index model. For the cotton growing period, there is a strong positive correlation between the variation of cotton yield at the boll stage (T4) and the monthly average precipitation, implying that the more precipitation, the more unfavorable the growth of cotton. On the one hand, excessive precipitation affects the photosynthesis of the crop, which is unfavorable to the synthesis and accumulation of organic matter; on the other hand, excessive precipitation leads to a large loss of sediment from the soil, which destroys the soil structure and fertility and leads to the death of the cotton root system, eventually causing a reduction in cotton yield.

TABLE 4 Parameter estimation results of the distribution model.

Distribution	Parameter estimation results
Normal	$(\mu, \sigma) = (0.091, 0.067)$
Lognormal distribution	$(\mu, \sigma) = (-2.70, 0.908)$
Weibull distribution	$(\lambda, k) = (1.448, 0.098)$
Gamma distribution	$(\beta, \alpha) = (1.834, 0.049)$
Logistic distribution	$(\mu, \gamma) = (0.083, 0.032)$

3.3 Regression analysis of yield reduction rate and precipitation

By conducting a regression analysis of the meteorological factors rainfall and yield reduction rate, we further tested whether the selected meteorological factors could accurately reflect the yield reduction of cotton and the rationality of the selected meteorological factors, and the regression analysis is shown in the following figure.

As can be seen from Figure 7, the regression equation is $Y = 0.0038X+0.0436$, and the yield reduction rate is positively correlated with the meteorological factor precipitation, with a value of 0.8199, indicating that the equation fits well. It reflects that if the current period without precipitation, cotton also has a certain probability of yield reduction, and the yield reduction rate caused by factors other than meteorological factors is about 4.36%.

3.4 Fitting the distribution of yield reduction rates and determining insurance premium rates

3.4.1 Distribution fitting of yield reduction rate

To determine the insurance rates using the yield risk distribution model, firstly, the distribution of crop yield reduction is fitted to find the most suitable probability distribution. Secondly, considering the distribution of the data, Normal, Lognormal, Weibull, Gamma, and Logistic distributions were selected for the distribution fitting. The parameter

FIGURE 6
Changes in cotton yield reduction rate in the Aksu region from 1988 to 2019.

TABLE 5 Comparison of fit of different models.

Distribution	Normal distribution	Lognormal distribution	Weibull distribution	Gamma distribution	Logistic distribution
p-value	0.056	0.026	>0.250	>0.250	>0.250
AD-value	0.692	0.819	0.427	0.405	0.471

estimation results of the distribution fitting are shown in Table 4 below.

Thirdly, based on determining the specific parameters of the five models, the probability density and frequency distribution plots corresponding to the five distribution functions were constructed, and finally, the best single yield distribution model was determined by comparing the fitting effect of the histograms as well as visual judgment. The probability density plots between functions and the fitting effects are shown in Figure 8.

The distribution functions with large deviations from the histogram fit, such as the Lognormal distributions, Weibull distributions, and Gamma distributions can be preliminarily excluded by observation in Figure 8, and according to the remaining two similar distributions then excluded by the AD test (Table 5) to finally determine the optimal distribution fit model.

The larger the p-value, and the smaller the AD-value, the better the fitting effect of the distribution model. According to this principle, it was determined that the Logistic distribution model with an AD value of 0.471 and a p-value greater than 0.25 fitted the sample data best. The probability density plot (left) and cumulative distribution plot (right) of the fitted distributions are shown in Figure 9 below.

3.4.2 Determination of pure premium rate for cotton precipitation index insurance

The product of the probability of a meteorological disaster and the corresponding crop yield reduction rate is used as the basis for determining the pure premium. If the yield reduction rate caused by the meteorological disaster is lower than the deductible, no compensation will be paid, and if it is equal to or higher than the deductible, the compensation work will be initiated according to the expected value (insurance amount) and the agreed yield reduction rate (Black et al., 2015). The yield reduction rate corresponds to the deductible, and the precipitation index corresponds to the payout trigger value, i.e., after the precipitation disaster, the pure insurance rate under different payout trigger conditions is calculated according to the different payout trigger values at all levels.

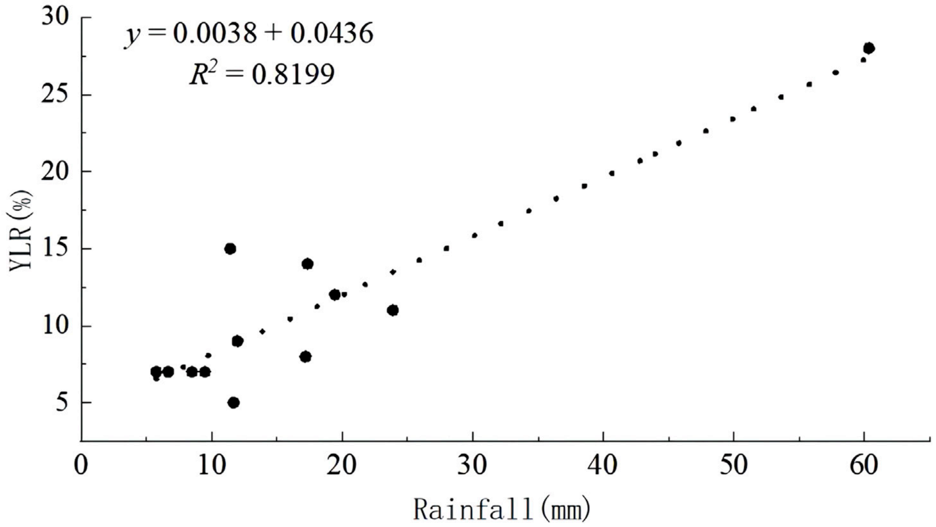

FIGURE 7
Regression graph of yield reduction rate and Precipitation.

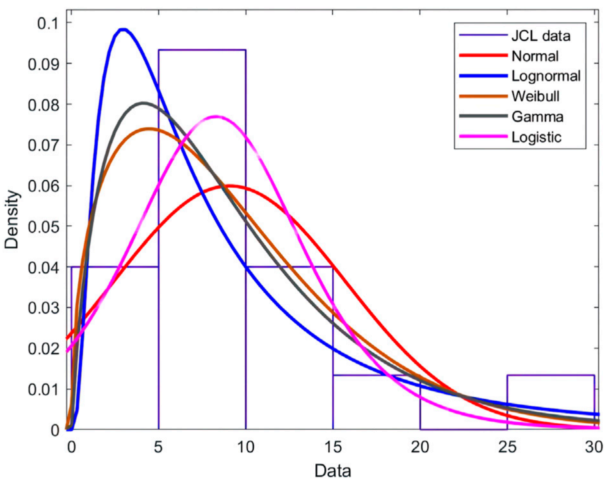

FIGURE 8
Fitting graph of the probability distribution of yield reduction rate.

3.4.2.1 Determination of deductible amount

From the regression analysis of yield reduction rate and precipitation index, it is known that when the precipitation is 0 mm, the yield reduction rate is 4.36%. At this point, by doing the integration of logistic probability density function, the probability of occurrence of precipitation disaster with yield reduction between (0, 4.36%) is calculated as 15.64%. Thus, the yield reduction rate of 4.36% was determined as the classification level of the weather hazard deductible.

3.4.2.2 Determining the precipitation index disaster level

In reality, the precipitation index is a positive number greater than 0. Based on the precipitation index, we determine that for every 3 units of yield reduction rate, the meteorological disaster level rises one level, combined with the historical maximum yield reduction rate in the Aksu area, the precipitation index disaster level in the Aksu area is divided into 9 levels, and the probability of precipitation disaster when the yield reduction rate of 28% falls within the interval of (27%, 30%) is only 0.19%.

3.4.2.3 Determining the pure premium rate

According to Eq. 6, the pure premium rate = yields reduction rate × probability of disaster event. Among them, the yield reduction rate is calculated by the precipitation index of each class of cotton boll period; the probability of disaster occurrence is calculated by the probability density function of the logistic fitting distribution. After the occurrence of the precipitation disaster, the probability of occurrence of the disaster is calculated according to the yield reduction rate under different precipitation disaster levels, and then the net insurance premium rate is derived, and the insurance company will finally settle the claim according to the net insurance premium rate of the disaster level in which the yield reduction rate is located. According to the survey report on cotton planting cost in Xinjiang in 2020, the cost of one mu of land is about 1900 RMB, so the pure premium and insurance pure rate under each disaster level can be calculated, as shown in Table 6.

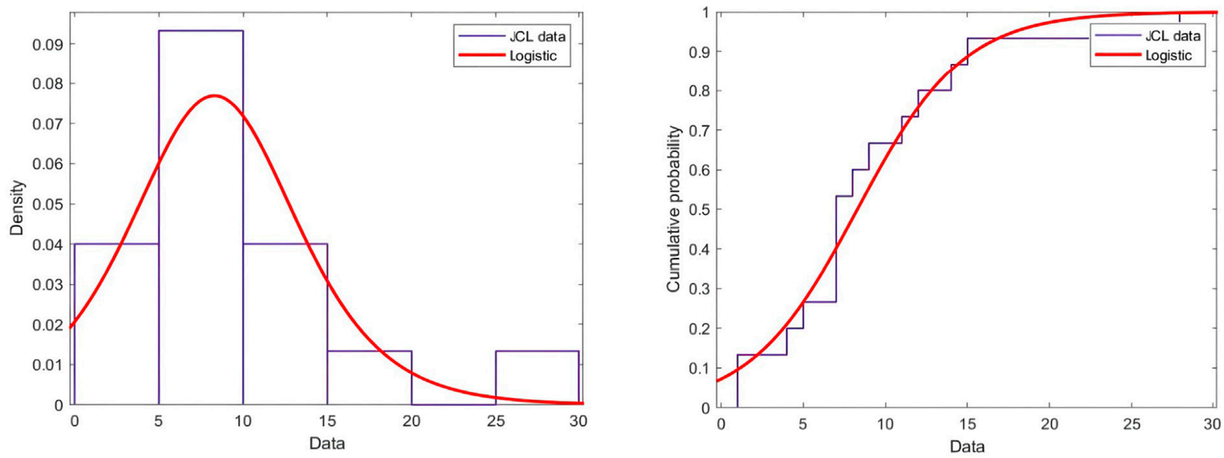

FIGURE 9
Probability density plot and cumulative distribution plot of the logistic distribution.

TABLE 6 Net premium rates under different disaster levels.

Disaster damage level	Precipitation index (mm)	Production reduction rate (%)	Disaster rate (%)	Pure premium rate (%)	Pure premium (yuan)
Deductible level	(−11.47, 0)	(0, 4.36)	15.64	0	0
1	(0,4.32)	(4.36, 6)	10.17	0.83%	15.77
2	(4.32, 12.21)	(6, 9)	22.36	1.79%	34.01
3	(12.21, 20.11)	(9, 12)	20.37	2.24%	42.56
4	(20.11, 28.00)	(12, 15)	12.95	1.81%	34.39
5	(28.00, 35.89)	(15, 18)	6.46	1.10%	20.90
6	(35.89, 43.79)	(18, 21)	2.84	0.57%	10.83
7	(43.79, 51.68)	(21, 24)	1.17	0.27%	5.13
8	(51.68, 59.58)	(24, 27)	0.47	0.12%	2.28
9	(59.58, 67.47)	(27, 30)	0.19	0.06%	1.14

4 Conclusion, policy implication, and future research

4.1 Conclusion

Weather index insurance covers a weather risk that is usually highly correlated with losses in agricultural production. As a proxy for economic losses, weather index insurance is becoming increasingly popular in low-income agricultural countries (Adger et al., 2007).

In this paper, a weather index insurance model was established based on precipitation data from 1988 to 2019 in the Aksu region to analyze cotton production. Through the establishment of the model, the trend yield and meteorological yield series were separated by the H-P filtering method, the correlation between relative meteorological yield and weather index in each period was simulated by using regression analysis, and five probability distributions were fitted for the actual occurrence of yield reduction rate, and the pure premium rate and pure premium amount under different disaster levels were calculated by combining with the expected loss method in insurance actuarial. The results of the study are important for cotton farmers in similar areas to carry out production activities within the environmental carrying capacity in order to cope with climate change and promote environmental sustainability.

By analyzing the relationship between precipitation data and cotton yield in each period, this paper examines the degree of influence of precipitation on cotton cultivation, proves that precipitation weather index insurance can effectively hedge the weather risk to cotton cultivation, provides a basis for the establishment of future disaster compensation mechanism, and is of significant importance to protect farmers' economic income, promotes the sustainable development of regional agricultural production and the implementation of rural revitalization strategy, and also provides a reference basis for the establishment of weather index insurance for other crops in the future.

4.2 Policy recommendations

4.2.1 Providing government subsidies and strengthening infrastructure investment

Weather insurance, as a new type of agricultural insurance, requires financial and material resources to promote, while the high risk and slow return drawbacks of agricultural insurance itself require government support (Xie and Lin, 2004). 1) Incorporate weather index insurance into the scope of policy cotton insurance, and set reasonable premium subsidies according to local financial levels and cotton production status. 2) The government should increase the construction of weather data collection infrastructure and a sufficient number of weather stations and weather databases that meet the standards. Weather index insurance claims are based on the weather information provided by local weather stations. A standard weather observation station can cover 20 square kilometers, according to this standard, there is a large gap between the number of existing stations and the actual demand in Xinjiang. 3) The meteorological department uses new technologies such as satellites and Doppler weather radar to improve the accuracy of meteorological forecasting, provide fast and comprehensive meteorological information to the relevant demand parties from all walks of life, establish a meteorological and insurance information sharing platform, carry out big data analysis, and improve the meteorological disaster warning system for agricultural insurance (Dong et al., 2020).

4.2.2 Strengthening insurance company publicity and innovative business practices

Farmers' awareness of weather index insurance is the key to taking out insurance. Publicize the content of weather index insurance through cooperatives or agricultural companies to increase farmers' awareness of weather insurance. Insurance companies use TV, radio, Internet, and other mass communication media to promote weather index insurance, so that farmers understand the content of weather index insurance subject matter, claims, preferential policies, business processes, and other related matters; use rural grassroots organizations to build a platform for promoting weather index insurance products, and play the role of grassroots organizations in pre-promotion training, information dissemination and insurance processing (Giné. and Vickery, 2007).

On the one hand, insurance companies strengthen cooperation with local rural financial institutions in their operations, and learn from the experience of bundling weather index insurance and loans in developing countries such as India to expand the scale and coverage of weather index insurance sales (Goodwin et al., 2004); on the other hand, using the outlets of local credit institutions for product promotion, sales and claims can effectively reduce operating costs, improve claims processing efficiency, and In addition, it can increase the business income of rural financial institutions and improve the rural credit environment. With this model of interaction between banks and insurance companies, the sustainable development of weather index insurance and agriculture can be effectively promoted (Besley, 1995).

4.3 Limitations of the study and future research

This study provides strong evidence for the sustainability of cotton production in Xinjiang. However, some limitations are noteworthy. First, the results of the empirical analysis show that the incidence of extreme disasters in the study area is less than 1%, and relevant statistics are scarce. How to use this part of tail data in the model will be one of the focuses of future research. Secondly, how constructing a weather index insurance risk transfer model based on different cotton areas and weather hazard levels in Xinjiang and combining the trigger values of the weather index will be the direction of future research.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

Conceptualization: YH and QZ. Data curation: ZY and YL. Formal analysis: IJ, SW, MA, and ZY. Funding acquisition: ZY and GL. Investigation: ZY and YH. Methodology: YH and LZ. Project administration: GL. Resources: YH and QZ. Supervision: ZY. Validation: GL, IJ, ZY, and JQ. Visualization: MA, GL, JQ, and ZY. Writing—original draft: ZY. Writing—review and editing: MA, QZ, GL, ZY, and JQ.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Environmental degradation in terms of health expenditure, education and economic growth. Evidence of novel approach

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Physical education benefits health and the environment because the world takes long-term steps to stop environmental degradation and its effects. Therefore, the present study examined the impact of health expenditure, education, economic growth, and population on environmental degradation in seven emerging economies from 2000 to 2019. The cross-sectional dependency (CSD) reflected the panel nations' CSD, whereas the second-generation panel unit root test confirmed all indicators' stationarity at first difference. Thus, the second-generation cointegration approach identified a long-term equation among the CO_2, health expenditure, education, economic growth and population. The long-run empirical estimations derived from the PFMLOS and PDOLS method emphasized that education increases the region's environmental sustainability and decreases CO_2 emissions. Conversely, health expenditure, economic growth, and population increase CO_2 emissions and reduce environmental quality in the E-7 bloc. Moreover, our findings are resilient to alternative measures by AMG and CCEMG, which might help policymakers develop long- and short-term initiatives for environmental protection. The study suggests adopting physical education and physical health activities to curb environmental degradation in the panel region.

KEYWORDS

CO_2 emissions, health expenditure, education, economic growth, PFMLOS, PDOLS

1 Introduction

Social policy concerns environmental protection, education, mental and physical health. People's life has changed tremendously since COVID-19 began. Open spaces, restaurants, and sports facilities were closed to manage the infection. People were urged to stay home and maintain social distance, organizations were forced to reduce operating hours or lay off personnel, and educational institutions began offering online courses. Physical inactivity is a major public health concern in most world areas. It won't be solved by organized sports or leisure-time activity alone. The influence of these changes in lifestyle on psychological aspects such as physical education, physical health, and climate raises concerns. The relationship between health expenditure (HEX), education (EDU), economic growth (ECG), population (POP) and environmental degradation (CO_2) has gained significant attention in both emerging and developed countries during the past 2 decades. These interactions between health expenditure, education, economic growth and population on environmental deterioration are complex and important.

Carbon emissions were chosen as one of the main factors since they are a significant contributor to environmental deterioration and the causes of falling health standards. Global energy usage and the related generation of greenhouse gases, mainly carbon dioxide, are key contributors to climate change (Figure 1). Major emitting nations pledged to limit the adverse impacts of growing carbon emissions in the November 2016 Paris Agreement. The aims to decrease global temperatures to 1.5°C levels (Jianguo et al., 2022). The "BP Statistical Yearbook of International Renewable Energy Agency (2021)," China now has the most significant CO_2 emissions globally among the E-7 nations. China's total CO_2 in 2020 contributed 28.8% of worldwide emissions; India contributed 7.3%, ranking third in the globe. Global warming jeopardizes human health, including catastrophic weather events, infectious diseases, food shortages, and more immense societal upheavals (McMichael et al., 2006).

CO_2 not only has an adverse influence on the overall health and environment, but they also significantly impact healthcare expenditures (I. Ullah et al., 2020). The surrounding atmosphere substantially affects human health, and medical research studies claims that air pollution causes a diversity of death (Fareed et al., 2020). The deprived quality of the environment has a detrimental influence on human well-being. Carbon intensity is the most important element impacting environmental protection, negatively impacting society's health. The outcome of environmental deterioration on health has substantial implications for health expenditures (After here HEX); while most prior research indicated that income is the key driver of HEX, CO_2, and poor environmental quality are also critical determinants. Those with more pollution have higher HEX, whereas countries with higher environmental expenditures have lower healthcare expenditures. Many studies (Chaabouni and Saidi, 2017; Wang et al., 2019) have found a positive association between HEX and environmental deterioration. Hence, health is one of the most significant aspects in determining the quality of human capital, but CO_2 emissions create climate change, which impacts public health care and overall productivity (GDP) (Mohmmed et al., 2019). Few studies have looked at HEX as an explanatory variable for environmental quality. Therefore, it is essential to analyze CO_2 for HEX in E-7 nations (Wang et al., 2019). Measuring the consequences of CO2 on the healthcare system has gained prominence in policy discussions.

The second field of study focuses on the connection between education (Hereafter EDU) and environmental degradation. There is a scant study according to whether EDU has had an impact in environmental degradation. UNESCO highlighted the significance of educating and learning, particularly EDU, in overcoming economic, societal, and environmental challenges. There are two points of view that EDU might increase or decrease the environmental sustainability in the region. (Katircioglu et al., 2020) investigated the nexus EDU-CO_2 emissions. According to them, the expansion of sectors and the rise of metropolitan regions may boost energy demands; the authors noted that EDU has become a worldwide industry and stressed that new constructions, dorms, and amenities created to suit student demand would cause CO_2 emissions. (Li et al., 2021) FMOLS and DOLS revealed a favorable influence of higher education on thirty provinces of China's CO_2 emissions. (Balaguer & Cantavella, 2018) claimed that a country's energy resources are heavily reliant on human capital and educational institutions and education may have a huge impact on the economy on many levels. EDU may decrease carbon emissions and increase sustainable environment by enhancing awareness regarding environmental education (Katircioglu et al., 2020; Shah et al., 2021). However, the association between economic growth and EDU, EDU might have a detrimental impact on a sustainable environment by stimulating ECG. So, therefore, governments can use physical education and environmental education as an instrument to combat environmental degradation. Theoretically, there can be a mutual interaction between EDU and the environment (Figure 2).

The third research area examines economic growth (after this ECG) and CO_2 emissions. According to (the IMF outlook report 2021–2022) among the emerging seven regions, China's ECG is predicted to be 8.1 and 5.6%, India's ECG is forecast to be 11.5% and 6.8%, Russia's ECG is projected to be 3.0% and 3.9%, and Brazil's ECG is predicted to be 3.6% and 2.6%, respectively. (Yang et al., 2020; Jahanger et al., 2022; Usman et al., 2022) the leading source of CO_2 emissions in many economies are ECG and energy consumption. Similarly, (Mohmmed et al., 2019; Ali et al., 2021; Shah et al., 2021; Jianguo et al., 2022; Ullah et al., 2022) indicate that ECG increases energy use and environmental degradation. Because of the requirements of ECG, the total amount of CO_2 continues to rise daily, posing several hazards to the health of people of the E-7 nations. Simultaneously, it will have a significant influence on medical and HEX (Figure 3).

In this regard, health expenditure, education, economic growth and population in the E-7 bloc, "China, Russia, India, Mexico, Indonesia, Brazil, and Turkey", have notable characteristics to play in comprehensive environmental sustainability. The E-7 region has the foremost records in environmental deterioration. China contributes the highest percentage of global CO_2, accounting for approximately 28.75% of total CO_2 emissions in 2019, while the other E-7 economies contribute about 18% of CO_2 emissions in the given period, thus making the E-7 region responsible for 46.09% of global CO_2 emissions in 2019 (BP, 2020). According to the (IEA), fourth of the world's highest CO2 emitter countries, "China

9300 Mt, India 2200 Mt, Indonesia 496.4, Russia 1500 Mt, Mexico 446.0 Mt and Turkey 378.6 Mt respectively," are part of this group. In 2018, they comprised 26 percent of the total the global GDP, 47% of the world's population, and more than 40% of the energy consumed globally. Relatively few works have studied the association between CO_2 emissions, HEX, EDU, ECG, and POP, in the aforesaid studies see for (Balaguer & Cantavella, 2018; Fareed et al., 2018, 2022; Li et al., 2021; Shah et al., 2021; I. Ullah et al., 2019, 2020).

This study makes three contributions to the academic research works. First, this research is one of the few that assesses the factors influencing health expenses, education, economic growth and population in E-7 bloc. Our findings will help policymakers develop and implement health and education strategies. The second contribution is concerned with the assortment of indicators in our study. Although there are several research in the literature on the link between health expenditure, education, economic growth and population, there are relatively few studies that incorporate factors, particularly for a sustainable environment in the E-7 region; this study adds to the current body of knowledge by giving actual evidence of the influence of health expenditure, education, economic growth, and population on CO_2 emission regarding of the E-7 bloc. Nonetheless, the current literature investigated the aforementioned link. Still, the inconsistent findings reflect a hazy picture of the relationship in emerging countries. Hence, this study, on the other hand, provides a clear depiction of the relationship mentioned above in emerging economies. Finally, we use scientific and empirical methodologies to analyze the long-term dynamics of E-7. The study used the modern econometric techniques such as cross-sectional dependency test (Pesaran et al., 2004), second-generation panel unit-root (Pesaran, 2007) and second-generation cointegration tests (Westerlund, 2007), and for lung run estimation used PFMOLS and PDOLS techniques. This study also used AMG-CCEMG methods for robustness findings. The study's outcomes are intended to lighten the relationships between HEX, EDU, ECG, and POP on environmental degradation. In order to accomplish high levels of health results across the nation, the policy suggestions based on scientific evidence will provide environmental health recommendations, implications for the use of physical fitness and physical education, and a more effective allocation of health expenditure.

The following portions are as follows: Section 2 describe synopsis of the previous research; Section 3 describes the methodology model; Section 4 presents the empirical findings and discussion; and Section 5 discusses the conclusion and implications for policy based on the empirical research outcomes.

2 Literature review

The relevant scientific studies can be grouped into three sub-categories: the affiliation between health expenditure and environmental deterioration, the relationship between physical education and environmental deterioration and the connection between economic growth and environmental deterioration.

2.1 The health expenditure and environmental deterioration (CO_2)

The relationship between environmental deterioration and HEX has been examined in empirical studies using various instances and analytical approaches, with varied empirical conclusions. The CO_2 emissions will have an adverse influence on the healthcare of individuals, hence affecting HEX. Considering the link between CO_2 and healthcare expenditures, (I. Ullah et al., 2019) studied the causation between trade, HEX, and CO_2 emissions in China from 1990 to 2017 by using a simultaneous equations model. Their outcomes showed that trade significantly effects on CO_2 emissions and results in a rise in healthcare expenditure in the country. (Apergis et al., 2020) examined the long-run dynamics among environmental degradation and HEX in four economic groups using data from 1995 to 2017. According to the findings, HEX would rise by 2.5% for every 1% rise in CO_2 emission. (I. Ullah et al., 2020) determined the drivers of healthcare expenditures in Pakistan during 1998–2017 by using 2SLS and 3SLS techniques. The empirical results showed that CO_2 emissions boost health expenditure. (Shah et al., 2021) examined the impacts of CO_2 and public expenditure on the atmosphere for life expectancy and utilized the ARDL technique for China from 1999 to 2017; the outcome revealed that life expectancy responds inversely to negative and positive tremors on sustainable environment. (Samah et al., 2020) analyzed the relation between HEX and environmental degradation for Malaysia under the influence of COVID-19 using the panel dataset with system GMM. According to estimates, rising HEX will boost CO_2 emissions. Several studies (Zaidi & Saidi, 2018; Apergis et al., 2020; Shah et al., 2021), have demonstrated a positive correlation among HEX and pollution emissions. Khan et al. (2020), utilized GMM and FMOLS techniques to examine the influence of HEX on environmental pollution in BRI from 1995 to 2016 and discovered that a rise in health spending had a harmful influence on environmental quality. Similarly, (Zaman and Abd-el Moemen, 2017; Apergis et al., 2018) discovered that a rise in HEX had a detrimental impact on CO_2 emissions. Few studies have examined the causal link among CO_2 and HEX, such as recent research (Chaabouni and Saidi, 2017) also discovered a unidirectional causal link between CO_2 and HEX. (Zaidi & Saidi, 2018) demonstrated a one-way causality from HEX to ECG and a bi-directional causal relation among HEX and CO_2 emissions in SSA economies. (I. Ullah et al., 2020) In Pakistan, a dynamic simultaneous equation model was used to evaluate HEX, CO_2 emissions, and ECG. The statistical evidence indicated the presence of two-way causation between CO_2 emissions and ECG, as well as one-way causality between HEX and ECG.

2.2 The education and environmental deterioration

Aside from health expenditure, environmentalists focus these days on the environment's response to society's expanding level of education (Balaguer & Cantavella, 2018). Among other initiatives, increasing knowledge and understanding of environmental devastation through social exhortation and environmental education can be crucial in decreasing CO_2 emissions and mitigating the detrimental impacts of global warming (Katircioglu et al., 2020). Education may play an essential part in teaching social responsibility in a society, which can aid in the reduction of pollution emissions. Although numerous elements connected to the primary drivers of CO_2 are employed in the literature, the prospective impacts of EDU on environmental deterioration did not attract the researchers' interest. There are various processes *via* which EDU might positively or negatively impact CO_2. The recent research of (Sart et al., 2022), observed the relationship of economic freedom, education and CO_2 in the context of EU members for 2000–2018, the causality analysis revealed that financial freedom and education can be favorable to mitigating environmental deterioration and increase environmental quality in the panel region. Similarly, the study of (Mehmood, 2022), utilized CS-ARDL for south Asian region for 1990–2020, and investigated that education expenditure will decrease the CO_2 emissions in the south Asian area. (Liu et al., 2022) evaluated the links between financial inclusion, education and CO_2, and using the ARDL approach, their outcomes showed that EDU could play a significant role in reducing CO_2 emissions in China.

Similarly, according to (Zaman et al., 2021) the outcomes show the negative association between EDU and CO_2 emissions for China and using ARDL and FMOLS techniques from 1991 to 20 indicates that EDU will help mitigate CO_2 in China. In contrast (Katircioglu et al., 2020), EDU development, like other sectors such as FDI, and economic growth, may raise total energy demand and increase CO_2 emissions. According to (Shields, 2019) there is a significant link between higher levels of education and worldwide climate shift. Consequently, the long-run effects of education cannot be disregarded, as it increases social and cultural awareness responsibility (Alkhateeb et al., 2020). (Subramaniam & Masron, 2020), examined the impact of education on the climate in 22 emerging nations from 1990 to 2016 using the ARDL method. They found that the significant impact of poverty on climate change can diminish after a specific level of educational accomplishment. Some new studies also examine the direct relationship between education and pollutant releases and environmental degradation (Shields, 2019; Zaman et al., 2021; Liu et al., 2022; Mehmood, 2022). Therefore, educational status, physical education and human resources contribute to reducing air pollutants and forming the EKC, since they promote renewable energy.

2.3 The economic growth and environmental deterioration

Many recent works have studied the connection between CO_2 emission and ECG, but no consent has been expressed (Wang et al., 2022). For instance, the causal relationships between HEX, ECG, and CO_2 emissions are examined by (Chaabouni and Saidi, 2017). Their Granger causality analyses revealed a substantial bidirectional causal relationship between these variables from 1960 to 2008. (Ali et al., 2021) investigate the link between numerous elements that generate CO_2 and ECG in Vietnam and discovered that as Vietnam's industrialization level increased, ECG was supported at the expense of using a massive amount of fossil fuels, which increased CO_2. (Mongo et al., 2021) utilize the ARDL approach for fifteen European economies and the outcomes show that the result of ECG, economic openness and other indicators increase environmental degradation. Similarly, (Majeed et al., 2021) discovered that ECG significantly and positively influenced CO2 emissions in GCC countries from 1990 to 2018. ECG increases CO_2 emissions in Asian countries, according to (Luo et al., 2021). Prior findings on the effects of ECG on the environment have often concentrated on the nexus ECG-CO_2 emissions, utilizing the EKC hypothesis as a theoretical underpinning. However, the current study on the ECG-CO2 emissions relationship under the EKC hypothesis produced contradictory results. For instance, the EKC hypothesis has been authenticated by (Luo et al., 2021) for selected Asian economies, (Jianguo et al., 2022) for the OECD region, (Shah et al., 2021)and (I. Ullah et al., 2019) for China. (Ali et al., 2021) for Vietnam. Finally, several scholars have observed at the relationship between CO_2, ECG and financial institutions (Khan et al., 2020), energy composition (Islam and Abdul Ghani, 2018), and quality of institutions (Wawrzyniak and Doryń, 2020).

3 Research design

The current work studied the impacts of health expenditure, education, economic growth and population on environmental deterioration in the E-7 bloc. The research performs the following approaches to scrutinize the effects of considered indicators (see details in Figure 4).

3.1 Model specification

In this work, we used the following dynamic panel regression model to link CO_2 emissions to HEX, EDU, ECG, and POP indicators:

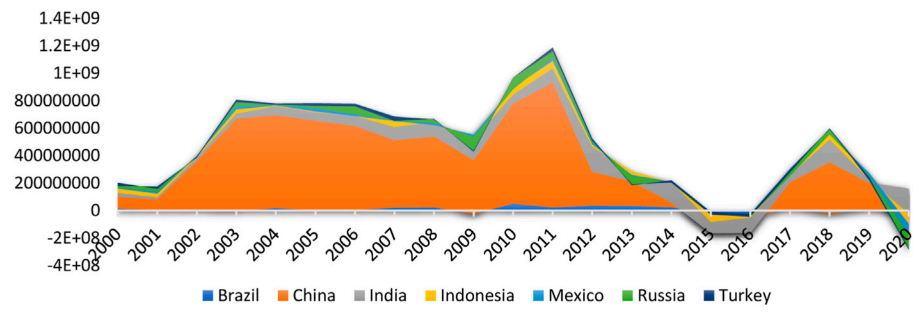

FIGURE 1
CO_2 emissions yearly change. Source: Author's estimation.

$$CO_{2i,t} = \alpha_i + \delta_t + \beta_1 HEX_{it} + \beta_2 ECG_{it} + \beta_3 EDU_{it} + \beta_4 POP_{it} + \varepsilon_{it} \quad (1)$$

Where CO_2 = represent the carbon dioxide emissions, i economies, t time, and α, β, δ are measured as the coefficient, and ε is the residual term. The coefficients $\beta 1$, $\beta 2$ ... $\beta 11$ represent the estimates of CO_2, explanatory and control variables. HEX, health expenditure, EDU, education, ECG, economic growth, and POP, population.

3.2 Estimation methods

3.2.1 The cross-sectional dependence (CSD)

CSD arises when macroeconomic tremors have similar impacts on cross-sections within a panel; hence these cross-sections are CSD and can generate ambiguous results if not addressed (Jianguo et al., 2022). International accords, trade contracts, and economic and socio combination may cause cross-sectional interdependence in E-7 economies. As mentioned in Equation, the CSD test established by (Pesaran et al., 2004) was utilized to address this methodological challenge using panel data.

$$Y_{it} = \alpha_i + \beta_i x_{it} + \varepsilon_{it} \quad (2)$$

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{t=0}^{N-1} \sum_{j=i+t}^{N} \rho_{ij} \right) \quad (3)$$

3.2.2 The panel unit root test

This is critical for ensuring stationarity since non-stationary series might generate deceptive findings. First-generation techniques, such as the, do not address CD concerns in datasets (Im et al., 2003). (Pesaran, 2007) introduced the CIPS and CADF second-generation panel unit root estimates to address the shortcomings of the first-generation method. This approach is expected to give dependable and consistent stationarity features in the existence of CD difficulties in the sample. The unit root equation is:

$$Y_{it} = \alpha_{it} + \beta_i x_{it-1} + \rho_i T + \sum_{j=0}^{n} \theta_{it} \Delta x_{it-j} + \varepsilon_{it} \quad (4)$$

3.2.3 The panel cointegration test

Similar to first-generation panel unit root approaches, first-generation panel cointegration estimators do not consider CD issues. (Westerlund, 2007) A second-generation panel cointegration estimate was published to identify the cointegrating properties between the parameters in the presence of CD. The bootstrapped approach is used in this procedure to assess the standard errors of four statistical tests, which resolves the CSD: "Gt, GA, Pt, and Pa. Gt and Ga" are group-mean statistics that are calculated when the alternative hypothesis of cointegration between the variables in at least one cross-section is tested against the null hypothesis of non-cointegration. In contrast, a stringent alternative hypothesis of series cointegration in all cross-sections predicts the two panel-mean statistics Pt and Pa.

$$\Delta Y_{it} = \alpha_i d_t + \rho_i y_{it-1} + \gamma_1 \chi_{it-1} + \sum_{j=1}^{\tau i} \rho_{ij} \Delta Y_{it-j} + \sum_{j=-\alpha i}^{\tau i} Y_{ij} \Delta \chi_{it-j} + \epsilon_{it} \quad (5)$$

3.2.4 The long run estimation results

The Panel Dynamic PEMLOS and PDOLS are applied and used to estimate the model's long-term coefficients. Some researchers claim that the PDOLS methodology not only helps assess robust results but also executes more reliably and produces enhanced characteristics of the respondents for small panel sizes (Luo et al., 2021). Furthermore, FMOLS and DOLS approaches solve the issue of heterogeneity and heterogeneous cointegration (Weimin et al., 2022). On the other hand, some researchers argue that the PFMOLS

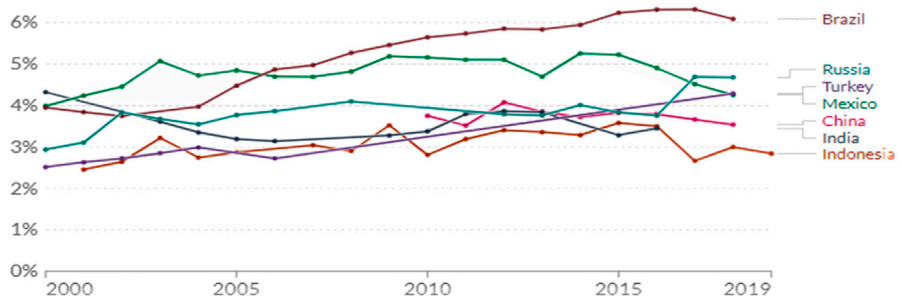

FIGURE 2
Total general government education spending. Source; authors estimation. OurWorldInData.org/global-rise-of-education.

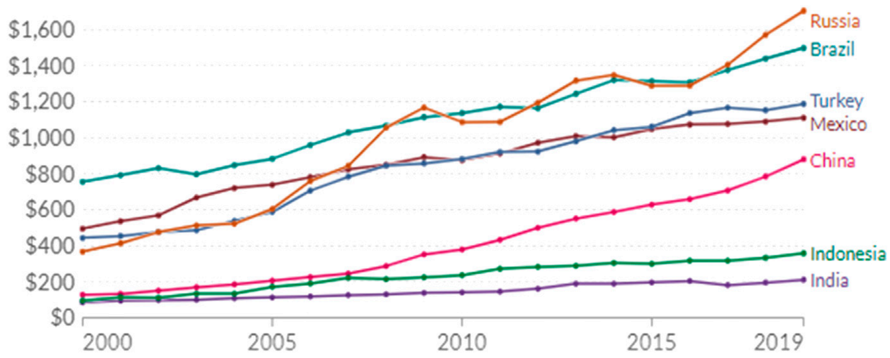

FIGURE 3
The amount of yearly public and private health expenditures per person measured in dollars. Source; authors estimation and OurWorldInData.org/financing-healthcare.

methodology is superior to the PDOLS technique since it addresses several data issues, such as simultaneity and autocorrelation, while also producing credible outcomes in smaller panel samples (Luo et al., 2021). As a result, in order to avoid any contradictions in the results, we use more than one econometric approach to produce more consistent results. The CO2 function for panel data is:

$$COE_{it} = \beta_i + \alpha_i z_{it} + \epsilon_{it} \quad (6)$$

The following Eqn. 7 is advocated by Pedroni (2004) to compute the α_i Coefficients through the PFMOLS method:

$$\hat{\alpha}_i = N^{-1}\sum_{i-1}^{N}\left(\sum_{t-1}^{T}(z_{it}-\bar{z}_i)^2\right)^{-1}\left[\sum_{t-1}^{T}(z_{it}-\bar{z}_i)\right]COE^{*}_{it} - e_i \quad (7)$$

Where $\bar{z}$ Reveals arithmetic mean of Z and COE$^{*}_{it}$ is equals to $(COE_{it} - COE^{*}_{t}) - [(\widehat{\frac{\lambda_{21}}{\lambda 22i}})]$ where $\hat{\lambda}$ Indicates the covariance. $\widehat{COE}$ is presented to determination the problem of inaccurate serial correlation.

Additionally, Pedroni signified the following Eqn. 8 by counting lead, and lag features for PDOLS estimators.

$$COE_{it} = \alpha_i + \beta_i z_{it} + \sum_{j=-n}^{ni} \pi_{in}\Delta Z_{i,t-1} + \epsilon_{it} \quad (8)$$

To evaluation the coefficients of $\hat{\beta}_i$ is:

$$\hat{\beta}_i = \left[N^{-1}\sum_{i-k}^{N}\left(\sum_{t-1}^{T}\delta_{it}\delta^{*}_{it}\right)^{-1}\left(\sum_{t=1}^{T}\delta_{it}\hat{\delta}_{it}\right)\right] \quad (9)$$

Where $\delta_{it} = 2(k+1)z1$ and $\hat{\delta}_{it}$ means $z_{it} - \bar{z}_i$.

3.2.5 The AMG and CCEMG

This work will also use two further approaches, AMG and CCEMG, to test the reproducibility of the PFMOLS and PDOLS results. CSD, heterogeneity, cointegration breakdowns, and non-stationarity are all handled in both of these approaches (Luo et al., 2021). CCEMG and AMG use

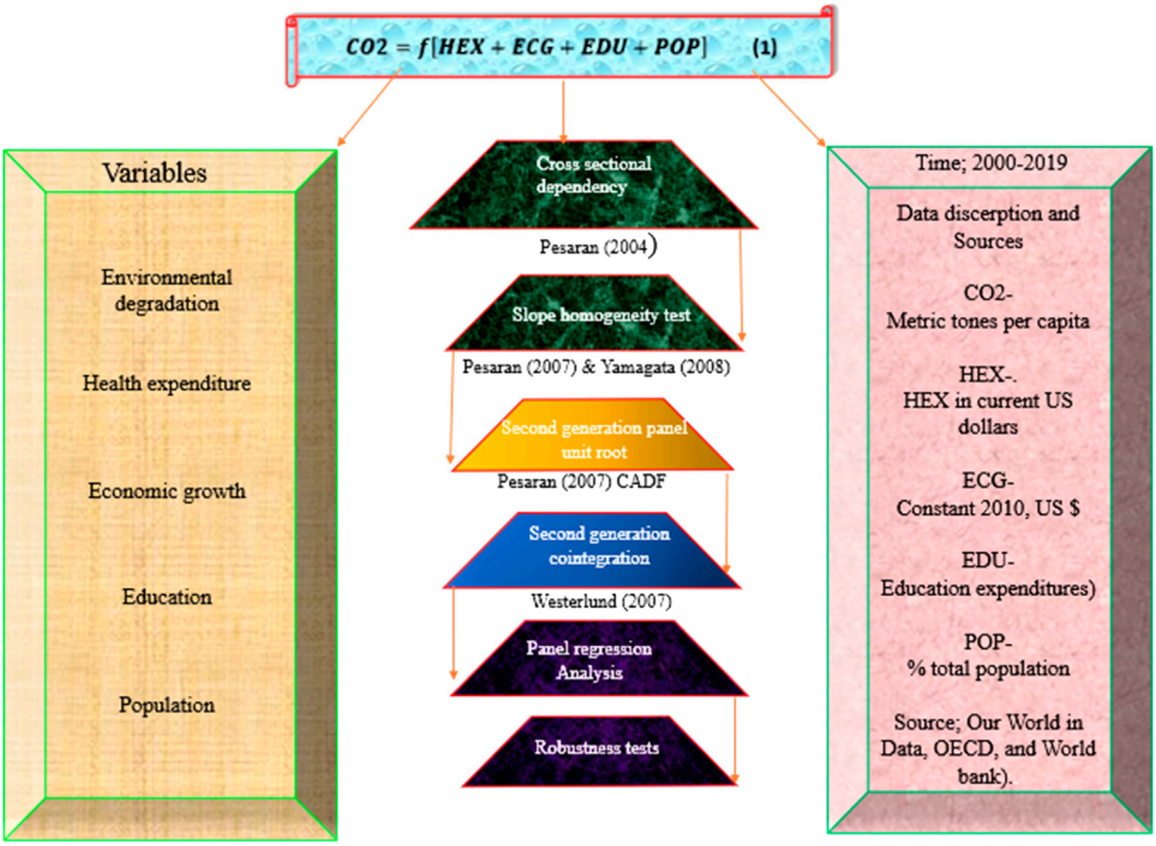

FIGURE 4
Methodological framework. Source, Authors own completion.

cross-sectional averages of both dependent and independent indicators.

4 Empirical results

4.1 Pre-regression statistics

The study analyzed to investigates the effect of HEX, ECG, EDU, and POP, on the CO_2 emissions for the panel of E-7 from 2000 to 2019. Table 1 shows the descriptive statistics and correlation matrix for all factors included in this study. The descriptive statistics for all indicators reveal various Min-Max values for all parameters. Similarly, the correlation matrix displays the positive relation of HEX, ECG, and POP, while the negative correlation of education indicators with CO_2 emissions.

Before examining the presence of the unit root and cointegration among the variables, it is required to explore the CSD among the sample nations. As a result, actions performed in one country may also impact another country. We used the Pesaran et al., 2004, Breusch and Pagan, 1980 technique to determine CSD among the E-7 economies. The findings in Table 2 corroborated the CD among the countries in the study, showing that any change in the amount of HEX, ECG, EDU, and POP in one country of E-7 might have an impact on the other E-7 country. Table 3 summarizes the findings of the (Hashem Pesaran and Yamagata, 2008) slope homogeneity test in the research, confirming that the model has a slope heterogeneity issue.The presence of CSD and SH in the data suggests that the indicators' stationarity and long-run connection should be confirmed using second-generation unit root and cointegration. According to both the CIPS and CADF tests, the results in Table 4 demonstrate that all of the variables considered in the study are stationary at first difference I (1). As a consequence, to address the issues of CD and heterogeneity in the model, we employed the Westerlund Cointegration approach, and the findings shown in Table 5 demonstrate the (Westerlund-2007) Cointegration results in the presence of a long-run link between the variables in all three models at the 1% significant level.

TABLE 1 The Descriptive statistics and Correlation.

	CO_2	HEX	ECG	EDU	POP
Mean	9.517	6.214	4.147	46.492	12.423
Std. dev	16.279	2.456	1.896	8.743	4.076
Min	0.826	−1.534	−2.419	10.472	0.000
Max	72.016	18.346	6.138	112.547	26.154
CO_2	1.000				
HEX	0.525**	1.000			
ECG	0.643**	0.182*	1.000		
EDU	−0.510**	0.214	0.589*	1.000	
POP	0.467**	0.521	0.384	0.610	1.000

TABLE 2 The Pesaran et al., 2004 CSD test.

Indicators	BP	LM	CD
CO_2	2142.81***	53.421***	22.416***
	(0.000)	(0.000)	(0.000)
HEX	1865.32***	89.614***	15.247***
	(0.000)	(0.000)	(0.000)
ECG	4183.67***	161.421***	34.52***
	(0.000)	(0.000)	(0.000)
EDU	4158.32***	2249.214***	42.1028***
	(0.000)	(0.000)	(0.000)
POP	2886.67***	55.471***	26.6432***
	(0.000)	(0.000)	(0.000)

Note. *** at 1%, values in () are *p*-values.

TABLE 3 The Slope homogeneity test.

Statistics	Values	*p*-values
$\tilde{\Delta}$	18.429***	0.000
$\widetilde{\Delta_{adjusted.}}$	22.529***	0.000

Note. *** indicates significance at 1%.

TABLE 4 The (Pesaran, 2007) Panel Unit-root test.

	CIPS		CADF	
	At Level	1st Difference	At Level	1st Difference
CO_2	−1.218	−3.146***	−1.279	−3.549***
HEX	−2.167	−4.638***	−2.042	−4.324***
ECG	−1.289	−4.587***	−1.637	−4.561***
EDU	−1.269	−3.631***	−1.596	−3.549***
POP	−1.841	−3.469***	−1.467	−4.461***

Note, *** indicates significance at 1%.

4.2 Regression results

After confirming the long-term association between the indicators, we used the PFMOLS and PDOLS tests to determine the variables' long-term coefficients. Table 6 presents the analysis using PFMOLS and PDOLS estimations. The findings reveal that CO_2 emissions have a positive and significant relationship with HEX. This result indicates that a 1% increase in CO_2 emissions leads in a (PFMOLS 0.16324% and PDOLS 0.26314%) rise in HEX. There are two potential effects of HEX on CO_2. The important policy is that the government aggressively regulates CO_2 because pollution increases healthcare costs. Because the impact of health expenses is proportional to population expansion, an increase in energy consumption leads in increased pollution of the atmosphere (Chaabouni et al., 2016; Chaabouni and Saidi, 2017). On the other hand, HEX raises people's awareness of pollution and reduces CO_2. The first effect is far more significant than the second (Shah et al., 2021). The findings support the claims made by Khan (Mohmmed et al., 2019; I. Ullah et al., 2019, 2020) that boosting CO_2 emissions raises health care costs.

In table 6, according to PFMOLS and PDOLS estimates, ECG increased CO_2 emissions in sample nations by PFMOLS 0.42142% and PDOLS 0.54328%, respectively. ECG has been identified as one of the key drivers of the rise in CO_2 emissions. As a result, it is realistic to conclude that, on average, chosen E-7 economies are on a sustainable path, in which greater ECG leads to enhanced CO_2 emissions up to a certain point due to fast industrialization (Ali et al., 2021; Luo et al., 2021).

Third, the outcomes recommend that EDU has a favorable impact on environmental quality, The relationship of education and CO_2 emission is favorable, its mean education increase the environmental quality in E-7 nations, results are consistent with recent findings (Balaguer & Cantavella, 2018). Our findings demonstrate that education alone, without an environmentally suitable curriculum, cannot reduce CO_2 emissions. Adding environmental content to EDU, promoting awareness through the media, and offering energy efficiency training to the workforce are all viable policy choices for promoting the environmental advantages of education. To reap any benefit from education, a comprehensive set of environmental protection laws is required; otherwise, education would raise people's purchasing power, energy usage, and, as a result, environmental damage. Education spending allows the majority of the population to comprehend their environment better. Citizens with greater awareness of the world are more likely to live sustainably. As a result, the outcomes of panel-level and country causality studies primarily corroborate theoretical predictions. Furthermore, the associated empirical research has typically indicated that education significantly impacts the environment (Balaguer & Cantavella, 2018; Li et al., 2021; Cui et al., 2022; Sart et al.,

TABLE 5 The (Westerlund-2007) Cointegration results.

Group Statistics	values	Panel Statistics	values
Gt	−9.514*** (0.000)	Pt	−16.043***(0.000)
Ga	−23.167***(0.000)	Pa	−19.159***(0.000)

Note. *** indicates significance at 1%.

TABLE 6 PFMOLS and PDOLS results.

I V	PFMOLS	PDOLS
HEX	0.16324***	0.26314***
	(4.61253)	(5.62415)
EGC	0.42142***	0.54328***
	(5.86321)	(4.69835)
EDU	−0.18632***	-0.16438**
	(−4.8342)	(−2.6314)
POP	0.63471**	0.36489**
	(2.9214)	(2.86314)

Note. *** indicates significance at 1%.

TABLE 7 AMG and CCEMG results.

IV	CCEMG	AMG
HEX	0.18523***	0.18614***
	(5.41380)	(3.13819)
ECG	0.48903***	0.52919**
	(5.08611)	(2.24381)
EDU	0.31381**	0.28391***
	(2.23179)	(5.08237)
POP	0.26372***	0.21839***
	(5.41286)	(4.08924)
Constant	0.83942***	0.631829***
	(7.27138)	(5.52764)
RMSE	0.0089	0.0083
Wald	31.2468	49.6217
	(0.0000)	(0.0000)

Note. *** indicates significance at 1%.

2022). As a result, education is one of the most important tools for improving environmental quality. Finally in table 6 findings show that, the sample nations, where a 1% rise in population growth resulted in PFMLOS 0.63471% and PDOLS 0.36489% increase CO_2 emissions, as assessed by PFMOLS and PDOLS, respectively. Population expansion has been identified as the primary cause of rising CO_2 emissions, raising energy consumption (Luo et al., 2021). A large body of evidence confirms the positive relationship between population and CO_2 emissions (Luo et al., 2021), and this is notably true in the context of E-7 countries, given their huge percentage of the global population. The population's position as a CO_2 augmenting factor may be seen from various perspectives. Higher use of resources, such as energy, fossil fuels, transportation, and other products and services, results in more significant CO_2 emissions as the population grows.

4.3 Robustness tests

Tables 7 show the results of the CCEMG and AMG tests, respectively. The CCEMG and AMG findings in Table 7 are identical to those obtained using PFMOLS and PDOLS in Table 6, confirming the consistency of our results. The CCEMG and AMG results also indicated the importance of the overall model, as the Wald test value was significant. Similarly, the Root Mean Square Error (RMSE) for both tests is approximately identical; however, the RMSE number for CCEMG is higher than that of the AMG model. However, (Luo et al., 2021) highlighted whether the tests CCEMG and AMG have a unit root problem, CSD, and cointegration or not.

5 Conclusion and policy suggestions

The effects of environmental quality are significantly mitigated by physical activity, education and health care systems. This study adds to the body of knowledge about the dynamic link between CO_2 emissions, healthcare expenditure, economic development, education, and population for the E-7 countries between 2000 and 2019. The CSD test was used to investigate cross-sectional dependence, CIPS and CADF tests to determine variable integration order, Westerlund cointegration test to validate variable cointegration, and PFMOLS and PDOLS to provide long-run coefficients of parameter estimates and also used AMG and CCEMG techniques for robustness checks. PFMOLS and PDOLS showed that education had a negative and substantial effect on CO_2 emissions in E-7, whereas health spending, economic growth, and population increase had a positive and significant influence. CO_2 emissions have severe repercussions for environmental quality and environmental health, resulting in health-related concerns and increased healthcare costs at both the individual and public levels. The outcomes of our study are validated and robust by applying AMG and CCEMG tests. As a result, the findings of this study are beneficial for E-7 nations in revising their policies to improve environmental quality.

Our paper makes recommendations for reducing CO_2 emissions and increasing environmental quality in E-7 economies based on the research findings. Government law for CO_2 control might be an acceptable instrument, and the government could reduce CO_2 emissions to a desirable level, particularly in the exporting industry, balancing healthcare costs and CO_2 emissions in the economy. Additionally, regulatory framework for CO_2 control may be a useful instrument. The government may reduce CO_2 emissions to the desired level, particularly in the exporting sector, which will balance healthcare costs and CO_2 emissions in the economy. Education may efficiently address environmental deterioration by using market-based environmental instruments, promoting environmental awareness, physical education, and producing green or energy-efficient technology. The econometric findings provide recommendations for environmental quality, physical education and a more efficient allocation of health spending to attain excellent health outcomes in the region. Education expenditure is ecologically friendly, hence more investments should be made in this area.

The research has some limitations since it only considers one component of a rise in HEX caused by CO_2 emissions using a case study of an emerging seven bloc, which may be expanded to other regions such as G-7, MENA, BRICS, etc. Both theoretical and empirical models may extend further to other factors, like life expectancy. Although the current study has significant outcomes, future research should be done using diverse environmental sustainability parameters, such as urbanization, financial development, trade, globalization, and industrialization, etc. This study employed CO_2 as a proxy for environmental deterioration; future research should use different proxies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JB: conceptualization; supervision; writing—original draft preparation and editing. KA: conceptualization; formal analysis; validation; methodology; review and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Assessing the role of financial development and financial inclusion to enhance environmental sustainability: Do financial inclusion and eco-innovation promote sustainable development?

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In the context of increasing uncertainty in the international economic environment and changes in the labor market, it is imperative to pay proper attention to the environmental quality and sustainability. This paper theoretically analyzes the impact of financial development and financial inclusion on the environmental sustainability. Based on the survey data of 2093 households in Xunyi and Yangling, Shaanxi Province, China, the 2SLS model, and the instrumental variable quantile regression model are constructed to test the association of variables. The results show that the development of financial inclusion and financial development have an inverted "U" shaped nonlinear effect on the environmental quality and efficiency; Only after the development of financial inclusion reaches a certain degree can the environmental quality and sustainability be effectively improved. The results of the quantile regression of instrumental variables show that financial inclusion significantly improves the environmental quality with medium and high degrees but does not have a significant effect on the environmental quality and sustainability with low degrees. After considering the endogeneity and robustness test, the above conclusion still holds. Further research shows that inclusive financial development improves environmental quality and results in sustainable development. Improving the convenience and depth of use of financial services is the key to effectively reducing rural household economic vulnerability and improve the environmental quality. The heterogeneity analysis shows that financial inclusion development has a stronger effect on improving the environmental quality. This study provides empirical evidence and policy implications to better promote financial inclusion to improve the economic vulnerability of rural households, improve environmental quality and achieve the sustainable development. These findings provide policy support to better promote financial inclusion to improve the economic vulnerability of rural households, improve environmental quality and achieve the sustainable development, which can ameliorate environmental degradation, and create a safe, healthy and sustainable environment for achieving sustainable development goals.

KEYWORDS

sustainable development, financial inclusion, environmental sustainability, environmental degradation, economic growth

1 Introduction

During global environmental change, the world is facing a huge loss or major blow to multiple natural resources and experiencing a significant reduction in biodiversity and a great threat of climate change (Fahad and Wang 2018). To prevent the rapid degradation of natural resources, users of resources and governments must strengthen the management of key environmental variables, and achieve sustainable social-ecological systems (Chen et al., 2022a; Fahad et al., 2022a). In social-ecological systems, human activities, social systems and natural resources are closely linked and interact with each other. Especially in rural areas, the frequent occurrence of natural disasters significantly impacts production and the economy. In the face of complex changes in the global environment, enhancing ecosystem services through adaptive management is a meaningful way to guarantee the sustainability of resources (Chen et al., 2022b; Han Yuan, 2022; Hu and Wang, 2022). Therefore, there is a need to analyze the relationship between resources, environmental quality and household resilience to effectively address the risks arising from global environmental change (Gaisie et al., 2021; Su et al., 2022a; Song et al., 2022).

Economic vulnerability is an essential indicator of household resilience, environmental quality and sustainability. With the uncertainty of the international external economic environment, repeated shocks from domestic and international epidemics, industrial restructuring, changes in the labour market, and births, illnesses and deaths have increased the number of risk events faced by rural households (Gutiérrez-Romero and Ahamed, 2021; Fahad et al., 2022b; Su et al., 2022b). In addition to environmental factors, the Medical expenses, death, unemployment, children's education, household balance sheet structure, and weddings are the main risk to the family (Flores and O'Donnell, 2016; Fernández-Blanco, 2022). The higher the family's economic vulnerability, the lack of the ability to properly handle the risk problems leads to the risk situation of income, and consumption, leading to or returning to poverty (Yue et al., 2021). According to [China Household Wealth Index Research Report (2020 Q1)]: Hit by the COVID-19 pandemic, 13.4% of the surveyed families said that their job stability had decreased significantly and 18.9% of the surveyed families' wages had decreased a lot. The impact on vulnerable groups was more significant and 34.3% of families with an annual income of 50,000 yuan or less had their wages reduced significantly. Among households with annual revenues of 50,000 to 1,00,000 yuan and 1,00,000 to 3,00,000 yuan, 16.7% and 9.9%, respectively, saw their salaries cut significantly. In this context, the study of how to effectively reduce the economic vulnerability of families has become an important issue to prevent rural scaling back to poverty and consolidate the achievement of poverty alleviation.

Finance is considered the main component in reducing vulnerability and promoting sustainable development. Since China proposed the inclusive financial development strategy in 2015, financial inclusion services play a crucial role in improving rural household income and welfare, improving the ability to cope with and resist risks, improving household vulnerability, and promoting the adoption of clean energy in households (Yang and Fu, 2019; Pomeroy et al., 2020; Yan et al., 2022; Yang et al., 2022). In theory, inclusive finance is mainly relevant to poorer groups where farmers and peasants may not have the wealth or credit to invest in renewable energy sources, such as solar energy, which is cheaper and emits less carbon monoxide (Hashmi et al., 2021; Wang et al., 2022b; Shah et al., 2022). Therefore, financial inclusion may increase rural households' adoption of healthier lifestyles for the environment, increasing affordability and adoption of healthy practices. However, current research has mainly documented the positive impact of financial inclusion on economic development. There are few empirical studies to demonstrate the impact of financial inclusion on household economic vulnerability and environmental sustainability. For example, Erlando et al. (2020) note that inclusive credit and insurance services can directly increases the access of rural families, especially the poor rural groups, to financial services. At the same time, inclusive financial services improve the level of family income by promoting entrepreneurial and innovative activities and alleviating educational poverty (Lensink et al., 2017; Camargo and Stein, 2022). Mina and Imai (2017) proposed that the level of coverage of banking institutions at the provincial and community levels can improve credit availability, financial service efficiency, and service quality and significantly reduce household economic vulnerability. Essel-Gaisey and Chiang, (2022) found that being financially included decreases households' probability of being environmentally poor by about 4.2%–5.1%.

To our knowledge, this is the first attempt to explore the link between financial inclusion and environmental growth at the rural household level. From reviewing the existing literature, we found that the role of financial inclusion on economic vulnerability and environmental sustainability has not been explored in-depth and the empirical results obtained have not been conclusive. Most existing studies have been analyzed at the macro level. Moreover, China has a large population of rural residents, but there is a lack of practical research on the impact of financial inclusion on the economic vulnerability and environmental sustainability of Chinese rural households. Therefore, there is an urgent need to explore the impact of financial inclusion on the economic vulnerability and environmental sustainability of rural households.

Different from previous studies, this study contributes to the existing literature in the following three aspects. Firstly, the heterogeneous rural household vulnerability effects of inclusive financial development are investigated by using the 2SLS model, and the results of heterogeneous estimates of the economic vulnerability quantile of financial inclusion are considered using an instrumental variable quantile regression model. Secondly, to deepen the understanding about the impact of financial inclusion, four dimensions of financial inclusion are considered: breadth of coverage, convenience, depth of use, and satisfaction. Thirdly, we analyse the heterogeneity of the results across different modes of operation, different levels of education, different income levels, and different social capital in order to capture the idiosyncratic effects of financial inclusion. The study focuses on rural China, rather than China as a whole, as there are significant differences in the household vulnerability profiles of rural and urban residents in China, with rural residents being generally more vulnerable than urban residents, which is related to differences in income and infrastructure.

Financial inclusion can contribute to a country's economic development and reduce the impact of extreme poverty and economic disparities. Still, it can have far-reaching effects on environmental quality and sustainable development that need to be explored. This study is an effort in this direction, and we have decided to examine the impact of financial inclusion on the economic vulnerability and environmental quality of rural households in China. We Use the data from rural Shaanxi, China, and apply the 2SLS model and instrumental variable quantile regression model to address the individual heterogeneity and potential endogeneity of rural households. Our data estimates suggest that environmental quality and sustainability can be effectively improved only after financial inclusion development reaches a certain level. Furthermore, we observed that increasing the ease and depth of financial service use significantly improved medium and high environmental quality but had no significant effect on low environmental quality. This suggests that issues of environmental quality and sustainability in rural China can be improved by increasing the ease and depth of use of financial services. Therefore, policies aimed at effectively improving environmental quality and sustainability in rural China may focus on improving the economic vulnerability of rural households by improving the ease and depth of financial service use, rather than solely emphasizing financial service coverage for rural households.

Our study is structured as follows. The next section introduces the theoretical analysis and Hypothesis. Section 3 introduces the data, variables, and empirical method, which are used to investigate the effect of inclusive finance on the household vulnerability, environmental quality and sustainability. Section 4 discusses the estimation results and our main findings. The last section concludes the study and provides policy implications according to our empirical findings.

2 Theoretical analysis and hypothesis

2.1 The impact of financial inclusion on the vulnerability

The rural financial market has long-term problems of imbalance and inadequacy of supply and demand, lack of standard collateral, and imperfect credit information for rural households, which make them excluded from the traditional financial system for a long time (Schoofs, 2022). Promotion of financial inclusion aims to allow all social strata, especially vulnerable groups, to enjoy fair and equal rights to financial services, and rural families are critical service groups of financial inclusion. However, according to the theory of public policy, the implementation of policy, the promotion of execution organization, and the construction and improvement of the system are gradual processes. On the one hand, there is a certain threshold for access to financial services. So, in the early stage of the development of financial inclusion, it is difficult for low-income people to obtain financial support. Only when financial development becomes more mature can it effectively benefit the poor (Bolarinwa and Akinlo, 2021). On the other hand, capital has a profit-seeking nature. In the short term, when limited financial resources enter the rural market, social elites with high income, rich social connections, and political status occupy a dominant position in resource allocation. This leads to the phenomenon of "elite capture," in which agricultural loan funds were appropriated by elites (Wen et al., 2016). For example, there is a serious phenomenon of "elite capture" in both "government bank-insurance" credit and urban and rural self-employment loans (Wang et al., 2021; Wang et al., 2022a). Affected by the loss of efficiency in resource propensity allocation and the lack of financial knowledge, improving the inclusion of banking services has not yet reflected the obvious benefit of poverty (Li and Han, 2019). Therefore, when the development of financial inclusion is relatively weak, the income and consumption gap between households without financial services and those with financial services may widen. In addition, financial inclusion helps nonpoor households prevent risks, smooth consumption, and accumulate factors, and exacerbates income inequality between poor and nonpoor households (Wang and Du, 2018). So, in theory, when the financial inclusion development level is at a low level, temporarily unable to overcome the rural financial market long-term existence of formal financial institutions, high threshold, high service costs, and adverse selection, the problem is captured by the "elite." This leads to financial products and services not being able to effectively meet all kinds of main body and diversification of income group operation and different demand; It is not conducive to improving the economic vulnerability of rural households.

With the continuous improvement of financial inclusion, the product and service system of financial inclusion will gradually be optimized. On the one hand, financial diversity can promote competition in the financial industry, reduce barriers to entry, etc. This will improve the traditional factors of the rural financial market and product market efficiency, further correcting the conventional financial system of "little" features and improving the accessibility of inclusive financial services for rural households (Gomez et al., 2015). On the other hand, it can improve the efficiency of financial capital allocation, increase investment opportunities, promote rural economic growth, and optimize income distribution to promote development benefits to more disadvantaged rural families (Emara and El Said, 2021). By optimizing resource allocation, inclusive credit services can provide more credit capital for agricultural production and rural development. Reduce the impact of current capital liquidity constraints that residents face, smooth sudden household consumption, and thus improve the total utility level of intertemporal household consumption (Deidda, 2014). Diversified innovation and wide popularization of inclusive insurance services can provide risk protection tools for families, improving the risk handling ability of rural families. Effectively improve families' financial vulnerability by avoiding the negative impact of risk impact on families (Contró et al., 2021), improve family welfare, and reduce the marginal effect of various risks on family economic vulnerability (Yue et al., 2021). Studies have shown that inclusive insurance can play complementary functions with financial services such as poverty alleviation microfinance, formal inclusive credit, and digital finance to jointly reduce household vulnerability to poverty. So, in theory, financial inclusion development, step by step, can enhance rural household savings, investment, and consumption ability. Improving rural households in consumer, health care, education, social security, employment, entrepreneurship, etc., and making them more economic conditions for the development of production and operation, doctor treatment, buy insurance against risks, improve the level of family education, etc. Finally, the structure of household income and consumption can be improved, which helps reduce the economic vulnerability of households. To sum up, our paper proposes the following hypotheses:

Hypothesis H1. Inclusive financial development has an inverted "U" shaped impact on the economic vulnerability of rural households.

Hypothesis H1a. When the development of financial inclusion is at a low level, it is not conducive to improving the economic vulnerability of rural households.

Hypothesis H1b. A higher level of financial inclusion can effectively reduce the economic vulnerability of rural households.

2.2 The impact of financial inclusion on the different dimensions of vulnerability

The economic vulnerability of rural households was caused by inter-village inequality, intra-village inequality, collaborative risk, heterogeneous risk, unexplained risk, and many other reasons (Ligon and Schechter, 2003; Zhang et al., 2016). Among them, inter-village and intra-village inequality is the primary indicator to measure household poverty or inequality; collaborative risk, heterogeneous risk, and unexplained risk are the changes of various risks affecting household economic vulnerability. Differences between rural spatial resources and initial household endowments (such as financial assets, social capital, human capital, etc.) will affect income and expenditure inequality within and between villages (Zhen and Ling, 2017). Additionally, inequality within villages is more severe than among villages (Xu et al., 2022). In this case, increasing the breadth and depth of inclusive financial services still helps alleviate consumption inequality in rural household goods, education, culture, transportation, and communication (Inoue et al., 2018; Urrea and Maldonado, 2011) and promote inclusive development. Therefore, financial inclusion development can improve the availability of financial services for rural households and focus on alleviating household economic vulnerability caused by inter-village and intra-village inequality by improving household consumption and welfare levels.

Thus, our paper proposes the following hypotheses:

Hypothesis H2. Financial inclusion development mainly improves household economic vulnerability caused by inter-village and intra-village inequality.

2.3 The heterogeneous impact of financial inclusion on vulnerability

In addition, the development of financial inclusion has prominent regional differences characteristics (Demirguc-Kunt et al., 2015). This unbalanced development will cause different economic entities to get differentiated benefit opportunities from

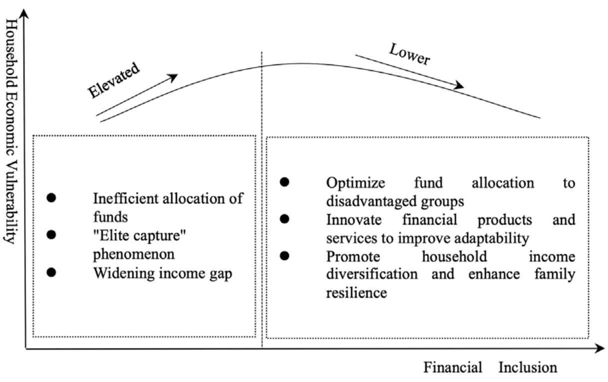

FIGURE 1
Regions of the surveyed farmers in Shaanxi province.

it. At the same time, due to differences in family resource endowment and educational background, the impact of financial inclusion development on the economic vulnerability of different types of families may also be different. For example, whether financial inclusion can play the role of risk management and reduce household economic vulnerability depends on whether vulnerable groups can obtain financial availability to meet financial credit needs and whether excluded individuals grasp the concept of financial knowledge (Lopus et al., 2019). Meanwhile, residents with higher education levels benefit more from developing financial inclusion (Grohmann et al., 2018). Therefore, due to differences in household resource endowments, the impact of financial inclusion on the economic vulnerability of different households may be heterogeneous. Based on the above, this paper proposes the following hypotheses:

Hypothesis H3. The effect of inclusive financial development on improving the economic vulnerability of different rural households is heterogeneous.

3 Methods

3.1 Data sources

The data in this paper are from the rural field household survey with the theme of "Rural Inclusive financial development and Household economic vulnerability" carried out by the research group in Xunyi County and Yangling Demonstration Zone, Shaanxi Province, China, from July to August 2018 to 2019. We chose this location for two reasons. Firstly, it is one of the demonstration zones for China's central financial support for inclusive financial development. Secondly, Xunyi County is located in the west of central Shaanxi, where droughts and floods coexist in the summer and some areas often experience catastrophic weather such as lightning, hail, heavy rain and high winds. Yangling is located in central Shaanxi and has a suitable climate. Therefore, farmers in the two areas are able to represent the differential characteristics of vulnerability under different environmental conditions.

We considered each township's economic development and used a combination of multi-stage stratified and random sampling. In Xunyi County, three townships (towns) with leading economic development, namely Taicun Township, Chengguan Township, and Zhanghong Township. And two townships with average economic growth, namely Chidao Township and Yuandi Township, were selected for sampling. In Yangling Demonstration Zone, three representative townships (towns) reflecting different levels of economic development were selected, including Jiugu Township, Wuquan Township, and Dazhai Township, as shown in Figure 1. In each township (town), we first select three to four villages according to population density, type of industrial development, and other indexes. Second, 40–50 sample farmers (mainly heads of households) were randomly selected in each sample village for interviews to ensure the randomness and representativeness of the sample.

In this survey, a total of 2,215 questionnaires were distributed, covering 27 natural villages in eight townships (towns) in two regions of Shaanxi province, China. After eliminating abnormal samples and extreme values, 2093 valid questionnaires were screened, with an effective rate of 94.49%. The sample households represent the distribution characteristics of farmers with different economic conditions and different types of agricultural management in the county area, which has a good representation.

3.2 Variable selection

3.2.1 Dependent variable

Household economic vulnerability reflects the impact of risk shocks on household consumption and welfare. There are three typical representative and mainstream measurement methods: First, the vulnerability-to-expected poverty (VEP) measurement method, which is an ex ante estimate and has often been used by scholars in poverty vulnerability research (Zhang et al., 2022), but this method depends on the setting of the poverty line and vulnerability line; Second, the vulnerability-of-risk exposure (VER) measurement method, which is an ex post estimation method, estimates the vulnerability through the risk shocks that have occurred. This method has strict requirements on data, so its utilization rate is not high. The third is the vulnerability to the expected utility (VEU) measure, which also belongs to ex-ante estimation. This measure reflects the subjective preferences of individuals or families in the choice of utility functions. It can objectively reflect the changes of risk shocks on family welfare according to household consumption or income changes (Ligon and Schechter, 2003).

Therefore, our paper uses the difference between household certainty equivalent utility and household expected utility (VEU) under risk shocks to measure the economic vulnerability of heterogeneous households.

The calculation process is as follows: first, set the expected utility vulnerability measure model; second, set the rural household utility function model. The model equation is as follows:

$$EV_{\mathrm{i}} \triangleq U_{\mathrm{i}}(z_{ce}) - EU_{\mathrm{i}}(\mathrm{c_i}) \tag{1}$$

$$U_{\mathrm{i}}^{i}(C) = C_{\mathrm{i}}^{1-r}/(1-r) \tag{2}$$

In Eq. 1, EV_{i} is the value of economic vulnerability for household i; $\mathrm{c_i}$ is the amount of household consumption; r is the type of risk avoidance for the family i, Generally set r equal to 2 or 3 (Ligon and Schechter, 2003); z_{ce} is deterministic equivalent consumption, reflecting the level of consumption of households without risk conditions, and the simple mean method is used to find the average amount of consumption of all households for all sample households in 2017 and 2018 for their consumption expenditure data. $U_{\mathrm{i}}(z_{ce})$ and $EU_{\mathrm{i}}(\mathrm{c_i})$ are the consumer utility and expected utility values, and the expected utility of the household is found separately for each household for 3 years using the simple average method. When the actual household consumption is greater than z_{ce} , the household economy is non-vulnerable, That is, when $EV_i \leq 0$, represents that the household is not vulnerable; when $EV_i > 0$, the household is vulnerable.

Referring further to Ligon and Schechter (2003) decompose the household economic vulnerability indicator into a poverty component and a risk component:

$$EV^{i}_{f} = \underbrace{\left[U^{i}_{f}(z_{ce}) - U^{i}_{f}\left(E\left(C^{i}_{f}\right)\right)\right]}_{\text{poverty component}} + \underbrace{\left[U^{i}_{f}\left(E\left(C^{i}_{f}\right)\right) - EU^{i}_{f}\left(C^{i}_{f}\right)\right]}_{\text{risk component}} \tag{3}$$

Among them, z_{ce} represents the level of consumption when a household falls into poverty, and C^{i}_{f} represents the expected level of household consumption. The poverty component reflects the deviation of the household's expected consumption utility relative to the utility at the poverty line level, expressed as the difference between the deterministic equivalent utility at the poverty line and the predicted consumption value utility. The risk component is the difference between the utility of household i's expected consumption and the expected utility of consumption. The expected utility of the risk component encompasses the various risks that can affect the economic vulnerability of households. To distinguish the impact of different types of risk on vulnerability, we further decompose rural household vulnerability into five components by referring to the relevant literature as follows.

$$EV^{i}_{f} = [U^{i}_{f}(z_{ce,t}) - U^{i}_{f}(z_{ce,t,v})] \quad \text{Inter-village inequality}$$

$$+[U^{i}_{f}(z_{ce,t,v})U^{i}_{f}(E(U^{i}_{ft}))] \quad \text{Inequality within the village}$$
$$+[U^{i}_{f}(E(C^{i}_{ft}))EU^{i}_{f}(E(C^{i}_{ft}|\bar{X}_t))] \quad \text{Collaborative risk}$$

$$+[EU^{i}_{f}(E(C^{i}_{ft}|\bar{X}_t)) - EU^{i}_{f}(E(C^{i}_{ft}|\bar{X}_t, X_{ft}))] \quad \text{Heterogeneity risk}$$

$$+EU^{i}_{f}(E(C^{i}_{ft}|\bar{X}_t, X_{ft})) - EU^{i}_{f}(U^{i}_{ft}) \quad \text{Unexplained risk}$$

Among them, inter-village inequality represents the changes in family welfare caused by comparing households in different counties and villages. The inequality within the town represents the change in household consumption welfare affected by the comparison between the residents of the same village; Collaborative risk represents the impact of different living habits in other counties and villages on household consumption, including county and village dummy variables. The heterogeneity risk represents a series of variables that affect the consumption of sample households in period T and the characteristics of sample households, including personal characteristics of the head of the household and family characteristics, etc. Unexplained risk refers to the changes in household welfare caused by the remaining unobservable variables.

3.2.2 Independent variable

Household financial inclusion index. The government and academic departments have unanimously recognized financial inclusion's multidimensional, comprehensive, and inclusive nature. Most existing studies construct the financial inclusion index at the provincial level and the county level (Sarma, 2015; Álvarez-Gamboa et al., 2021; Macedo et al., 2022), and there are few works of literature on the construction of the financial inclusion development index at the micro-home level. Compared to the macro-measurement index of financial inclusion, the micro-household financial inclusion index has apparent advantages because it can capture the determinants and influencing factors of access to financial services at the individual or household level (Zhang and Posso, 2019). Some scholars tried to construct the financial inclusion development index from the household level (Yin et al., 2019), which provides a reference for this paper. Combined with data availability, this paper constructs a family-level financial inclusion index system that includes four dimensions: breadth of coverage, convenience, depth of use, and satisfaction. Table 1 presents the meanings of each index. Further, referring to the practice of Sarma (2015) and Xu et al. (2020), the average Euclidean distance method was used to calculate the indexes, and the entropy weight method was used to weigh each index and each dimension. Finally, the rural inclusive financial development index (FI) has been synthesized. Given the space constraints, we will not describe the specific formula and calculation process in detail.

TABLE 1 Index system of rural household financial inclusion.

	Dimensionality	Indicators	Indicators definition
Supply Level	Coverage	Number of bank branches per sq. km	= (total number of township bank branches/square kilometer area of township)
		Number of financial service points per sq. km	= [total number of financial service points in the community (village)/square kilometer area of the community (village)]
		Number of bank branches per 1,000 people	= (total number of township bank branches/total population of the township) * 1,000
		Financial service points per 1,000 people	= (total number of community financial service points/total population of the community) * 1,000
	Convenience degree	Distance to the nearest bank branch	= distance from the nearest bank branch to the community (unit: km)
		Distance to the nearest financial service point	= distance from the nearest financial service point to the community (unit: km)
Demand Level	Use depth	Number of bank accounts per household	= total number of bank accounts/total household labor force size
		Get a bank loan	= 1 if the household has received a bank loan in the last 3 years; 0 = otherwise
		Medical Insurance Ratio	= number of family members with health insurance/total family size
		Pension insurance ratio	= number of household members with pension insurance/total household workforce
		Agricultural insurance participation	=1 if the household buys agricultural insurance; 0 = otherwise
		Digital financial services use	=1 if the household engages in one or more digital payments, internet lending, and internet financial management behaviors; 0 = otherwise
	Satisfaction	Financial services evaluation score	If a household evaluates the non-cash payment, loan service, and insurance service as "very satisfied" or "relatively satisfied," the individual service evaluation score is 1, and the combined score equals to the average value of the three scores

Notes: In the survey, financial service points include self-service banks, ATMs, farmers' withdrawal service points, and other financial service points that benefit farmers.

3.2.3 Control variables

According to theoretical analysis and previous studies, the amount of household consumption, as a core indicator of household economic vulnerability, is influenced by internal factors such as personal characteristics of the household head and household characteristics (Wang et al., 2021) and external factors such as regional characteristics (Peng et al., 2021). Therefore, 15 variables, such as individual characteristics of household heads, household characteristics, and village characteristics, were selected as control variables in this paper. Table 2 shows the descriptive statistics of the variables. The personal characteristics variables include gender, age, education level, marital status, and health status. Household characteristics include variables such as household management, household dependency ratio, land management area, social capital, and severity of illness of household members in the current year. Regional characteristics are dummy variables for the location of the household.

3.3 Model construction

3.3.1 Benchmark model

Our paper first examines the aggregate effect of financial inclusion on household economic vulnerability, with the underlying empirical equation set as:

$$EV_{it} = \alpha_1 + \beta_1 FI_{it} + \delta_1 X_{it} + \varepsilon_{it} \quad (4)$$

$$EV_{it} = \alpha_2 + \beta_2 FI_{it} + \gamma_2 FI_{it}^2 + \delta_2 X_{it} + \varepsilon_{it} \quad (5)$$

EV_{it} represents the economic vulnerability index of the sample rural household i in year t; FI_{it} represents an index of financial inclusion development for rural households i. Considering that the impact of financial inclusion development on household economic vulnerability may be non-linear, we add the square term variable FI_{it}^2 of the financial inclusion development index into the formula. X_{it} represents groups of control variables at the individual level and at the household level, ε_{it} is the random perturbation term. Considering that there may be endogeneity problems caused by reverse causality and omitted variables in the econometric model, the OLS model and the two-stage least squares (2SLS) model were used to estimate Eqs 4, 5, respectively.

3.3.2 Quantile regression model for instrumental variables

The essence of the OLS and 2SLS models is to use a function of the conditional mean of the explanatory variables to describe the mean of the explanatory variables dependent on each particular value of the explanatory variables without considering the more specific impact of financial inclusion development on rural households with lower or better household economic vulnerability.

To avoid the phenomenon of "average covering up the majority" and solve the parameter estimation problem when

TABLE 2 Definition and summary of variables.

Variable type	Variables	Definition	Mean	S.D.	Min	Max
Dependent variable	Household Economic Vulnerability Index	The difference between the household's deterministic equivalent utility and expected utility under a risk shock (VEU)	0.715	0.098	−1.510	0.8173
Independent variable	Financial inclusion Index	Calculated from the above	0.312	0.033	0.209	0.568
Individual characteristics variables	Age	= 1 if 16–29 years old, = 2 if 30–39 years old, = 3 if 40–49 years old, = 4 if 50–59 years old, = 5 if 60 years old and above	3.685	3.685	1	5
	Education	= 1 if illiterate, = 2 if elementary school, = 3 if junior high school, = 4 if high school (including junior college), = 5 if college and above	2.742	1.068	1	5
	Marital status	= 1 if married, = 0 otherwise	2.016	0.420	1	4
	Health status	= 1 if very unhealthy, = 2 if relatively unhealthy, = 3 if average, = 4 if relatively healthy, = 5 if very healthy	4.023	1.031	1	5
Household characteristics variables	Household Business Type	= 1 if pure agriculture, = 2 if mainly agriculture and other, = 3 if mainly non-agriculture and other, = 4 if non-agriculture	2.284	1.010	1	4
	Ln Household income	Log of total household income for the year	10.795	0.790	7.600	14.620
	Total family size	Total number of family members (unit: pcs)	4.823	1.702	1	13
	Household support ratio	Share of non-labor force in total household size (unit: %)	0.823	0.669	0	1
	Labor force ratio	Share of labor force in total household size (unit: %)	0.620	0.242	0	1
	Whether any member of the family had a severe illness	= 1 if yes, = 0 no	0.3578	0.479	0	1
	Social Capital Index	Calculated according to factor analysis method	0.089	0.049	0	0.385
	Ln Land operating area	Log of actual operating area	1.586	0.607	−1.609	4.605
	Ln Crop operating area	Log of crop operating area	1.394	0.918	−1.609	8.389
Region variable	Region variable	= 1 if from Xunyi, = 0 if from Yangling	0.554	0.497	0	1

Notes: The social capital index is calculated as follows: This paper draws on relevant studies and selects three questions "whether there are friends and relatives who are village cadres," "whether there are friends and relatives who work in government departments" and "whether there are friends and relatives who work in banks" to represent the village social capital, government relationship capital and bank relationship capital of households, respectively. The above questions take the value of 1 if yes; otherwise, 0. Then we used factor analysis for the above three questions, and each household's comprehensive social capital index was calculated according to the factor score formula.

the endogeneity problem exists in the quantile regression model, we further used the linear instrumental variable quantile regression (IVQR) model proposed by Chernozhukov and Hansen (2005) to investigate the differential impact of financial inclusion development on the economic vulnerability of heterogeneous rural households. IVQR model set as follows:

$$P(Y \le Q_\tau (D, X, \tau)|X, Z) = \tau \tag{6}$$

In Eq. 6, Y is the dependent variable, D is the independent variable, X denotes exogenous variables, Z stands for tool variable, τ is the conditional quantile. Then converting Eq. 6 to matrix form in the linear form:

$$Y_D = D'\alpha(U) + X'\beta(U) \tag{7}$$

In Eq. 7, Y_D is the potential output corresponding to the different policy variables D, $= \delta(X, Z, V)$, $\delta(\bullet)$ is a function of unknown form, the X vector contains all exogenous variables, and V is a set of unobservable variables. Other unobservable variables affect Y_D through U_D , U_D obeys a uniform distribution on (0,1). Set the minimum objective function as.

$$Q_n(\tau, \alpha, \beta, \gamma) = \frac{1}{n}\sum_{i=1}^{n}\rho_\tau\left(Y_i - D'_{i\alpha} - X'_{i\beta} - Z'_{i\gamma}\right) \tag{8}$$

In Eq. 8, ρ is the test function for quantile τ .For the given quantile τ and its corresponding $\alpha(\tau)$ condition, the above minimization objective function is:

$$\left[\hat\beta(\alpha, \tau), \hat\gamma(\alpha, \tau)\right] = \text{argmin}_{\beta,\gamma} Q_n(\tau, \alpha, \beta, \gamma) \tag{9}$$

Through Eq. 9, the estimated value of $\alpha(\tau)$ can be obtained as follows:

$$\hat\alpha(\tau) = \text{arginf}\,[Wald(\alpha)] \tag{10}$$

By using the iterative method to make $\hat\gamma(\alpha, \tau)'$ approach to 0, $\hat\alpha(\tau)$ can be obtained, and Wald statistic is used to test, and finally, the estimated values of α and β at the partial site τ can be obtained.

4 Results and analysis

To check whether unobserved factors influence, we computed the estimation effect of financial inclusion index and square term of financial inclusion index on household vulnerability variable using OLS model and 2SLS model, respectively. We further computed the quantile estimation effect of household vulnerability using

TABLE 3 Model fitting results of financial inclusion on economic vulnerability of rural households.

Variables	(1)	(2)	(3)	(4)
	OLS	OLS	2SLS	2SLS
Financial inclusion index	1.079 (1.37)	1.142* (1.60)	1.892*** (4.29)	1.509* (2.58)
Financial inclusion index squared		−9.469*** (−7.52)		−10.56** (−2.61)
Age	−0.014 (−0.34)	−0.052 (−0.01)	0.085 (0.14)	0.089 (0.61)
Education	−0.084 (−1.90)	−0.088* (−2.24)	−0.075 (−1.16)	0.024 (1.50)
Marital status	−0.027** (−2.78)	−0.053 (−0.55)	−0.047** (−3.23)	−0.048 (−1.31)
Health status	−0.002** (−2.70)	−0.005 (−1.35)	−0.002** (−2.62)	0.005 (0.36)
Household business type	0.018*** (3.74)	0.021*** (4.50)	0.017* (2.17)	−0.056 (−0.03)
Ln household income	−0.036*** (−50.34)	−0.035*** (−54.23)	−0.029*** (−28.11)	−0.021*** (−8.67)
Total family size	−0.007 (−0.91)	−0.003*** (−3.93)	−0.002* (−1.99)	−0.003 (−1.04)
Household support ratio	0.003*** (4.05)	0.002* (2.48)	0.004* (2.43)	−0.003 (−0.92)
Labor force ratio	0.011 (1.96)	−0.029 (−0.67)	0.006 (0.86)	−0.011 (−0.72)
Whether any member of the family had a severe illness	−0.002 (−1.89)	−0.006*** (−8.26)	0.008 (0.64)	0.001 (0.34)
Social Capital index	−0.034*** (−3.80)	−0.039*** (−4.92)	−0.045*** (−3.44)	0.072* (2.20)
Ln Land operating area	−0.080 (−0.54)	−0.010 (−0.13)	−0.010 (−0.09)	−0.033 (−1.16)
Ln Crop operating area	0.036** (−2.91)	0.039 (−1.27)	−0.004* (−2.32)	0.011* (2.22)
Region variable	−0.065*** (−6.49)	−0.049*** (−5.02)	−0.031*** (−5.38)	0.035* (2.46)
Constant	1.177*** (20.92)	1.147*** (18.13)	−0.097 (−0.35)	−99.33* (−2.52)
Observations	2093	2093	2093	2093
Pseudo R^2	0.799	0.860	0.599	0.632

Notes: ***, **, and *denote significance at the 1% level, 5% level, and 10% level, respectively. T-values are presented in parentheses.

the IVQR model. Finally, we further checked the robustness of the main results by substituting variables and winsorizing the data.

4.1 OLS estimation for the effects of financial inclusion

Firstly, ordinary least squares estimation is taken when endogeneity effects are not considered, and Eq. 1 is regressed by gradually adding the core independent variables and it is squared terms. Table 3 as (1) to (2) shown OLS results for the impact of financial inclusion development on rural households' economic vulnerability. The result in column (1) shows a nonsignificant positive effect of financial inclusion development on rural households' economic vulnerability. Based on Eq. 1, we added the squared term of the inclusive financial development index. The results were presented in column (2), and the estimated parameter of the squared term was found to be significantly negative at the 1% level. The above results suggest that there may be an inverted "U" nonlinear relationship between the impact of financial inclusion development on household economic vulnerability.

4.2 2SLS estimation for the effects of financial inclusion

4.2.1 Selection of the instrumental variable

Further considering the possible endogeneity problems caused by mutual causality and omitted variables, we refer to Zhang et al. (2016) and choose "the mean value of the financial inclusion development index of farmers in other villages in the county where the sample is located" as the instrumental variable. The reasons are as follows: First, the average value of the inclusive financial development index of farmers in other villages within the county except their village does not directly impact the economic vulnerability of the sample farmers. Second, the impact of policy, planning, infrastructure, and other factors on the development of financial inclusion in all towns (villages) in the same county is basically the same. The inclusive financial development index of the sample must be strongly correlated with the inclusive financial development index of farmers in other villages in the county. Therefore, the instrumental variables selected in this paper meet the exogeneity and correlation conditions and are reasonable and effective.

The results of the endogeneity test also show that the Hausman endogeneity test rejects the original hypothesis at the 1% significance level, indicating that there is an

TABLE 4 IVQR results for the effects of financial inclusion on economic vulnerability.

Variables	(1)	(2)	(3)	(4)	(5)
	Q10	Q25	Q50	Q75	Q90
Financial inclusion index	4.536 (0.55)	19.241*** (12.41)	22.924*** (7.47)	13.693*** (11.00)	1.071*** (3.53)
Financial inclusion index squared	−6.551 (−0.51)	−21.461*** (−11.42)	−24.058*** (−6.83)	−17.222*** (−10.07)	−1.808*** (−5.01)
Region variable fixed	Yes	Yes	Yes	Yes	Yes
Control variables fixed	Yes	Yes	Yes	Yes	Yes
Constant	0.270 (0.20)	−2.282*** (−9.50)	−1.304*** (−4.59)	−2.860*** (−8.94)	0.865*** (14.33)
Observations	2,093	2,093	2,093	2,093	2,093
Pseudo R^2	0.168	0.174	0.185	0.189	0.040

Notes: ***, **, and * denote significance at the 1% level, 5% level, and 10% level, respectively. T-values are presented in parentheses.

endogeneity problem in the model. Considering that the Hausman test is no longer valid under the heteroskedasticity condition, this paper also adopts the DWH test, and the results show that both the Durbin and Wu-Hausman tests reject the original hypothesis at the 1% significance level, thus concluding that the financial inclusion development index variables are endogenous. Regarding the validity of the instrumental variables, in the one-stage estimation results, the t-value of the instrumental variables is 5.13, and the one-stage estimated F-value is 40.23, which rejects the original hypothesis of "weak instrumental variables." Therefore, the instrumental variables selected in this paper can effectively solve the endogeneity problem.

4.2.2 2SLS estimation results

Then we use the 2SLS two-stage least squares method for empirical tests, and the regression results are reported in columns (3) to (4) of Table 3. The regression results show that the primary term of the inclusive financial development index has a significant positive effect on the economic vulnerability of rural households. And the second term of the inclusive financial development index has a significant negative effect on the economic vulnerability of rural households. It reflects that when the development of financial inclusion is at a low level, it does not have an improving effect on economic vulnerability. Only when the development of financial inclusion reaches a certain level can it significantly improve household economic vulnerability, i.e., the development of financial inclusion has a nonlinear inverted "U" shape effect on rural household economic vulnerability. Thus, Hypothesis 1 is confirmed.

4.3 IVQR estimation for the effects of financial inclusion

Thispaper further employs instrumental variable quantile regressions to analyze the impact of financial inclusion on households at different points of economic vulnerability. Table 4 presents the regression results for the entire sample of rural households in the quartiles 10, 25, 50, 75, and 90 of the economic vulnerability index. It can be found that, except for the Q10 quantile, the impact of the squared terms of the inclusive financial development index and the development index on the economic vulnerability of rural households at each point is all significantly negative and passes the significance level test, further confirming more fully the inverted "U" shape impact of inclusive financial development on household economic vulnerability. When the economic vulnerability is at the Q10 quantile, the household financial inclusion index and the squared term have a negative but insignificant effect on their economic vulnerability. Probably because the economic vulnerability of households is low at this time, households have relatively complete measures to cope with risks and have a solid ability to cope with risks. Hence, the effect of financial inclusion on the improvement of its economic vulnerability is not yet apparent.

Looking at the magnitude of the coefficients of financial inclusion and its squared term, we find that the coefficients at Q25 and Q50 are the largest, indicating that the development of financial inclusion has the most potent effect on improving economic vulnerability for moderately vulnerable households. On the contrary, the impact on improving economic vulnerability for highly vulnerable households is relatively weak.

4.4 Robustness check

The following three methods conduct robustness tests:

1. Using the equal-weight method to determine the weights, the financial inclusion index is remeasured, Eqs 1, 2 are re-estimated, and the regression results are presented in column (1) of Table 5.

TABLE 5 Robustness test results.

	Household economic vulnerability			
	(1)	(2)	(3)	(4)
Financial inclusion index	1.311* (1.95)	2.738 (1.08)	7.142*** (9.27)	7.441*** (7.40)
Financial inclusion index squared	−7.854*** (4.03)	−9.275***	−9.469*** (−7.52)	−9.838*** (−6.22)
Region variable fixed	Yes	Yes	Yes	Yes
Control variables fixed	Yes	Yes	Yes	Yes
Constant	0.089 (1.012)	0.207 (−1.90)	−0.249 (−1.90)	−0.393* (−2.43)
Observations	2,093	2,093	1,870	1,870
Pseudo R^2	0.673	0.417	0.240	0.297

Notes: ***, **, and * denote significance at the 1% level, 5% level, and 10% level, respectively. T-values are presented in parentheses.

TABLE 6 Model fitting results of different dimensions of financial inclusion on the economic vulnerability of rural households.

Variables	Household economic vulnerability				
	(1)	(2)	(3)	(4)	(5)
Coverage	−0.097*** (−2.64)				−0.062 (−1.49)
Coverage Squared	0.188 (−0.16)				0.005 (0.18)
Convenience degree		0.018 (0.67)			0.137*** (3.22)
Convenience degree Squared		−0.004*** (3.10)			−0.204*** (−3.81)
Use depth			0.149*** (4.07)		0.013 (0.50)
Use depth Squared			−0.215*** (−4.42)		−0.136** (−2.24)
Satisfaction				−0.010 (−0.24)	0.008 (0.18)
Satisfaction Squared				0.021 (0.54)	0.020 (0.51)
Region variable fixed	Yes	Yes	Yes	Yes	Yes
Control variables fixed	Yes	Yes	Yes	Yes	Yes
Constant	0.977*** (18.40)	0.957*** (17.80)	0.970*** (18.04)	0.959*** (16.83)	0.945*** (16.48)
Observations	2,093	2,093	2,093	2,093	2,093
Pseudo R^2	0.049	0.059	0.047	0.050	0.065

Notes: ***, **, and * denote significance at the 1% level, 5% level, and 10% level, respectively. The T-values are presented in parentheses.

2. Using the factor analysis method, the inclusive financial index is remeasured, and the regression results are reported in column (2) of Table 5.
3. Exclude extreme samples. The data were winsorized by 10% and 90%, respectively, and re-estimated. Columns (3) to (4) of Table 5 show the regression results.

We found that the direction of the impact of the inclusive financial development index and its squared term on the economic vulnerability of rural households are consistent with the benchmark regression among the three robustness tests. This result indicates that the fit of the benchmark regression model is more robust and verifies the previous findings that inclusive financial development has an inverted "U" nonlinear effect on rural households' economic vulnerability.

5 Further discussion

5.1 Impact of different dimensions of financial inclusion

This paper further empirically analyzes the effects of different dimensions of financial inclusion on the economic vulnerability of rural households. In addition to the satisfaction index, the development indices of the three dimensions of the breadth of coverage, convenience, and depth of use are also measured by the

TABLE 7 Model results of financial inclusion on different dimensions of rural household economic vulnerability.

Variables	(1)	(2)	(3)	(4)	(5)
	Inter-village inequality	Inequality within the village	Collaborative risk	Heterogeneity risk	Unexplained risk
Financial inclusion index	3.829*** (−3.22)	4.816*** (3.10)	−2.673 (−0.73)	9.208 (0.72)	18.416 (0.72)
Financial inclusion index squared	−4.294** (2.41)	−4.414** (−2.49)	6.266 (0.85)	−11.453 (−0.84)	−24.906 (−0.84)
Region variable fixed	Yes	Yes	Yes	Yes	Yes
Control variables fixed	Yes	Yes	Yes	Yes	Yes
Constant	4.685* (1.78)	−2.669 (−0.79)	7.220 (1.03)	−6.454 (−1.03)	−3.908 (−1.03)
Observations	2,038	2,037	1,988	1,988	1,988
Pseudo R^2	0.045	0.015	0.023	0.023	0.023

Notes: ***, **, and * denote significance at the 1% level, 5% level, and 10% level, respectively. The T-values are presented in parentheses.

average Euclidean distance method for indicators. The entropy weighting method is used to assign weights to each indicator and each dimension, and finally, the development indices of each dimension are derived. Table 6 reports the regression results. The results in column (1) show that the effect of coverage breadth on rural households' economic vulnerability is negatively significant at the 1% level, indicating that coverage breadth can effectively reduce rural households' economic vulnerability, which is consistent with the findings of Wang Bank. (2000). The results in columns (2)–(3) show that both convenience and depth of use have an inverted U-shaped significant effect on rural household economic vulnerability, indicating that only deepening convenience and depth of use of financial services can effectively reduce the economic vulnerability of rural households. The results in column (4) show that satisfaction has no significant effect on the economic vulnerability of rural households. Finally, in the regression in column (5), the impact of financial inclusion coverage, convenience, depth of use, and satisfaction on the economic vulnerability of rural households is investigated simultaneously. The regression results show that the effects of the breadth of financial inclusion coverage, convenience, and depth of use on rural households' economic vulnerability are consistent with the previous paper, indicating that the regression results are powerfully robust. The above findings suggest that the key to financial inclusion to reduce the economic vulnerability of rural households is to make more efforts to improve the convenience and depth of use of inclusive financial services.

5.2 Impact of financial inclusion on different dimensions of household economic vulnerability

This paper also uses the 2SLS model to explore the economic vulnerability of households and, specifically, what types of risk and inequality are ameliorated by financial inclusion. Columns (1) to (5) of Table 7 report the empirical regression results of the development of financial inclusion on the five dimensions of household economic vulnerability: intra-village inequality, inter-village inequality, synergistic risk, heterogeneous risk, and unexplained risk, respectively. We found that the development of financial inclusion and its squared term significantly affected inter- and intra-village inequality at the 1% and 5% levels, respectively. On the contrary, it did not significantly affect synergistic, heterogeneity, or unexplained risk. An explanation was that the development of financial inclusion could effectively improve income distribution inequality and narrow the income gap (Li and Han, 2019), and at the same time, improve rural households' capital accumulation and risk coping capacity using financial resource allocation and risk aversion, thus helping to reduce inter- and intra-village inequality. The reason for the insignificance of the latter three types of risks may be that the three types of threat are mainly caused by differences in geographical living habits, differences in individual characteristics, and unobservable factors. Accessibility and availability of rural financial inclusion services have not yet had a direct and significant impact on differences in living habits and individual differences between geographical areas. In summary, the development of financial inclusion mainly improves household economic vulnerability caused by inter- and intra-village inequalities. Thus, Hypothesis 2 was confirmed.

5.3 Heterogeneity analysis

In this section, we introduce the interaction term between the core independent variables (financial inclusion development index and its squared term) and household-specific variables (household business type, education level of household head,

TABLE 8 Heterogeneous effects of financial inclusion on household economic vulnerability.

Variables	(1)	(2)	(3)	(4)
	Differences: Family business type	Differences: Education	Differences: Ln household income	Differences: Social capital index
Financial inclusion index	1.134 (0.63)	0.516* (1.96)	3.276** (2.49)	3.672*** (4.20)
Financial inclusion index squared	−0.446*** (−3.88)	−0.503*** (−5.29)	−5.506** (−2.36)	−3.609*** (−2.60)
Financial inclusion index × differences	−2.956*** (3.90)	3.338*** (5.56)	−2.532** (−2.08)	−3.580*** (5.26)
Financial inclusion index squared × differences	−4.831*** (−3.89)	−5.475*** (−5.78)	−4.046** (2.05)	−6.000*** (−5.52)
Region variable fixed	Yes	Yes	Yes	Yes
Control variables fixed	Yes	Yes	Yes	Yes
Constant	0.662** (2.39)	0.748*** (3.19)	−4.592** (−2.13)	0.258* (1.79)
Observations	2,093	2,093	2,093	2,093
Pseudo R^2	0.250	0.261	0.252	0.260

Notes: ***, **, and * denote significance at the 1% level, 5% level, and 10% level, respectively. The T-values are presented in parentheses.

household income level, and household social capital) in the original model. The purpose is to verify the heterogeneous effect of financial inclusion on the economic vulnerability of rural households.

Table 8 presents the heterogeneity effects of the inclusive financial development index and its squared and interaction terms on household economic vulnerability. The results show that the interaction terms of the inclusive financial development index and its squared term with the education level of the sample household head, the level of household income and the individual education level of the social capital of the household all pass the significance level test. And all impact directions are consistent with the previous benchmark regression, except for the introduction of the type of household business. This indicates that the inverted U-shaped effect of financial inclusion development on rural households' economic vulnerability is consistent with the previous paper when differences in household characteristics are taken into account. In addition, the significance of the interaction term shows that financial inclusion development has a stronger effect on improving the economic vulnerability of households operating in agriculture, low income level, and with less abundant social capital. Thus, Hypothesis 3 is confirmed.

6 Conclusion and policy implications

6.1 Conclusion

Financial inclusion is increasingly discussed as an essential means of improving household vulnerability and environmental quality and achieving sustainable development, especially in China. This paper estimates the impact of inclusive financial development on rural household vulnerability using survey data from 2,093 rural households in Xunyi County and Yangling District, Shaanxi Province, China, for 2018 and 2019. We apply 2SLS and IVQR models to address endogeneity due to bidirectional causality and unobservable factors.

We find that financial inclusion has an inverted "U"-shaped non-linear impact on the vulnerability of rural households; the vulnerability of rural households can only be effectively reduced when the development of financial inclusion reaches a certain level. Specifically, the development of inclusive finance is primarily concerned with improving household vulnerability caused by inter and intra-village inequalities. After endogeneity and robustness tests, the results are consistent. In addition, the effect of financial inclusion on mitigating household vulnerability is more pronounced among agricultural households, low-income households and households with insufficient social capital. Further analysis suggests that increasing the ease and depth of access is key to improving the vulnerability of rural households. We, therefore, conclude that the comfort and depth of access to financial inclusion can be essential and practical measures to improve vulnerability and environmental quality in rural areas. Based on this, policymakers can consider increasing innovation in inclusive financial products and services in poor rural regions and directing more financial resources to rural areas through fiscal and monetary policy instruments. By doing so, we can realise the benefits of financial inclusion in improving household vulnerability while simultaneously improving environmental quality and achieving sustainable development goals.

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6.2 Policy implications

The results of our study have important practical and policy implications. Firstly, government departments should use monetary and fiscal policy tools to guide rural financial institutions to increase lending to rural areas, thereby providing financial capital to improve vulnerability and environmental quality.

Secondly, rural financial institutions can use digital and intelligent empowerment tools to achieve innovation in differentiated and personalized products and services for household groups with different endowment characteristics. Through the above improvements, it is possible to increase the coverage and depth of use of credit in rural areas, lower the barriers to entry to the rural financial market and help rural households improve their resilience to development across the board.

In addition, the research in this paper confirms that the development of inclusive finance can reduce household vulnerability, improve environmental quality and achieve sustainable development. However, farmers' environmental awareness and behavior play a crucial role in environmental quality, so it is essential to promote institutional innovation to achieve sustainable development by regulating and guiding farmers' environmental behavior.

However, this study also has some significant limitations. Firstly, this paper mainly examines the impact of financial inclusion development on environmental quality and sustainability from the perspective of household economic vulnerability, lacking analysis and examination of the mechanisms of action. Future research could use econometric methods such as structural equation modelling or mediating effect modelling to reveal the complex relationships between the relevant factors. Second, many variables measure environmental quality and sustainability, and this paper only measures them in terms of vulnerability. Future research will analyse the relationship between finance and environmental quality and sustainability in a multidimensional manner when data are available. In addition, this paper only uses data from Shaanxi Province, China. Considering that the financial environment and economic behaviour of different regions and households may differ significantly, this leads to various changes in farmers' environmental behavior. So the heterogeneous effects of inclusive financial development on different types of households in different regions need to be further studied.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

Conceptualization, YW and LW; Methodology,YW and LW; Software, YW and LW; Validation, YW, LW, and BL; Formal analysis, YW; Investigation, YW and LW; Resources, YW and LW; Data curation, YW; Writing—original draft preparation, YW, SF, and LW; Writing—review and editing, LW, BL and JL; Funding acquisition, JL. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tracing carbon emissions convergence along the way to participate in global value chains: A spatial econometric approach for emerging market countries

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The proliferation of trade agreements has offered a viable framework for the economic and trade integration of many nations. Additionally, the growth and expansion of global value chains has increased prospects for knowledge and technological spillovers as well as the potential for production method convergence. This might have possible effects on the environment in both developed and developing nations. The objective of this study is to determine whether participation in global value chains (GVCs) can serve as a foundation for the convergence of carbon emission across nations. Spatial panel data econometrics is used to examine data from 22 emerging economies between 1995 and 2019 in order to provide an answer. The findings support the global value chains-based conditional carbon convergence of the countries and show a spatial link between global value chains participation and CO_2 growth. Furthermore, results show that increasing global value chains participation with other variables; both directly and indirectly, *via* spillover effects, encourages closing the CO_2 emission gap across nations. The findings show that global value chains may be able to increase how successful carbon efficiency initiatives are. Therefore, when developing environmental legislation, many aspects of global value chains participation and their advantages should be considered.

KEYWORDS

global value chains (GVCs), carbon emisions, environmental patents, spatial econometric approach, emerging market countries

1 Introduction

Over the past 3 decades, the effects of trade on the environment and greenhouse gas emissions have been among the contentious issues in the economic literature. Further the global climate change is significantly impacted by industrial upgrading and international production cooperation. It is still challenging to evaluate whether trade is beneficial for the environment or not (Frankel and Rose, 2005). Trade agreements and integrations have increased the likelihood of the eventual convergence of environmental indicators of different countries, aside from how trade affects the environment (Baghdadi et al., 2013; Apergis and Payne, 2020; Shahzad et al., 2022). The advent of global value chains (GVCs) participation and the globalization of production, among other significant changes in trade and globalization processes, have increased chances for trade integration and the expansion of knowledge and technology transfers across nations.

The structure and organization of international trade have been fundamentally altered by the recent rise in the number of trade agreements and the emergence of GVCs participation, which account for more than half of all trade globally. This has sparked the growth of global production networks and massive bilateral trade, especially for intermediate goods. Additionally, this new wave of globalization has altered the relationships between developed and emerging nations while redefining the frontiers of knowledge, production structure, and comparative advantages among various nations (Baldwin, 2017). GVCs have facilitated the transfer of technological innovations, skills, and knowledge from developed countries to developing countries, allowing developing countries to enter international markets and reap potential benefits without having to develop ancillary industries and revert to the local production of all necessary inputs (Rodrik, 2018; Jangam and Rath, 2020).

The objective of this study is to determine if GVCs may serve as a foundation for national carbon convergence and how growing GVC membership impacts carbon convergence development. The answers to these queries can help to partially fill the literature gap that how this new kind of trade can close the carbon emission gap between nations and how increasing GVC participation can be a tactic to slow down environmental deterioration. The solutions might even show that this novel kind of trade is both harmful and advantageous to the environment. Thomakos and Alexopoulos (2016) accept that carbon emission is the Environmental Performance Index's greatest explanatory variable. These are, in other words, two sides of the same coin. As a result, carbon emission changes can accurately gauge a nation's environmental performance. If we can determine how GVCs participation influence countries' carbon emission changes, we can then generalize it to environmental performance, take advantage of GVC capabilities to create environmental protection policies and regulations, and come to multilateral climate change mitigation agreements. Expanding GVCs participation may thereby increase prospects for the participating nations' environmental performance to converge. However, in order to validate or disprove such assumptions, empirical studies are necessary, which is why this study was conducted.

This article is unique in its novelty to identify and assess the impact of GVCs participation with other variables in CO_2 convergence among EMCs and its selection of the countries is based on the Morgan Stanley Capital International Emerging Market Index criteria (the MSCI Index). The interdependence of trade in intermediate goods and foreign direct investment (FDI) has increased as a result of GVCs participation, and the MSCI index asserts that its designation of countries as emerging markets is due to the long-captivated imagination of investors that continued to reshape the global investment and trade landscape to embrace these countries over the past 20 years. (see Appendix 1)

The remainder of this essay is structured as follows: The history of the research and theoretical underpinnings are reviewed in Sections 2 and 3. In Section 4, the data analysis approach is introduced, and Section 5 presents the findings. Section 6 then discusses the findings and presents the conclusions.

2 Literature review

To the best of our knowledge, no research has been done on how GVCs participation can help countries with their environmental performance. However, some research has focused on how trade and foreign direct investment (FDI) affect how energy intensity and carbon emissions are converged. The global value chain (GVC) not only bridges trade gaps among partner nations but also produces multifaceted reciprocal benefits through technological spillover and industrial technology consolidation. The GVC participation produces credible environmental outcomes, and two perspectives exist among researchers on the relationship between the GVC and the environment (Wu et al., 2020). One of the perspectives looked at the "pollution heaven" hypothesis and the possible damage to the environment in developing countries because of trade with developed countries. According to the second perspective, GVC participation positively affects the environment through technology development and transfer, as well as has positive spillover effects on the economy.

As GVCs participation proliferate around the world, developing economies have been able to adopt technical innovations, skills, and knowledge from developed countries (Jangam and Rath, 2020), without the need to establish auxiliary industries, restore production of all necessary inputs, or develop the national value chain (Rodrik, 2018). In this way, developing countries are able to achieve static and dynamic efficiency, which can increase their value addition and per

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capita income (Kummritz, 2016). The increase in per capita income and the adoption of new technologies as a result of GVC participation encourage economies to reduce environmental threats. Participation in GVCs promotes long-term environmentally friendly economic growth by increasing the per capita real gross domestic product (GDP). However, as more countries participate in GVCs, CO_2 emissions rise, but they fall as per capita GDP rises (Wang et al., 2022). Moreover, modern environmental-friendly technologies' adoption and prevention of environmental deterioration are also associated with GVC participation (Jiang and Liu, 2015; Song and Wang, 2017), so the countries participating in GVC can combat climate change through increasing their carbon efficiency and bridging the carbon intensity gap among countries (Kazem et al., 2021). Therefore, in favor of GVC, it might not be awkward to say that the GVC can help countries protect the environment through the development and spillover of environmentally friendly technologies (Lovely and Popp, 2011; Nemati et al., 2019). GVC promotes the diffusion of technology, the sharing of technical information, and reduces carbon emissions (Javorcik, 2002; De Marchi et al., 2018). Landsperger and Spieth (2011) describe how the embedment in GVC augments the low-carbon innovation competences of global corporations. This low-carbon innovation competency tends to increase long-term competitive advantages as well as low-carbon technology adoption (Uyarra et al., 2016; Sears, 2017; Shahzad et al., 2022). Zhang et al. (2020) reported that a 1% rise in the degree of China's participation in GVC reduced carbon intensity by 11.7%. Similarly, Liu and Zhao (2021) described the negative relationship of GVC participation with carbon emission intensity based on the analysis of 42 countries. Countries that are part of the GVC must meet international standards for good quality products and environmental certification. This has led them to cut back on their carbon emissions in order to stay in the GVC (Wu et al., 2020).

On the other hand, some scholars have argued that participation in GVC contributes to environmental degradation (Liu et al., 2018), while the expanding participation in GVC enhances the use of energy and CO_2 emissions. They are concerned that the great differences in technology and industrial structure of the countries or regions also contributed to the major difference in GVC participation as well as the impact on carbon intensity (Wang et al., 2021a; Zhang et al., 2021). For example, developing countries have the advantages of capital and technology over developing countries, thereby occupying the upstream of the GVC of various industries. Therefore, these countries and regions are responsible for the links of high value addition, such as product development, product design in GVC, and low carbon intensity (Wang et al., 2020; Jin et al., 2022). On the other hand, the developing countries stay at GVC's downstream end, which prevents them from getting potential benefits from GVC due to their labor and energy-intensive processing and assembling parts (Sun et al., 2019). Similarly, the developing countries at the tail and in the middle of GVC have to make hard efforts to expand their production of GVC while simultaneously addressing the resultant environmental degradation. They also have to focus on the core environmental interests of energy preservation, sustainable growth, and extreme cuts in CO_2 (Shahzad et al., 2021). Therefore, GVC results in the transmission of hazardous particles and polluting agents from developed economies to underdeveloped economies. The extensive differences in GVC participation and carbon intensity between developed and developing countries generate environmental threats in developing countries, such as a rise in CO_2 intensity. The GVC's participation degree of developed countries significantly reduces carbon intensity, while that of developing countries actually increases their carbon intensity. In addition, industries in developing countries with low CO_2 intensity see a big rise in CO_2 intensity (Jin et al., 2022). Elhedji and Merrick (2012) and Bonilla et al. (2015) found that country participation in GVC is linked to the long distances between the nodes in GVC distribution networks. This long distance increases the chance that logistics and transportation will emit grater amount of CO_2. Poulsen et al. (2018) say that the logistics and transportation used to move different GVCs from one country to another country or one region to another region is one of the main sources of air pollution. This is why it is important for GVCs to have environmentally friendly logistics and transportation.

3 Theoretical background

In the economic literature, there are various points of view on how trade and the environment are related. Some address the pollution haven hypothesis (PHH) and the possible deterioration of the environment in developing nations through trade with industrialized countries, while others argue the beneficial environmental implications of trade through technological development and transfer and spillover effects. However, some contend that trade harms the environment because it expands economic activities that are already environmentally destructive and motivates polluting nations to engage in more extensive high-polluting activities (Copeland and Taylor, 2013; Weber et al., 2021). The creation and spread of environmentally benign technologies can therefore assist safeguard the environment (Lovely and Popp, 2011; Nemati et al., 2019), but commerce can also contribute to environmental degradation, as stated by the pollution haven hypothesis and the factor endowment theory (Antweiler et al., 2001; Shen, 2008; Cherniwchan et al., 2017).

International trade has long been practiced by nations (e.g., developing countries import parts and technology to produce and supply goods to the domestic market). In contrast to more traditional trade approaches, the new type of commerce has boosted the use of international production networks by the countries, strengthened knowledge information transfers (Taglioni et al., 2016), and facilitated more knowledge spillovers. Because the outsourcer delivers the required knowledge and technology to the input producer firm to ensure the inputs are produced efficiently and in accordance with its production standards, information can move more readily throughout the supply chain (Piermartini and Rubnová, 2014).

GVCs can improve both static efficiency (i.e., altering current processes and capacities) and dynamic efficiency by reallocating scarce resources to the most lucrative activities (i.e., creating new processes and capacities). The growth of GVCs is anticipated to increase per capita income, investment, productivity, and green domestic value-added output, as demonstrated by Kummritz (2016) and Hu et al. (2022). Participation in global supply networks and production networks can also result in learning-by-doing advantages, economies of scale, technological advancements and spillovers, and even speed up the industrialization process and the growth of the nation's service sector (Bernhardt and Pollak, 2016; Kummritz, 2016; Taglioni et al., 2016; Gunnella et al., 2019; Raei et al., 2019; Pigato et al., 2020). Markusen (1984) also makes the case that the expansion of multinational corporations (a crucial component of GVCs) is connected to the development in global technical efficiency because there is evidence of technology spillovers as a result of their operations (Keller, 2010).

Expanding membership in GVCs has benefits and repercussions that go beyond economic expansion. For instance, the development of GVCs and the exchange of intermediate inputs can both enhance South-South trade (Hanson, 2012). Additionally, growing GVCs may result in changes to international trade policy as well as intensified shock transmission, synchronized global business cycles, and changes to specialization patterns (Wang et al., 2017). The impact of GVCs on national environmental performance and their part in environmental phenomena, however, have not received much attention in the pertinent literature.

The integration of GVCs with technical advancement and transfer will raise the countries' income level, perhaps facilitating the convergence of some of their economic indicators (Rodrik, 2018), if GVCs promote the convergence of production processes as envisaged (Ignatenko et al., 2019). According to the evidence now available, trade, trade integration, and regional cooperation aid in the convergence of a country's energy efficiency, energy intensity, and environmental performance (Wang et al., 2015; Han et al., 2018; Qi et al., 2019). To eliminate trade frictions and enhance trade flows, trade integration necessitates adjustments to the nations' current standards and regulations (including environmental standards and regulations) (Nicoletti et al., 2003) (Holzinger et al. 2008) also demonstrated how strengthening international ties will cause the environmental policies of the participating nations to converge. The development of low-CI production technologies, information transfer, and sustainable management are all aided by the growth of international firms (López et al., 2019).

On the other hand, the new kind of commerce may not only assist nations in convergent growth by balancing the costs of production factors, but also enhance national environmental performance by boosting technology spillovers and environmentally friendly knowledge. The spillover, diffusion, and transfer of cleaner technology to nations with lower energy and environmental efficiency, particularly developing nations, will advance technical advancement and enhance environmental performance (Gerlagh and Kuik, 2014; Huang et al., 2020; Jaffe et al., 2002; LeSage and Fischer, 2008; Wan et al., 2015). According to Jiang et al. (2019), countries with trading partners who are technologically advanced release less carbon because they are permitted to share the resources they create with their main trading partners. Furthermore, the exchange of information among businesses in GVCs might hasten the development of eco-friendly technologies. The growth of GVCs may potentially result in more economical and cost-effective technologies for the production and use of clean, efficient energy sources.

Following the theoretical framework discussed above, we can claim that expanding GVCs may offer more possibilities for the convergence of the environmental performances of the selected countries. However, empirical testing will be necessary to support or reject such hypotheses, and this study's main goal is to accomplish that objective.

4 Data and methodology

4.1 Spatial autocorrelation

In order to determine whether there is a GVC-based association between nations' rates of CO_2 expansion, this study looks at that first. It then looks into how increased GVC participation affects the countries' CO_2 convergence. Participation in GVCs may have spillover consequences that are also discussed. Therefore, it is essential to use proper statistical approaches that can predict spillover effects as well as take into account the spatial dimensions of the statistical data. The next subsections will go over the geographic statistics that were employed in this study's data analysis for the variables described in Table 1.

$$MI = \frac{\frac{1}{W}\Sigma_i \Sigma_{i \neq j} W_{ij}\left(C_i - \bar{C}\right).\left(C_j - \bar{C}\right)}{\frac{1}{n}\Sigma_i\left(C_i - \bar{C}\right)^2}, \quad (1)$$

where MI stands for Moran's I, C_i for carbon emission growth, and i and j for one through n. (i.e., the number of sample countries). Additionally, W_{ij} is a spatial weight matrix that displays how close i and j are to one another (this was determined using GVCs in this study; and its definition is given in Section 4.3), and W is the sum of these matrices. Positive and negative values of Moran's MI denote positive and negative spatial autocorrelation, respectively, much like positive and negative values of Pearson's correlation coefficient. The former assesses the interaction between i and j based on their difference, not based on standard deviation (Gangodagamage et al., 2008; Kalkhan, 2011, chap. 3), which is one distinction between Geary's GC and Moran's MI:

$$GC = \frac{(n-1)\Sigma_i \Sigma_j W_{ij}\left(C_i - C_j\right)^2}{2\Sigma_i \Sigma_j W_{ij}\left(C_i - \bar{C}\right)^2}. \quad (2)$$

In this equation, GC stands for Geary's GC, which has a value between 0 and 2. Positive autocorrelation is associated with values less than 1, whereas negative autocorrelation is associated with values higher than 1. By assuming spatial randomness under the normal distribution, one can investigate the importance of Geary's GC and Moran's MI.

We created the inverse GVCs-based distance spatial matrix for each nation before performing the spatial autocorrelation assessment. Given that the study area contains major emerging economies and that most of the nations are close to one another and have a compact spatial distribution, the inverse GVCs-based distance spatial matrix was deemed adequate for the calculation:

$$W = \left\{ \begin{matrix} \frac{1}{dij} & d_{ij} > d \\ 0 & d_{ij} < d \end{matrix} \right\}. \quad (3)$$

Based on the above discussed analysis of the GVCs-augmented carbon convergence, dij is the distance between the spatial subjects in country i and country j, and W is the inverse distance weight matrix; yearly results are available for each country from the author(s) and can be provided on special request.

4.2 Spatial panel data regression

The potential correlation of CO_2 emission growth between countries i and j as a result of their GVC-based relationship is measured by spatial autocorrelation. To determine whether there is a CO_2 growth convergence and how growing GVCs impact this convergence, spatial panel data regression is used. Additionally, it points out potential GVC spillover effects. These models are particularly crucial because, according to Anselin (2003a), certain phenomena—such as neighborhood effects and the race to the bottom—are examples of interactions between economic agents, necessitating the employment of interactive and spatial models to study them.

The Spatial Lag Model (SLM), the Spatial Error Model (SEM), and the Spatial Durbin Model (SDM) are the three types of regularly used spatial econometric panel data models (LeSage and Pace, 2009). The SLM model presupposes that the spatial mean weight of the dependent variables of a section's neighbors as well as external regressors have an impact on the observed value of the dependent variable in that section. Following is the way to present the regression:

(1) Spatial lag model (SAR)

$$y_{it} = \alpha \sum_{J=1}^{N} W_{ij} y_{jt} + \beta x_{it} + \mu_i + \lambda_i + \varepsilon_{it}. \quad (4)$$

(2) Spatial error model

$$\begin{aligned} y_{it} &= \beta x_{it} + u_{tt} + \mu_i + \lambda_i \\ u_{tt} &= \alpha \sum_{J=1}^{N} W_{ij} u_{jt} + \varepsilon_{it} \end{aligned} \quad (5)$$

(3) Spatial Durbin Model

$$y_{it} = \alpha \sum_{J=1}^{N} W_{ij} y_{jt} + \beta x_{it} + \gamma \sum_{J=1}^{N} W_{ij} x_{jt} + \mu_i + \lambda_i + \varepsilon_{it}. \quad (6)$$

In this equation, y_{it} is the dependent variable for section i at time t, $\sum_{J=1}^{N} W_{ij} y_{jt}$ stands for endogenous interactive effects of the dependent variables y_{it} and y_{jt} in neighbouring sections (N sections), and α is the spatial autoregression coefficient, which quantifies the magnitude of the simultaneous spatial correlation between a section and its neighbors. Additionally, x_{it} is the matrix of independent explanatory variables, β is the vector is a representation of the effects of these independent variables, also known as the exogenous regressor, and the μ_i represents the fixed effects, which are the effects unique to each section. Additionally, it is expected that the ε_{it} error component has an i. i.d, zero mean, and constant variance. Additionally, W_{ij} is the spatial weights matrix, which may be determined using both geographical and economic indicators.

The interactional effects between the error components are also taken into consideration by SEM. When independent factors that were not included in the regression have an impact on the interacting effects of the sections, this model is more significant. The following is a presentation of this model:

$$y_{it} = x_{it}\beta + \mu_{it} + \lambda \sum_{J=1}^{N} W_{ij} \delta_{jt} + \varepsilon_{it}. \quad (7)$$

The spatial autocorrelation coefficient, which measures the impact of neighboring sections' residuals on each section's residual, is denoted by λ. In this case, δ_{jt} is a component of the spatial autocorrelation error.

The SDM model combines the SEM and SLM models. The vector of spatial autocorrelation coefficients of the explanatory variables in this model is denoted by the symbol γ. The model becomes a SAR if $\gamma = 0$ and $\alpha \neq 0$; otherwise, it becomes a SEM if $\gamma = -\beta\alpha$. As a result, the SDM model, which also contains the SEM and SLM models, is a testable broad specification (LeSage and Pace, 2009).

TABLE 1 Variables description and data sources.

Variables	Definition	Sources
CO_2 emission	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring. CO_2 emission is measured as CO_2 emissions (metric tons per capita)	World Bank, World Development Indicators (2019)
GDP per Capita	It measures a nation's gross domestic product per capita	World Bank, World Development Indicators (2019)
	The variable is adjusted for purchasing power parity and is expressed in 1000s of US dollars. It has been used as a proxy to measure the level of economic development by many studies	
GVCs Participation Index	Country's participation in global value chains is defined as the sum of both forward participation and backward participation divided by gross exports	Eora-MRIO Global Value Chain (GVC) database (2018)
Energy Consumption	Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport. Energy consumption is measured as kg of oil equivalent per capita	World Bank, World Development Indicators (2019)
Environmental Patents	Total Patents Registered for Technology Innovation Related to Environment	OECD, (2019) OECD DATABASE

Due to spatial correlation in spatial regressions, the coefficients of the explanatory variables do not adequately reflect the final effects of the variables. Additionally, due of geographical links and real-time feedback, the model includes both direct and indirect (spillover) impacts. As a result, estimating the direct and indirect impacts is required rather than interpreting point estimate coefficients. According to SDM, we have:

$$\sum (Y_t) = (I_n - \alpha \mathrm{W})^{-1}\mu + (I_n - \alpha \mathrm{W})^{-1}\left(X_t\beta + \mathrm{W}X_t\gamma\right). \tag{8}$$

It has the spatial multiplier matrix $(I_n - \alpha \mathrm{Q})^{-1}$. Where I_n represents the unit n×n matrix. If

$$(I_n - \alpha W)^{-1} = I_n + \alpha W + \alpha^2 W^2 + \alpha^3 W^3 + \ldots \tag{9}$$

With respect to the explanatory variables k in other sections, the matrix of partial derivatives of the dependent variable (GVCs) in various parts at any time t is equal to:

$$\left[\frac{\partial E(Y)}{\partial x_{1k}} \cdots \frac{\partial E(Y)}{\partial x_{Nk}}\right] = \begin{bmatrix} \frac{\partial E(y_t)}{\partial x_{1k}} & \cdots & \frac{\partial E(y_1)}{\partial x_{Nk}} \\ \vdots & \ddots & \vdots \\ \frac{\partial E(y_N)}{\partial x_{1k}} & \cdots & \frac{\partial E(y_N)}{\partial x_{Nk}} \end{bmatrix} = (I_n - \alpha \mathrm{W})^{-1} \begin{bmatrix} \beta_k & W_{12}\gamma_k & \ldots W_{1n}\gamma_k \\ W_{21}\gamma_k & \beta_k & \ldots W_{2n}\gamma_k \\ \vdots & \vdots & \ddots \quad \vdots \\ W_{n1}\gamma_k & W_{n2}\gamma_k & \ldots \beta_k \end{bmatrix} \tag{10}$$

It can also be expressed more succinctly as follows:

$$\frac{\partial E(Y)}{\partial x_k} = (I_n - \alpha \mathrm{W})^{-1} W \tag{11}$$

As a result, the mean direct effects of a unit of change in the explanatory variables x_k on Y (GVCs) can be calculated by averaging the diagonal elements of Matrix W, the mean total effects can be calculated by averaging the sum of the rows or columns of Matrix W, and the mean indirect effects (spillover effects) are equal to the difference between the direct effects and the total effects. In writing, we have:

Total effect:

$$\frac{1}{n}\sum_{ij}^{n} \frac{\partial E(y_i)}{\partial x_{kj}} = \frac{1}{n} I_n^{'} \left[(I_n - \alpha \mathrm{W})^{-1} W \right] I_n \tag{12}$$

Direct effect:

$$\frac{1}{n}\sum_{i}^{n} \frac{\partial E(y_i)}{\partial x_i} = \frac{1}{n} trace\left[(I_n - \alpha \mathrm{W})^{-1} I_n \beta \right] \tag{13}$$

Indirect effect:

$$\left(\frac{1}{n} I_n^{'} \left[(I_n - \alpha \mathrm{W})^{-1} W \right] I_n\right) \frac{1}{n} trace\left[(I_n - \alpha \mathrm{W})^{-1} I_n \beta \right] \tag{14}$$

As a result, by calculating the subsequent SDM, the following effects of GVC involvement and their contribution to carbon convergence can be assessed:

$$\ln \frac{CO2_{it}}{CO2_{it\_-1}} = \beta lnCO2_{it\_-1} + \alpha \sum_{j=1}^{N} W_{ij} \ln \frac{CO2_{jt}}{CO2_{jt\_-1}} + \theta lnGVC_{it-1} + \pi lnx_{it-1} + \sum_{j=1}^{N} W_{ij} lnGVC_{it-1}\delta + \mu_i + \varepsilon_{it} \tag{15}$$

In which, respectively, CO_2 emission, GVC, and x stand for carbon intensity, GVC participation, and a vector of other variables describing CO_2, such as real per capita income (Y), technological innovations and energy consumption (EC) [other components are the same as Eq. 3]. In order to interpret the regression findings, the direct, indirect (spillover), and total effects are computed for each variable after the aforementioned regression is estimated using the maximum likelihood (ML) approach. Additionally, conditional convergence must be established if the total effect of $\ln CO2_{it\_-1}$ is indicated by B, and B must range from 0 to

TABLE 2 Descriptive statistics.

Variables	Obs	Mean	SD	Min	Max
CO_2	550	1.372203	0.9326519	0.2672569	3.930924
GDPPC	550	26.58435	1.11439	24.24049	30.29102
EC	550	7.386645	0.9008326	5.846219	10.00426
PAT	550	6.799878	2.375945	0	14.14756
GVC	550	4.306081	0.9152172	3.60853	9.48273

Note: All variables are in log form.

TABLE 3 Spatial autocorrelation of CO_2 growth.

	MI	E (MI)	SD (MI)	Z	*p*-value
Moran's I	0.04	-0.02	0.03	2.68	0.00
Geary's c	GC	E(GC)	SD(GC)	Z	p- value
	0.53	1.00	0.16	-2.43	0.05

*2-tail test, null hypothesis: There is spatial randomization.

-1 and be statistically significant. Using ln (B+1), the conditional convergence rate can also be determined (LeSage and Fischer, 2008).

4.3 Data

A set of chosen countries' economic and GVC-based trade data was used to elaborate our objectives. Carbon emissions (CO_2) are taken as CO_2 emissions (metric tons per capita). Real per capita income (i.e., GDP at constant 2010 USD divided by population), energy consumption as per kilogram equivalent of crude oil, environmental patents is used as environmental friendly technology and innovation measure and its data is taken as number of applications for patens within given time period, are also added to the model as regressors. The World Bank's WDI Database was used to extract data for 22 EMC countries for the years 1995–2019. Further the selection of the countries is based on the Morgan Stanly Index (MSI) and detail of this index is given in Appendix A.

The GVC participation index, which was developed by Koopman et al. (2010), is the most well-known indicator of a nation's participation in GVCs. This index is produced by adding the foreign value added in domestic export (backward participation) and the domestic value added in foreign export (forward participation). The range of the value is 0–100. The more the value, the greater the country's participation in GVC, i.e., the prevalence of trade in intermediate goods in overall trade and the fragmentation of the production process According to this method, country i's level of GVC participation at time t is equivalent to:

$$GVCs_{it} + \frac{DVX_{it} + FVA_{it}}{Gross\,Exports_{it}} \tag{16}$$

In which DVX_{it}, FVA_{it}, and Gross Exports, in that order, stand for, respectively, domestic value added and foreign value added, and the entire amount of a nation's exports within a given period. No matter how big or small a country's economy is, this indicator measures the level of GVC participation. The UNCTAD-EORA Database was used to extract the information on FVA, DVX, and Gross Exports. Further, Levin et al. (2002) unit root test has been performed and found that all variables follow an I (0) process (see Table 4). Variables description and their data sources are given below:

5 Results

We experimentally examined the economic data of 22 emerging market countries from 1995 to 2019 based on the 4 selected indicators. Table 2 displays descriptive data for the variables considered in this analysis.

In order to assess the GVC-based spatial autocorrelation of the country's carbon emission growth, Moran's MI and Geary's GC are first estimated. The variable whose spatial autocorrelation is evaluated is the carbon emission increase of each nation from 1995 to 2019, and the weight matrix is created using Eq. 3. The study's primary goal is to find out whether the carbon emission growth of the nations with bilateral value-added trade correlates with one another. The findings of Moran's MI and Geary's GC are shown in Table 3. Both coefficients showed the GVC-based positive spatial at a 95% confidence level, the null hypothesis of spatial randomness indicated by autocorrelation of CO_2 growth is rejected in both tests.

As a result, inside GVCs, nations with comparable carbon emission growth rates are nearer to one another. To put it another way, there is a correlation between nations with higher bilateral value-added trade. This is known as spatial clustering in spatial econometrics. This space in this study is GVC-based trade. Biasing is a term used to describe what happens when spatial factors are not taken into account when estimating a regression.

In order to assess the carbon emission growth convergence of the countries, spatial data panel regressions are performed after the spatial autocorrelation is estimated. Table 4 displays the panel unit root results and Table 5 reports SAR, SEM, and SDM outcomes. To compare their coefficients with the spatial regressions, the results of fixed-effects (FE) panel regression are also presented.

No matter whether the trend is included or excluded, Table 4 shows the results of the unit root tests for all the selected series at

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TABLE 4 Pesaran's (2007) unit root test results.

Variables	Level		Order of integration
	Intercept	Intercept and trend	
Pesaran CISP			
$lnCO_2$	−4.13*	−5.14*	I (0)
lnY	−3.66**	−4.47***	I (0)
lnEC	−4.11*	−5.36*	I (0)
lnPAT	−4.18*	−3.97*	I (0)
lnGVC	−3.89***	−4.22**	I (0)
Pesaran CADF			
$lnCO_2$	−4.73**	−4.10***	I (0)
lnY	−4.04*	−4.66*	I (0)
lnEC	−3.27*	−3.12*	I (0)
lnPAT	−4.38***	−4.37**	I (0)
lnGVC	−4.42*	−4.55*	I (0)

***$p < 0.01$, **$p < 0.05$, *$p < 0.10$ are significance levels.

various levels. According to the findings, every variable is stationary at the first difference, or at I (0). Given that all the series are stationary at level or I (0), we can use spatial panel data approach to attain the results of GVCs-augmented CO_2 convergence model for emerging market countries.

Before analyzing the findings, specification and model selection tests are evaluated. All regressions' significance is validated by the Wald test's findings. According to the Hausman specification test, FE regression is preferable to random effects. The model selection experiments further demonstrate that SDM is favored over SAR and SEM. Further the results suggested that SDM is the best regression model. The α coefficient in regression shows a positive spatial autocorrelation, and the coefficient in SEM demonstrates the same conclusion. Since spatial regression has spillover effects, taking into account Moran's MI and Geary's GC, the direct, indirect, and total effects in Table 6 should be determined by using Eqs. 12–15 in order to interpret the coefficients of the variables. Convergence rates in all of the regressions vary from 0 to 1, and conditional convergence is not disregarded. Additionally, as compared to FE regressions, the spatial regression has a far larger explanatory power and a lower conditional convergence rate. This may be a result of the regression models' exclusion of spillover effects. It follows that the rate of carbon emission conditional convergence is accelerated by GVC-based spatial spillover effects. As a result, the relevant driving factors have a spatial impact on the CO_2 convergence in emerging market countries, further showing that if the spatial effect is ignored, it may result in incorrect empirical results. The regression coefficients of independent variables in the spatial panel model are unable to capture the marginal effects of dependent variable. To examine the effect of each variable on the CO_2 convergence, the spatial impacts should be split into direct effects, indirect effects, and total effects using partial differential equations.

According to the direct negative effect of $\ln(CO2)_{t-1}$ that a strong carbon emission growth is followed by a period of low carbon emission growth. Additionally, its detrimental indirect impacts suggest that GVC-based spillover effects exist on adjacent nations. As a result, the overall impacts of $\ln(CO2)_{t-1}$ show the countries' carbon emission conditional convergence. These effects are also seen, either directly or indirectly, on real per capita income (Y). As a result, as countries' real per capita income rises (which is correlated with economic growth and wellbeing), so do their carbon emission rates as well as the spillover effects on nearby GVC nations. The findings indicate that the technological innovations (PAT) direct, indirect and overall effects are all noticeably favorable. The findings also suggest that higher patents are followed by higher carbon emission growth, irrespective of per capita income. The patents coefficient, however, is not statistically significant in situations where per capita income is under control, making it impossible for it to be a factor in carbon emission growth and its conditional convergence.

The outcomes show that the participation in GVCs has considerable direct, indirect, and overall effects on carbon emission convergence. As a result, it may be said that increasing GVC participation can aid in slowing carbon emission expansion and promoting its conditional

TABLE 5 Estimated spatial panel data regressions.

Dependent Variable: Ln ($\frac{CO2_t}{CO2_{t-1}}$)		**Model**															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Method		**FE**	**SAR**	**SEM**	**SDM**	**FE**	**SAR**	**SEM**	**SDM**	**FE**	**SAR**	**SEM**	**SDM**	**FE**	**SAR**	**SEM**	**SDM**
Independent variable																	
Main	**ln $(CO2)_{t-1}$**	**−0.21**[a] (0.01)	**−0.23**[a] (0.01)	**−0.20**[a] (0.01)	**−0.20**[a] (0.01)	**−0.21**[a] (0.01)	**−0.22**[a] (0.01)	**−0.23**[a] (0.01)	**−0.22**[a] (0.01)	**−0.13**[a] (0.01)	**−0.16**[a] (0.01)	**−0.20**[a] (0.01)	**−0.20**[a] (0.01)	**−0.19**[a] (0.01)	**−0.23**[a] (0.01)	**−0.24**[a] (0.01)	**−0.25**[a] (0.01)
	ln $(Y)_{t-1}$	**−0.05**[a] (0.01)	**−0.07**[a] (0.01)	**−0.05**[a] (0.01)	**−0.04**[a] (0.01)												
	ln $(EC)_{t-1}$					**−0.05**[a] (0.01)	**−0.04**[a] (0.01)	**−0.05**[a] (0.01)	**−0.03**[a] (0.01)								
	ln $(PAT)_{t-1}$									0.05 (0.03)	0.05 (0.03)	**0.18**[a] (0.05)	**0.23**[a] (0.05)				
	ln $(GVC)_{t-1}$													**−0.06**[b] (0.03)	**−0.05**[b] (0.03)	-0.07 (0.05)	**−0.04**[b] (0.03)
Spatial	**α**		**0.44**[a] (0.05)		**0.38**[a] (0.05)		**0.50**[a] (0.06)		**0.51**[a] (0.04)		**0.40**[a] (0.05)		**0.32**[a] (0.05)		**0.47**[a] (0.06)		
	λ			**0.48**[a] (0.06)				**0.45**[a] (0.06)				**0.54**[a] (0.06)				**0.58**[a] (0.06)	
	Wln $(GVC)_{t-1}$				**0.14**[a] (0.05)				**0.22**[a] (0.06)				**0.25**[a] (0.06)				**0.18**[a] (0.06)
Wald test statistic		66 (0.00)	243 (0.00)	255 (0.00)	232 (0.00)	88 (0.00)	211 (0.00)	232 (0.00)	268 (0.00)	53 (0.00)	228 (0.00)	241 (0.00)	223 (0.00)	30 (0.00)	233 (0.00)	282 (0.00)	263 (0.00)
Pseudo R^2		0.18	0.33	0.35	0.30	0.19	0.31	0.27	0.28	0.18	0.31	0.15	0.39	0.19	0.32	0.32	0.39
	Hausman test	chi2 (3) = 153.1		Prob > chi2 = 0.00		chi2 (4) = 139.4		Prob > chi2 = 0.00		chi2 (4) = 163.2		Prob > chi2 = 0.00		chi2 (4) = 141.4		Prob > chi2 = 0.00	
Model Selection Tests	SAR vs. SDM	chi2 (1) = 21.8		Prob > chi2 = 0.00		chi2 (1) = 33.6		Prob > chi2 = 0.00		chi2 (1) = 33.7		Prob > chi2 = 0.00		chi2 (1) = 19.6		Prob > chi2 = 0.00	
	SEM vs. SDM	chi2 (1) = 15.6		Prob > chi2 = 0.00		chi2 (1) = 24.7		Prob > chi2 = 0.00		chi2 (1) = 13.6		Prob > chi2 = 0.00		chi2 (1) = 44.7		Prob > chi2 = 0.00	

*a: *p*-value <0.01, b: *p*-value <0.05, c: *p*-value <0.1 and Standard Errors are reported in the brackets.

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TABLE 6 Estimated direct effects, indirect effects, and total effects; and the conditional convergence of CO_2 emission.

Dependent variable: ln $\left(\frac{CO2_t}{CO2_{t-1}}\right)$		**Model**															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Method		**FE**	**SAR**	**SEM**	**SDM**	**FE**	**SAR**	**SEM**	**SDM**	**FE**	**SAR**	**SEM**	**SDM**	**FE**	**SAR**	**SEM**	**SDM**
Independent variable																	
Direct Effect	**ln $(CO2)_{t-1}$**	**-0.21^{a}** (0.01)	**-0.20^{a}** (0.01)	**-0.23^{a}** (0.01)	**-0.20^{a}** (0.01)	**-0.21^{a}** (0.01)	**-0.22^{a}** (0.01)	**-0.21^{a}** (0.01)	**-0.20^{a}** (0.01)	**-0.18^{a}** (0.01)	**-0.18^{a}** (0.01)	**-0.22^{a}** (0.01)	**-0.23^{a}** (0.01)	**-0.20^{a}** (0.01)	**-0.21^{a}** (0.01)	**-0.26^{a}** (0.01)	**-0.24^{a}** (0.01)
	ln $(Y)_{t-1}$	**-0.7^{a}** (0.01)	**-0.7^{a}** (0.01)	**-0.6^{b}** (0.01)	**-0.6^{b}** (0.01)									**-0.11^{a}** (0.01)	**-011^{a}** (0.01)	**-0.6^{a}** (0.01)	**-0.7^{a}** (0.01)
	ln $(EC)_{t-1}$					**-0.6^{b}** (0.01)	**-0.6^{b}** (0.01)	-0.2 (0.01)	-0.2 (0.01)					-0.3 (0.01)	-0.3 (0.01)	-0.006 (0.01)	-0.002 (0.01)
	ln $(PAT)_{t-1}$									-0.2 (0.01)	-0.2 (0.01)	**0.21^{a}** (0.01)	**0.16^{a}** (0.01)	**0.18^{a}** (0.01)	**0.18^{a}** (0.01)	**0.27^{a}** (0.01)	**0.22^{a}** (0.01)
	ln $(GVC)_{t-1}$	**-0.04^{c}** (0.02)	**-0.04^{c}** (0.01)	-0.006 (0.01)	-0.03 (0.01)	**-0.6^{a}** (0.01)	**-0.04^{c}** (0.01)	-0.007 (0.02)	-0.03 (0.01)	**-0.7^{a}** (0.02)	**-0.7^{a}** (0.01)	-0.03 (0.02)	-0.03 (0.01)	**-0.06^{b}** (0.02)	**-0.5^{a}** (0.01)	-0.18 (0.02)	**-0.04^{c}** (0.01)
Indirect Effect	**ln $(CO2)_{t-1}$**		**-0.15^{a}** (0.04)		**-0.14^{a}** (0.05)		**-0.15^{a}** (0.04)		**-0.15^{a}** (0.04)		**-0.13^{a}** (0.04)		**-0.12^{a}** (0.04)		**-0.14^{a}** (0.05)		**-0.14^{a}** (0.05)
	ln $(Y)_{t-1}$		**-0.06^{b}** (0.01)		**-0.04^{c}** (0.12)			**0.52^{a}** (0.06)							**-0.06^{b}** (0.02)		**-0.05^{b}** (0.01)
	ln $(EC)_{t-1}$						**-0.06^{b}** (0.01)		0.03 (0.01)						-0.008 (0.01)		-0.03 (0.01)
	ln $(PAT)_{t-1}$										0.006 (0.03)		**-0.6^{b}** (0.04)		**-0.13^{b}** (0.05)		**-0.13^{b}** (0.05)
	ln $(GVC)_{t-1}$		-0.03 (0.01)		**-0.29^{a}** (0.08)		**-0.04^{b}** (0.01)		**-0.4^{b}** (0.07)		**-0.3^{b}** (0.01)		-0.48^{a} (0.09)		-0.04^{c} (0.01)		-0.29^{a} (0.09)
Total Effect	ln $(CO2)_{t-1}$	-0.21^{a} (0.01)	-039^{a} (0.05)	-0.21^{a} (0.01)	-037^{a} (0.05)	-0.22^{a} (0.01)	-0.34^{a} (0.05)	-0.21^{a} (0.01)	-0.34^{a} (0.05)	-0.16^{a} (0.01)	-0.34^{a} (0.05)	-0.22^{a} (0.01)	-0.35^{a} (0.04)	-0.24^{a} (0.01)	-0.34^{a} (0.06)	-0.24^{a} (0.01)	8 (0.06)
	ln $(Y)_{t-1}$	-0.7^{a} (0.01)	-0.10^{a} (0.03)	-0.4^{b} (0.01)	-0.6^{b} (0.02)									-0.11^{a} (0.01)	-0.18^{a} (0.04)	-0.06^{a} (0.01)	-0.11^{a} (0.03)
	ln $(EC)_{t-1}$					-0.06^{a} (0.01)	-0.06^{b} (0.03)	0.02 (0.01)	0.03 (0.01)					-0.03 (0.02)	-0.02 (0.03)	-0.009 (0.02)	-0.005 (0.03)
	ln $(PAT)_{t-1}$									0.03 (0.04)	0.02 (0.07)	-0.22^{a} (0.05)	-026^{a} (0.08)	-0.18^{a} (0.05)	-0.28^{a} (0.09)	-0.27^{a} (0.05)	-0.36^{a} (0.09)
	ln $(GVC)_{t-1}$	-0.4^{c} (0.02)	-0.4^{c} (0.03)	0.06 (0.01)	-0.34^{a} (0.08)	-0.5^{a} (0.01)	-0.8^{a} (0.03)	-0.008 (0.02)	-0.35^{a} (0.07)	-0.5^{a} (0.02)	-0.11^{a} (0.03)	-0.02 (0.02)	-0.52^{a} (0.09)	-0.06^{b} (0.02)	-0.07^{c} (0.03)	-0.018 (0.02)	-0.41^{a} (0.09)
Convergence rate		0.22	0.43	0.24	0.43	0.22	0.43	0.26	0.44	0.18	0.43	0.26	0.41	0.23	0.46	0/28	0.49

*a: p-value <0.01, b: p-value <0.05, c: p-value <0.1 and Standard Errors are reported in the brackets.

convergence in emerging market countries (EMCs). When the indirect (spillover) impacts of bilateral value-added trade or GVC-based trade are taken into account, this link becomes more pronounced. This implies that raising and extending involvement in GVCs will slow the carbon emission growth in emerging market countries (EMCs). In actuality, increasing participation in GVCs has an impact on both the countries' and their trading partners' carbon emission growth. Expanding engagement in GVCs can result in technological advancements, learning-by-doing, knowledge spillovers, economic growth, and improved wellbeing in countries under analysis. By enhancing technological innovations, promoting the use of cleaner energy sources, and raising demand for environmental protection laws and regulations, these possible advancements can improve carbon emission convergence.

6 Conclusion and policy recommendations

Participation in global value chains (GVCs) offer a new mode of value-added trade that enables nations to take advantage of their comparative advantages in production tasks after transforming the structure and processes of production in emerging nations. The environmental advantages and downsides of GVC-based trade are among the contentious issues in the economic literature, in addition to the economic advantages of increased participation in GVCs. In order to ascertain whether value-added based on GVCs could help in the CO_2 convergence of the emerging markets (EMCs); this study examined the role of GVCs in the environmental performance of countries. The study assessed how participation in GVCs affected the countries' CO_2 growth. Modeling and analysis of the data gathered from 22 nations between 1995 and 2019 used spatial econometric approach. Empirical analysis revealed a link between CO_2 growth and countries with greater bilateral GVC-based trade. Additionally, the conditional convergence of EMCs in terms of CO_2 growth was confirmed when taking into account the GVC-based trade between nations. The findings also show that increasing country participation in GVCs has an impact on the CO_2 growth of its trading partners in addition to reducing country CO_2 growth through spillover effects. Therefore, emerging market countries' environmental performance will generally increase if it has GVC-based trading partners who have superior environmental performance.

Additionally, it may be said that this new kind of value-added trade offers different opportunities for EMCs, in particular, to get access to their trading partners' knowledge and technology for economic and environmental goals. Accordingly, the promotion of production processes and their adaptation to the global production structure can be encouraged by the need to adapt local production processes to global processes within GVCs framework. Further, emerging market countries' environmental policies are more likely to align in the setting of GVC-based trade. Multinational corporations, for instance, that outsource their production processes within GVCs, are likely to pass technology and knowledge to their partners in partner nations as well as demand that they abide by a number of rules and regulations, including environmental norms. Additionally, GVCs could be a platform for enhancing national environmental performance or at least lowering CO_2 growth and bringing environmental convergence together in emerging market countries.

The findings indicate that environmental policies and actions to prevent climate change should take GVC capacities into account in countries under analysis. The findings demonstrated that, notwithstanding the presence of carbon leakage in trade, increasing country's participation in GVCs increased the carbon efficiency, which is an essential (albeit insufficient) step in attaining environmental goals in EMCs. A good way for EMCs to improve their environmental performance is to increase value-added trade with nations that are moving toward greater carbon efficiency.

By examining the CO_2 correlation and conditional convergence of emerging market countries within the setting of GVC-based trade, this study adds to the empirical literature on the relationship between value-added trade and the environment. Another aspect of GVCs trade is that value added trade enables to upgrade regional environmentally sustainable technological infrastructure, but due to industrial isomorphism and a lack of unified dispatch, there is fierce competition among regions, which increases value added trade in one region at the expense of other regions' participation opportunities. At the same time, the upgrading of industrial structure caused by the increase of value added trade in other regions has led to the outflow of relevant natural resource factors in other regions, thus affecting their environmental sustainability. To better understand the role of GVCs in the convergence of the emerging market countries' environmental performance; more research must be done on the topic, particularly on the production of greenhouse gases and pollutants like CO_2. Future studies should individually evaluate various GVC environmental impact mechanisms in order to better understand the scope, makeup, and technological consequences of expanding GVCs on environmental performance among emerging market countries.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://www.scopus.com/authid/detail.uri?authorId = 57208878403.

Author contributions

Conceptualization, MN, YC and ZW; methodology, MN; software, SH; validation, MN; formal analysis, YC; investigation, YC; resources, YC; data collection, YC; MN writing—original draft preparation, MN; writing—review and editing, YC an MN. The contributions of both newly added authors is the analysis of data and results interpretation of the study All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A: List of emerging market countries (EMCs) under analysis

Brazil	Mexico
Chile	Morocco
China	Peru
Colombia	Philippines
Czech Republic	Poland
Egypt	Qatar
Greece	Russia
Hungary	Thailand
India	Turkey
Indonesia	South Africa
South Korea	Malaysia

According to MSCI of 2019, there are 26 emerging market countries (EMCs), but our analysis is focusing on 22 countries due to the non-availability of data of *Argentina*, Taiwan, Saudi Arabia, and UAE.

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Green HRM and employee efficiency: The mediating role of employee motivation in emerging small businesses

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The modern organizational structure expects that the human resource department should train the employees effectively to sustain the environment. This study aims to understand the role of green human resource management (GHRM) in the efficiency of organizations' employees in small and medium enterprises (SMEs) of Pakistan. The questionnaire was developed on a five-point Likert scale to collect primary data from the target respondents, and the target respondents of this study were the employees of SMEs in Pakistan. The results of the study indicate that GHRM is an important tool to motivate and train employees, which ultimately increases the efficiency of employees. This study demonstrates that the SMEs in Pakistan need to consider the critical role of GHRM as it is emerging and provides reliable resources as per the organization's requirements for better performance. This study provides recommendation for future studies to consider and contribute to the literature and to the practices of SMEs in Pakistan for the efficiency of their employees.

KEYWORDS

green human resource management, employee motivation, employee training, team work, employee efficiency, sustainable goals

Introduction

Today's world places considerable emphasis on employee productivity since it enhances a company's competitive position in the market. However, it is also critical to remember that staff productivity is strongly tied to the effective teamwork and training that the organization's human resource department has a responsibility to ensure in the organization. Significantly, Aboramadan (2020) demonstrated that most organizations failed to get the best human resource team that would work following the guidelines of corporate social responsibility (CSR) to enhance the experience of the employees and their performance in the organization. In this way, if the management of the organization is motivated and concerned about developing the efficiency of the employees, then the HRM department of the organization must work according to the pattern of GHRM (Ehmann et al., 2022; Kim & Kim, 2016). In the conclusion of Renwick, Redman, and Maguire (2008), GHRM is emerging and it can change the traditional working of the HR department in any organization for a sustainable environment. In Saudi Arabia, GHRM is practiced in different large and small organizations that are environmentally friendly (Faisal & Naushad, 2020), and SMEs are also benefiting from GHRM. To lower the cost of HR functions, the first step is to put more resources into technology, which can track information about employees and their health status (Naz, Jamshed, Nisar, & Nasir, 2021). In contrast, GHRM is not adopted in backward countries due to less training of the employees, and it is a challenge for the environment (Renwick et al., 2008).

GHRM refers to the human resource department's working following the guidelines and policies for the sustainability of the environment and an eco-friendly working system (Bhatti et al., 2019). In modern times, it is expected that the human resource department is required to train the employees effectively to sustain the environment (Aboramadan, 2020). Employee motivation refers to the employees' motivation to perform well and get training for effective teamwork to provide better output in the organization (Mafini & Dlodlo, 2014). The training of the employees is critical in the organization as it is important to ensure the employees are working in the best way by utilizing minimum resources to provide maximum output (Hina, Selvam, & Lowry, 2019). Similarly, Shareef and Atan (2018) demonstrated that teamwork is critical in the organization because it is carried out to achieve the single direction-oriented goal of the organization. Importantly, the efficiency of the employees is needed in the organization because it is a source of competitive advantage. The SMEs in Pakistan working with the GHRM concept are contributing to environmental sustainability because fewer resources are used (Muisyo, Su, Hashmi, Ho, & Julius, 2022). Modern technology has changed the traditional trends of work, and it has enhanced the improvement in the HR department (Faisal & Naushad, 2020). Meanwhile, the SMEs without green innovation acceptance concepts are still working on traditional patterns, and less use of technology is adopted in these organizations (I. Ahmad, Ullah, & Khan, 2021; Rubel, Kee, & Rimi, 2021).

In the existing literature, the influence of GHRM was checked in the context of employees' behavior (Ababneh, 2021). Similarly, the influence of GHRM on green service behavior has been studied in the literature (Rubel et al., 2021). Moreover, GHRM is also discussed in the context of green competitive advantage (Muisyo, Qin, Ho, & Julius, 2021). The relationship between GHRM and green creativity in the hotel industry was also discussed in the earlier literature (Muisyo et al., 2022). However, no existing study in the literature has discussed the role of GHRM for employees' training and employees' teamwork (I. Ahmad et al., 2021; Naz et al., 2021). There is a significant gap in the literature related to the role of GHRM for employees' training and employees' motivation. Meanwhile, many earlier studies presented the importance of GHRM for employees' best working and low turnover intentions (Renwick et al., 2008; Dumont, Shen, & Deng, 2017; Naz et al., 2021). Based on the grounds of existing research in the literature, the objective of this study is to determine to what extent GHRM plays a critical role in the efficiency of the organization's employees in the SMEs of Pakistan. It is important to understand that no particular study was conducted to check the relationship between GHRM to develop teamwork effectiveness and employee training for the efficiency of the employees in the SMEs of Pakistan. In the earlier research, the role of employee motivation in the GHRM model was not taken into account (Ababneh, 2021). Furthermore, the relationship between employees' motivation and employees' working performance was not discussed widely in the existing studies in the context of GHRM. Therefore, this study's theoretical framework is designed to provide detailed information related to the relationship between GHRM, employee motivation, employee training, teamwork, and employee efficiency. This study has been developed to contribute to the literature because no study was conducted to check the relationship of GHRM in the management of the employees of the SMEs in Pakistan.

No doubt, modern organizations have a goal of working in a sustainable way (Wheeler et al., 2012; Krause, Feiock, & Hawkins, 2016; Shahzad & Fareed, 2022), and many studies have been carried out to safeguard the environment from different perspectives (Shahzad, Bouri, Mokni, & Ajmi, 2021; Shahzad et al., 2022), but the role of GHRM is still underexplored. According to the recommendations of Faisal and Naushad (2020), the influence of GHRM should be tested on the motivation of employees. Therefore, this study is significant because it is designed to provide substantial theoretical and practical implications in the relationship of GHRM in the SMEs in Pakistan. Importantly, no earlier study was conducted to discuss this critical issue in the performance of SMEs in Pakistan that are facing challenges related to HRM and CSR. Indeed, every organization needs to improve the working efficiency of the employees in the organization with the help of the HR department because the modern market demands to work sustainably, as it helps to develop a competitive advantage in the target market. In this way, this study would provide significant implications that would be useful for managing the SMEs of Pakistan. Importantly, this study also provides recommendation for future studies to consider contributing to the literature and to the practices of businesses effectively.

Literature review

The role of HRM is critical to consider because it provides the guidelines and strategy for the employees to work effectively for the organization's benefit (Mafini & Dlodlo, 2014). GHRM can influence the employees to work in an environmentally friendly way (Aboramadan, 2020). Notably, the concept of GHRM has emerged in the last decade because organizations are expected to perform well in eco-friendly and environment-friendly systems effectively. In this regard, it is the responsibility of the HRM to provide adequate training to the employees to ensure that they are working on the guidelines and procedures of the organization (Barreiro & Treglown, 2020). Accordingly, Ullah et al. (2022) stated that HRM is responsible for motivating the employees to work in an environment-friendly situation to make sure that the organization is working on the vision and mission that are developed for the values of CSR and green innovation and green performance. GHRM has a significant impact on the performance of employees (A. J. Khan, Ansari, Ahmed, & Malik, 2022; Muisyo et al., 2021). On one hand, organizations in America are working in an eco-friendly system to improve employee experience by providing the opportunity to work by getting effective training to ensure that all organizations are working on the CSR guidelines that are important to the principal for the sustainability of the organization in the target market (Mafini & Dlodlo, 2014; Empowerment, 2018). Employees with appropriate working ideas are influenced by GHRM because they welcome the new innovation to have changes in their learning (Muisyo et al., 2021). In the organizations that are working on the CSR guidelines, these organizations are improving the standard of the working environment because it is important to consider the employees' training and proper output from the employees of the organization (Rita, Payangan, Rante, Tuhumena, & Erari, 2018; Hermawan, Thamrin, & Susilo, 2020). However, on the other hand, the organizations that badly failed to integrate the CSR values into HRM are not developing effectively (Rita et al., 2018; Hermawan et al., 2020). In modern times, GHRM work has become a responsibility of businesses (Naz et al., 2021). CSR provides the guideline for different organizations to work in an eco-friendly system to ensure that the working of the organization is based on the values and concerns of CSR to influence the employees of the organization for better performance (Singh & Misra, 2021; Ya, Tungsawad, Laohanan, & Pun-ngam, 2022). GHRM has changed the traditional practices of working for the employees of large corporations (Dumont et al., 2017; A. J. Khan, Shah, Bashir, & Iqbal, 2021).

The concept of the GHRM helps for an effective strategy in an organization's HR department to develop a strategy useful for the proper training and motivation of the employee to make sure that the employees are working following the organization's guidelines (Aboramadan, 2020). GHRM has changed organizational working in Saudi Arabia because the employees are collaborating and cooperating with management to establish these practices in organizations (Faisal & Naushad, 2020). Importantly, it is the management's responsibility to train the HRM employees in an effective manner and provide them with the latest knowledge and equipment to operate the department in a reliable manner (Luu, 2018; Deng, Cherian, Ahmad, Scholz, & Samad, 2022; López-Cabarcos, Vázquez-Rodríguez, & Quiñoá-Piñeiro, 2022). The employees are more protected in the organization with GHRM because all of their information and health statuses are monitored properly (Muisyo et al., 2022). It is also noted that if the employees are motivated and are working on the guidelines provided by HRM, then a more accurate performance of the employees would be expected because they are always working hard to perform well in the organization (Bezner, Franklin, Lloyd, & Crixell, 2020), but they want the appropriate resources to get the work done in an effective way to provide maximum benefit to the organization as per the guidelines of CSR (Farid et al., 2019; Cheema, Afsar, & Javed, 2020). In the advanced and developed countries, organizations are bound to adopt GHRM practices because these organizations are contributing to the economic sustainability of the country (Rubel et al., 2021). Therefore, organizations need to consider the vital role of GHRM as it is emerging and provides reliable resources following the organization's requirements for better performance.

In a business organization, the critical responsibility of the HR department is to train the employees effectively to get work done efficiently and effectively (Bhatti et al., 2019). In this regard, Aboramadan (2020) highlighted that the business organization's responsibility is to consider the critical role of CSR because by the guidelines of CSR, it would be more effective for the organization to work for the sustainability of the environment and resources (Y. J. Kim & Kim, 2016). Notably, organizations that work on the guidelines of CSR (Ehmann et al., 2022) influence their employees to be productive and perform well in the organization following the strategies of the organization that are developed with the help of the mission of the organization (Cheema et al., 2020; Farid et al., 2019; W. G. Kim, McGinley, Choi, & Agmapisarn, 2020). Significantly, the responsibility of the HRM is to train the employees and motivate them to work in teams because when an employee works in a team, they will perform well. Indeed, in many organizations, the employees come from different cultures and with different values, and they have a different set of beliefs (Leung, Sun, Zhang, & Ding, 2021). The responsibility of the HRM is to motivate the employees effectively and get better output from them. The employees are from different cultures and values, and in this way, the HRM is required to consider its responsibility reasonably and ensure that teamwork is as per the values of the organization (S. Ahmad, Shafique, & Jamal, 2020). The influence of GHRM practices on employees has changed the traditional work of employees because now they are more

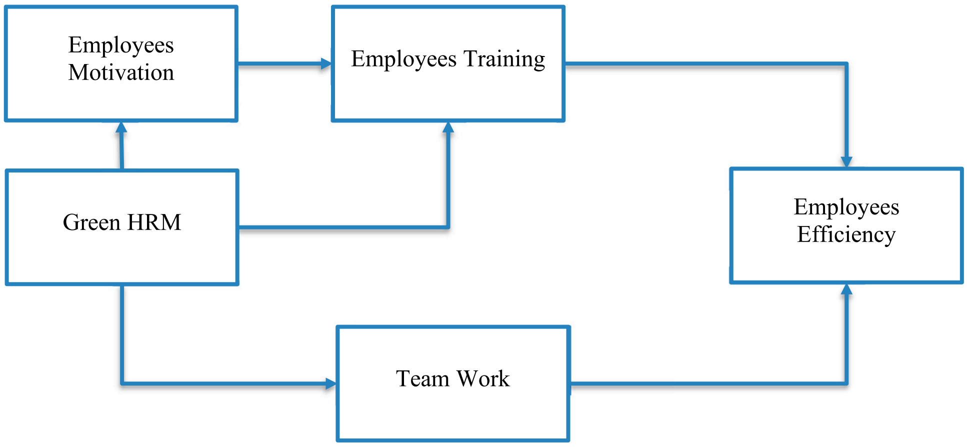

FIGURE 1
Theoretical framework.

motivated to perform in a better way (Aboramadan, 2020). The HR department with sustainable practices is more innovative at work for the employees (Aboramadan, 2020). The GHRM practices enhance the teamwork tasks because the employees from different departments collaborate with each other based on their data (Dumont et al., 2017).

In this way, the employees of the organization should be motivated to work in a team, and they should be rewarded for it because when the employees of the organization follow the ethical guidelines and standards, they not deviate from the vision and mission of the organization (Leung et al., 2021). Still, they would try their best to develop strategies regarding the values of the organization to develop their capacities in teamwork. Indeed, it is noted that when the organization provides an effective teamwork environment to the employees, the performance of the organization is increased, and it is for the competitive advantage of the organization (Mafini & Dlodlo, 2014). In the modern world, resources are available to every organization because of globalism as the trade barriers are reduced, and organizations have success in getting every kind of raw material and supporting material for the functionality of the organization (S. Ahmad et al., 2020). Importantly, in the modern world, the critical role of employees is important because the organization is developing a competitive advantage in the target market based on teamwork and the best employees. After all, the best employers are visionaries (Han, Wang, & Yan, 2019), and they provide appropriate services to the organization effectively by motivating the other employees to perform well (López-Cabarcos et al., 2022). However, on the other hand, in the organization that badly failed to perform well in the target market it is considered that teamwork was absent from the employee relationship of that organization. Teamwork in any organization enhances the capability of the employees because they are directly working to improve the projected task (Muisyo et al., 2022). The sustainability of the employee's performance is also based on teamwork (Ehmann et al., 2022). The employees with low performance in the team also learn within the team because his/her performance is improved by working with other employees with expertise (Rubel et al., 2021).

Moreover, it is also noted that the effective teamwork and the working of the organization on the guidelines of the top management helps the management to develop CSR and perform well in the target market (Leila & Laily, 2011; Arraya, Pellissier, & Preto, 2015; Oshodin & Omoregbe, 2021). In this way, organizations are required to consider the vital role of teamwork and provide a sustainable environment for teamwork to ensure that the employees collaborate to perform well and get rewards (Yulianto, Sisko, & Hendriana, 2021). In the future, the success of the organizations in the target market will be based on effective teamwork (N. A. Khan, Khan, & Gul, 2019) because teamwork provides target-oriented guidelines in which the employees are working accordingly to achieve success collectively (Kotzé & Smit, 2008). In Figure 1, the theoretical framework of the study is presented. The employees who are motivated by the HR managers performing more in the organization (Ababneh, 2021). The lack of motivation by the HR manager can reduce the performance of employees in the organization (I. Ahmad et al., 2021). The relationship between HR managers and employees should be friendly, and employees should be motivated to reduce the intention of turnover (Rubel et al., 2021). The best organizations facilitate their employees to better work in teams. HR manager motivation has significant impact on employees' performance (Aboramadan, 2020; Muisyo et al., 2021).

H1: There is a relationship between green human resource management and employees' motivation.

H2: There is a relationship between employee motivation and training.

H3: There is a relationship between green human resource management and employees' training.

H4: There is a relationship between employee training and an employee's efficiency.

H5: There is a relationship between green human resource management and teamwork.

H6: There is a relationship between teamwork and employees' efficiency.

H7: There is a mediating role of employees' motivation in the relationship between green human resource management and employee training.

Methodology

Research in the area of social sciences provides the primary data for data analysis. In this regard, this study uses the quantitative approach to collect the primary data from the targeted population on a five-point Likert scale. It is because a survey-based questionnaire for data collection is appropriate to collect data in less time with very little cost. In this study, the respondents were the employees of SMEs in Pakistan. All of the scales were adapted from previous studies. The questionnaire for this study integrated these items in the second section because the first section of the study was dedicated to a brief introduction of the study to the respondent. GHRM was measured using four items adopted from the study of Dumont et al. (2017): employee motivation by Rizwan, Tariq, Hassan, and Sultan (2014), the employee training scale adopted from the research of Chiaburu and Tekleab (2005), teamwork measured using four items from the work of Kakemam et al. (2021), and the employee efficiency scale from the study of Rizwan et al. (2014). The reliability and validity of these items were tested before being integrated into the questionnaire. Cronbach's alpha for all scale items was greater than 0.70, and composite reliability (CR) was above 0.70. Moreover, the data were collected from the target respondents by providing them with a questionnaire with an introduction to the study. The random sampling technique is used in this research because it is an appropriate way to collect data. The employees of different SMEs were contacted randomly, and the information was collected on the questionnaire. In this way, 500 questionnaires were distributed to the respondents to collect quantitative data with an expected response rate of 50%. However, after analyzing the questionnaires, 215 questionnaires were considered appropriate to analyze the data with the help of the software SmartPLS version 3. The respondents were praised for delivering thoughtful answers to the survey.

Study findings

Convergent validity

The convergent validity was checked using the PLS algorithm. As can be seen in Figure 1, no value is less than the minimum threshold of 0.60, and CR is above 0.70, as

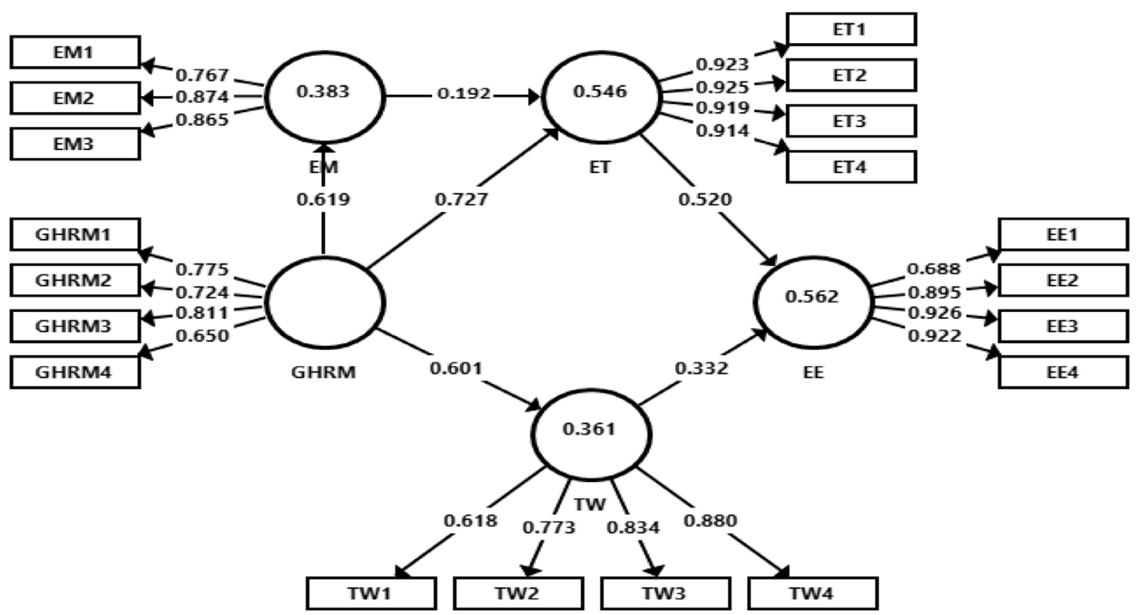

FIGURE 2
PLS measurement model.

TABLE 1 Factor loadings, Cronbach's alpha, CR, and AVE.

Variable	Item	Description	Factor loadings	Cronbach's alpha	CR	AVE
Employee efficiency	EE 1	My performance is better than that of my colleagues with similar qualifications	0.688	0.853	0.906	0.714
	EE 2	I am satisfied with my performance because it is mostly good	0.895			
	EE 3	My performance is better than that of employees with similar qualifications in other banks	0.926			
	EE 4	My performance is better than that of employees with similar qualifications in my banks	0.922			
Employee motivation	EM 1	I feel a sense of personal satisfaction when I do this job well	0.767	0.783	0.875	0.700
	EM 2	My opinion of myself goes down when I do the job badly	0.874			
	EM 3	I like to look back at a day's work with a sense of a job well done	0.865			
Employee training	ET 1	My company provides me with the opportunity to improve my skills	0.923	0.940	0.957	0.847
	ET 2	There are a lot of chances to learn new things in this company	0.925			
	ET 3	My company frequently arranges training programs for the employees	0.919			
	ET 4	Doing a job in this company will benefit me	0.914			
Green HRM	GHRM 1	My company sets green goals for its employees	0.775	0.728	0.830	0.551
	GHRM 2	My company provides employees with green training to promote green values	0.724			
	GHRM 3	My company provides employees with green training to develop employees' knowledge and skills required for green management	0.811			
	GHRM 4	My company considers employees' workplace green behavior in performance appraisals	0.650			
Teamwork	TW 1	My manager provides opportunities to discuss the unit's performance after an event	0.618	0.782	0.861	0.612
	TW 2	My manager ensures that adequate resources are available	0.773			
	TW 3	Employees monitor each other's performance	0.834			
	TW 4	Employees exchange relevant information as it becomes available	0.880			

GHRM, green human resource management; EM, employee motivation; ET, employee training; TW, teamwork, and EE, employee efficiency.

recommended by Fornell and Larcker (1981). Moreover, the values of average variance extracted (AVE) were checked, and all of the values were not less than 0.50, as recommended by Hair, Money, Samouel, and Page (2007). As a result, all of the values demonstrated the significant reliability and validity of the scale items used for this study (see Figure 2 and Table 1).

Discriminant validity

The discriminant validity test is to identify the distinction between the scale items used in the questionnaire to measure any variable. Along with reliability and validity, discriminant validity is also tested to check the scale difference in measuring the impact of the same variables. In this regard, PLS algorithm computations were used in this portion of the study to examine the discriminant validity of the scale items. However, the most reliable and recommended method by Gold, Malhotra, and Segars (2001), HTMT, was adopted to check the discriminant validity (Table 2). The results revealed that all of the values of discriminant validity were not greater than 0.90, as recommended by Gold et al. (2001). Therefore, the study has apparent discriminant validity for the scale items used to collect the data.

TABLE 2 Discriminant validity (HTMT).

	EE	EM	ET	GHRM	TW
EE					
EM	0.673				
ET	0.775	0.547			
GHRM	0.736	0.817	0.857		
TW	0.739	0.841	0.610	0.773	

GHRM, green human resource management; EM, employee motivation; ET, employee training; TW, teamwork; and EE, employee efficiency.

The PLS-SEM results

Hypothesis testing for this research was carried out using the PLS bootstrapping test. For a significant hypothesis, the recommended t-value is 1.96 and the p-value is 0.05 (Hair Jr,

TABLE 3 Result of direct and indirect relationships.

Hypotheses	Relationship	Beta	STDEV	T-value	*p*-value	Remarks
H1. GHRM- > EM	Direct	0.619	0.047	13.286	0.000	Significant
H2. EM- > ET	Direct	0.192	0.049	3.918	0.000	Significant
H3. GHRM- > ET	Direct	0.727	0.044	16.478	0.000	Significant
H4. ET- > EE	Direct	0.520	0.054	9.560	0.000	Significant
H5. GHRM- > TW	Direct	0.601	0.043	13.856	0.000	Significant
H6. TW- > EE	Direct	0.332	0.058	5.707	0.000	Significant
H7. GHRM- > EM- > ET	Mediation	0.098	0.027	3.629	0.000	Significant

GHRM, green human resource management; EM, employee motivation; ET, employee training; TW, teamwork; and EE, employee efficiency.

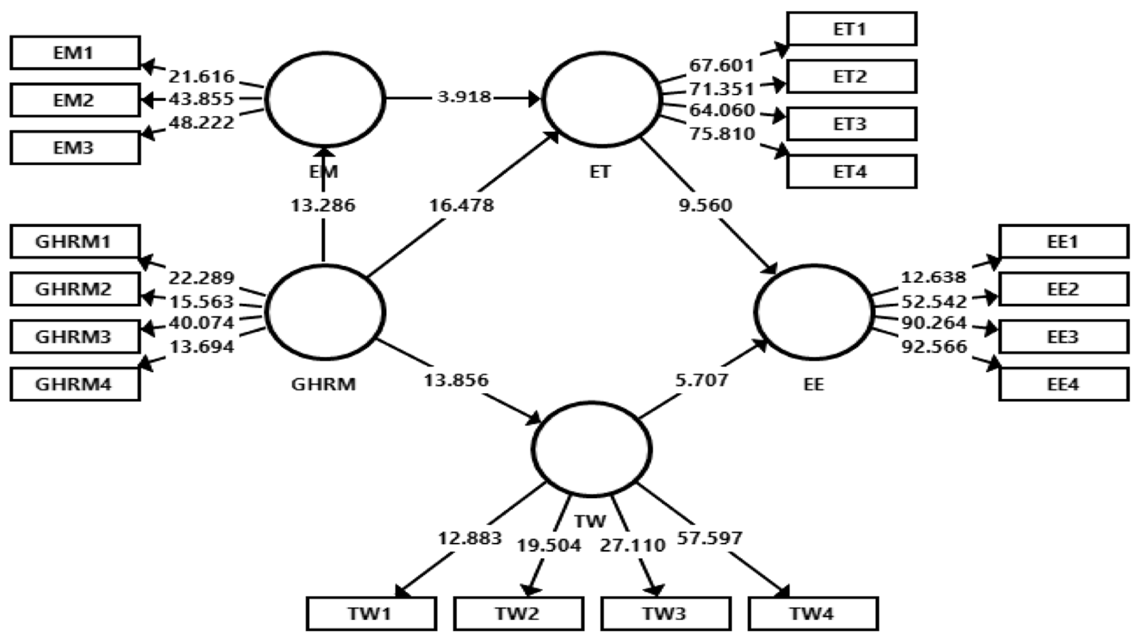

FIGURE 3
PLS structural model.

Sarstedt, Hopkins, & Kuppelwieser, 2014). First, the significance of H1 was investigated, and the results suggest that H1 is significant and that GHRM positively affects EM (β= 0.619, t = 13.286, p = 0.000). Second, the significance of H2 was determined, and the findings suggest that H2 is significant and that EM has a substantial effect on ET (β= 0.192, t = 3.918, and p = 0.000). Third, the relevance of H3 was determined. The findings show that H3 is important and that GHRM has a substantial effect on ET (β= 0.727, t = 16.478, and p = 0.000). Fourth, H4 was tested for significance. The results indicate that H4 is significant and that ET significantly influences EE (β= 0.520, t = 9.560, and p = 0.000). Fifth, the result of H5 indicates that GHRM has a positive significance on TW (β= 0.601, t = 13.856, and p = 0.000). Sixth, the result of H6 shows that TW significantly affects EE (β= 0.332, t = 5.707, and p = 0.000). In the end, the result of H7 indicates that EM significantly mediates the relationship between GHRM and ET (β= 0.098, t = 3.629, and p = 0.000), as indicated in Figure 3 and Table 3.

Discussion and conclusion

The findings of H1 show that GHRM and employees' motivation are significantly correlated. The findings of this study are similar to the findings of earlier studies (Aboramadan, 2020; Muisyo et al., 2021). As per the results of H2, the relationship between employees' motivation and employee training is significant. Moreover, the results of this hypothesis are in line with earlier studies (Dumont et al., 2017; Naz et al., 2021). Similarly, the results of H3 indicate the significant relationship between GHRM and employee training. The results of this hypothesis are also identical to the results of earlier studies (Faisal & Naushad, 2020; Muisyo et al., 2022). The results show a significant relationship between employee training and efficiency, and H4 is significant. Importantly, these findings validate the results of existing research in the body of literature (Ababneh, 2021; I. Ahmad et al., 2021; Renwick et al., 2008). The H5 results indicate the significant relationship between GHRM and teamwork. Meanwhile, these findings are lined up with the findings of previous research (Muisyo et al., 2021; Muisyo et al., 2022). Furthermore, the results of H6 show the significant relationship between teamwork and employee efficiency. Also, these findings are similar to the findings of previous work in the body of knowledge (Naz et al., 2021). Lastly, the results of H7 demonstrate the significant mediating role of employees' motivation in the relationship between GHRM and employee training. This relationship was not tested in the earlier research. Therefore, it is a contribution to the body of knowledge that extends the framework of employees' training. It is reasonable to understand that there is a critical tool for GHRM in Pakistan's small and medium enterprises. To develop the employees' efficiency, the management's responsibility is to work effectively by adopting new tools and mechanisms for improving the efficiency of the employees for better development (Jang, Kim, & Lee, 2022; M. M. S. Khan & Ghayas, 2022; Qi, Liu, Wei, & Hu, 2019).

In the advanced and developed countries, small and medium enterprises are working based on the guidelines of CSR because by working on the guidelines of CSR (Farid et al., 2019; Latif et al., 2022; Murad, Bhatti, Bakar, Ahmad, & Khan, 2022), it would be more reasonable for the businesses to grow in the target market and develop a competitive advantage (Favero, 2020). However, in modern times, customers are mature and willing to become loyal to the business, that is, working for the eco-friendly system (Avotra, Chenyun, Yongmin, Lijuan, & Nawaz, 2021). The function of the corporate organization's management is to develop an effective GHRM for the training and the teamwork environment of the employees to provide a reasonable way to work in the target market (Phina, Arinze, Chidi, & Chukwuma, 2018). Significantly, in the study by Kakemam et al. (2021), the organizations that work on the guidelines of CSR are the top-ranked organizations in developed countries. Therefore, the responsibility of the critical stakeholder related to the business is to ensure that the small and medium enterprises in Pakistan are working in an eco-friendly system with the development and proper implementation of GHRM to develop a competitive advantage by improving the efficiency of the employees.

Research implications

This study provides essential theoretical and practical implications that are worthy of consideration when examining the relationship between GHRM and employee productivity in Pakistan's small and medium enterprises. On one hand, this study emphasizes that corporate management needs to consider the role of GHRM since it helps to increase employee performance and efficiency. Indeed, there was a gap in the literature as no earlier study was conducted to determine the relationship of GHRM as an emerging variable with the efficiency of the employees in the SMEs in Pakistan. In this way, this study highlights that the organization's vision and mission should be according to the values of CSR and GHRM. Significantly, this study highlights the relationship between a different variable that is integrated into the study's theoretical framework, and this relationship would be effective for future studies to consider in a single document.

In contrast, the link between GHRM and employee productivity in the workplace is required to consider the study's substantial practical implications. No doubt, the objective of every organization is to provide better output with the help of an employee. Therefore, if the employees of the organization are trained with the concept of GHRM, then more productivity in the employees would be developed, which would be beneficial for the prosperity and competitive advantage of the organization in the modern mature market of Pakistan. Therefore, the responsibility of the management of SMEs in Pakistan is to consider the critical role of GHRM in developing the capability of their employees for better performance. Importantly, considering the conclusion of the study would be effective for the management to design the working environment in the best way for developing the efficiency of the employees of the organization.

Limitations

There are some limitations to this research. To begin with, this research is based on the cross-sectional data collected on the questionnaire that has limited importance for monitoring the GHRM capacities. Therefore, future research may focus on monitoring the GHRM activities in different organizations in the long term to validate the results of this study. Second, this research has determined the role of employees' motivation; however, the employees can be motivated with performance and rewards. Hence, future research may focus on performance and reward factors to determine the findings and contribute to the framework of an employee's performance. Finally, this study is limited as it discusses a single aspect of GHRM for the employees. Moreover, future research should enhance the literature by determining the impact of sustainability in human resource management and its impact on the competitive advantage of the organization.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

Conceptualization, AK; methodology, AK and WU; software, WU; validation, JI and AS; formal analysis, WU; investigation, WU; resources, WU and JI; data curation, WU; writing—original draft preparation, AK, WU, and AS; writing—review and editing, AK and MT; visualization, WU; and supervision, MT and JI.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Revisiting EKC hypothesis in context of renewable energy, human development and moderating role of technological innovations in E-7 countries?

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The present study examines the potential of the traditional environmental Kuznets curve (EKC) with an extension for growing industrialized economies, including Brazil, China, India, Indonesia, Russia, Mexico and Turkey (E-7 economies) spanning from 1995 to 2019. Since the E-7 economies are still in a growing phase, this study adds to the EKC phenomenon by taking into description human development, the use of renewable energy, and technological innovations for investigation. Second-generational panel econometrics techniques, such as cross-sectional augmented autoregressive distributive lag (CS-ARDL), Augmented Mean Group (AMG), and Dumitrescu-Hurlin causality tests, form the basis of the experimental framework's design. The study confirms the existence of the EKC phenomena in E-7 economies, where income expansion is prioritized in relation to environmental sustainability. The study's findings demonstrate that technological modernization helps to mitigate pollution level. Therefore, human development, technological innovation, and the use of renewable energy are held up as the panacea for reducing carbon emissions over the time period under study. Finally, some further policy suggestions are provided.

Abbreviations: AMG, Augmented Mean Group; CO_2, CO_2 Emissions; CS-ARDL, Cross-sectional augmented autoregressive distributive lag; CSD, Cross-sectional dependency; E-7, Brazil, China, India, Indonesia, Russia, Mexico and Turkey; ECM, Error Correction Model; EKC, environmental Kuznets curve; G-7, Canada, France, Germany, Italy, Japan, United Kingdom, and United States; GDP, Economic growth; GMM, generalized method of moments; HDI, Human Development Index; OECD, The Organization for Economic Cooperation and Development; PHDI, Planetary Pressures-adjusted Human Development Index; R&D, Research and Development; RE, Renewable energy; SDGs, Sustainable Development Goals; TECH, Environmental Technologies; UNDP, United Nation Development Program; Y, GDP *per capita*.

KEYWORDS

environmental kuznets curve, human development, renewable energy, economic growth, E-7 economies

1 Introduction

Global environmental threats have emerged in recent years due to pollution's rapid expansion. CO2 is the primary cause of this contamination; and it increased from 3.80 to 4.50 metric tons (Mt) *per capita* annually between 1995 and 2019 (WDI, 2022). The combustion of non-renewable energy resources like natural gas, oil, and coal for purposes like energy production and hauling is a large contribution to carbon dioxide (CO_2) emissions, despite the fact that energy utilization is a key component in income growth (Raza et al., 2015; Phong, 2019). In order to address the problem of pollution on a worldwide scale, every nation will need to switch to alternative energy sources like renewable and cleaner energy. This is a prudent step in that direction to make sure the transition has an as little adverse effect on the economy as possible. However, every nation on Earth is susceptible to pollution's impacts. It is logical to assume that the nations that produce the most of the world's largest CO_2 emissions will also be expected to do the most to solve the problem (IPCC, 2007; Shahbaz et al., 2013). The U.S., China, India, and Russia are among the top polluting nations; their cooperation is crucial to a worldwide effort to improve air quality. China (22.40%), India (15.6%), Brazil (2.0%), Russia (5.3%), and Indonesia (1.60%) together account for 46.9% of global energy demand, so the high level of emissions in 2019 not surprising. The U.S. population accounted for only 4% of the global population yet used 16% of all energy. China and India, on the other hand, consumed more than 22% and 6% of global energy, respectively (IEA, 2018).

The priority of COP27 will be on converting commitments made at past conferences into concrete measures during the 2020's. In light of this, the underlying technical and political challenges of these agenda items will not be resolved by COP27. However, it is maintained that any progress, no regardless how small, in each of these agenda topics will help improve the global response to the effects of climate change. At COP27, low and middle-income countries will be forefront and centered as the world discusses how to best address the effects of climate change. To further complicate problems, low- and middle-income countries have historically and currently contributed minimally to global greenhouse gas emissions, the main source of climate change. But because of their climate and their acute impoverishment, low-middle income nations are especially at risk from climate change. The implications for low- and middle-income countries in global climate change governance have risen as a result of this dilemma.

Between 2016 and 2050, pollution is expected to keep rising at a rate of 2.6% per year. Most of this increase will come from the E-7 economies' rapidly developing countries, which include Brazil, India, China, Indonesia, Russia, Mexico, and Turkey, where growth rates are expected to average 3.5% per year (PWC, 2017). The methodology behind the E-7 economy's growth projection out to 2050 is based on a reliable long-run model of income growth (Solow, 1957), which facilitates growth projections by factoring in developments related to a wide range of factors like capital accumulation, human development, and technological innovations. Some other growth studies have also conducted empirical investigations of the applied growth model such as (Barro and Lee, 2001; Hao and Wei, 2015). Moreover, according to Hawksworth and Cookson (2006), the E-7 economies are those with the highest potential for population increase among developing nations, making them ultimately as economically powerful as the G-7 countries. By the end of 2018, these nations accounted for the global population (47%), global GDP (26%), global energy use (40%), and global CO_2 emissions (45%). Understanding the association between the factors of CO_2 emissions in E-7 economies is crucial because of the extreme vulnerability they face to the risks of climate change and CO_2 emissions as a consequence of their, GDP growth, energy use, and CO_2 emissions. Emissions of carbon dioxide per person reflect the total number of tons of CO_2 emissions released due to the deployment of non-renewable energy sources (i.e., coal, natural gas, crude oil, and other fossil fuels) divided by the population in the world. The carbon output of Russia is the greatest of the E-7 economies, whereas India has the lowest carbon output. According to Figure 1, the E-7 economies have a relatively high CO_2 output.

There is progress being made toward a low-carbon economy, but this trend must be extended to include social and environmental considerations. The Human Development Index (HDI) is a composite measure of a country's health, income, and education that is based on the Sen's capacity approach (UNDP, 1990). Improvements in people's standards of living are seen as a consequence of the HDI rising. Every nation strives to develop its people to their fullest potential. The guarantee of energy utilization and the need for CO_2 emissions, nevertheless, are necessary for the actualization of the right to human development (Pan, 2002). The human development report included a new indicator, the Planetary Pressures-adjusted Human Development Index (PHDI), to highlight the way in which human behaviors exert tremendous pressure on the planet's environment and biodiversity. As a result of human development, these factors will cause climate change and species annihilation that will reduce or eliminate HDI (UNDP, 2020). Thus, policymakers will have greater evidence for attaining sustainable development if the connection between CO_2 emissions and human development is studied (Hossain and Chen, 2022).

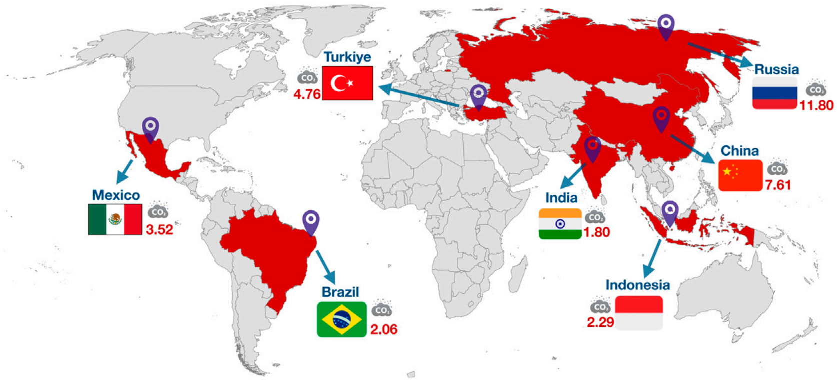

FIGURE 1
Trend of total CO_2 emissions in E-7 economies in million tons *per capita* in 2019.

A transition to a world without atmospheric carbon requires renewable energy sources for instance wind, hydro, solar, geothermal, and biomass. Two recent studies support this theory (Cheng et al., 2019; Kirikkaleli and Sowah, 2020). Natural capital stocks and the generation of energy from renewable sources are essential to sustaining economic growth, which in turn necessitates their frequent monitoring (Schmalensee, 2012). To further promote the consumption of alternative and cleaner energy sources, the Kyoto Agreement also mandates that countries lessen their negative effects on the environment (Becker and Posner, 2005). One of these benefits is eliminating the need to import non-renewable resources, which is why the deployment of renewable energy sources is so essential (Saqib et al., 2022b; 2022c). Since the costs of imported non-renewable energy sources are extremely unpredictable, stabilizing oil prices on the international market is another way to ensure consistent growth of the economy (Menyah and Wolde-Rufael, 2010). Another study discovered a favorable association between *per capita* use of alternative energy sources and income growth per person (Saqib, 2022).

Developing new environmental technologies (TECH) is an example of innovation. It illustrates patents that fall under the category of environmental technology, such as those that deal with groundwater adaptability or mitigation of global warming. The number of patents issued is often used as a proxy for innovation in previously existing literature (Hagedoorn and Cloodt 2003; Wurlod and Noailly, 2018). The frequency of environmental innovations is calculated as a ratio of high-value inventions per million inhabitants living in a given region. Figure 2 displays the TECH time series for the E-7 economies for the year 2019 and also shows that in 2019, Brazil kept its highest TECH while Turkey maintained a low TECH.

Figure 2 shows the number of environmental patents filed in the E-7 economies has increased over the past year, while the E-7 economies' combined CO_2 emissions continue to rise. Consequently, the E-7 economies should implement climate change policies with the assistance of research that analyzes the impact environmental patents have on carbon emissions. Given the importance of environmental patents in combating environmental problems, this research aspires to reveal the interaction between carbon emissions, human development, economic growth, and renewable energy usage in the E-7 economies. In order to establish policies that would support economic development, particularly in the E-7 economies, policymakers need to understand the consequences of technical innovation, deployment patterns of renewable energy, and HDI on CO_2 emissions. This research stands out from the rest because it adds fresh information to the EKC framework by examining the influence of technology innovation, human development index, and renewable energy. The E-7 economies are prioritized because of their lack of recorded documentation in the aforementioned literature and the E-7 nations are responsible for a substantial percentage of the world's overall energy consumption and carbon emissions. We also provide an extensive empirical analysis of second-generational panel methods and findings for future policy directions. After a thorough empirical investigation of how well SDGs 3, 4, 7, 8, and 13 are being met, the E-7 countries are given a set of new and effective policy suggestions.

The remaining sections of this study are structured as follows: Section 2 reviews an earlier literature. Sections 3, 4 describe the data and econometric modeling strategy respectively. Section 5 discusses and interprets the results. The policy recommendations and last thoughts are reported in Section 6.

2 Review of literature

The EKC hypothesis is the initial assertion regarding the link between carbon emissions and their determining variables to be

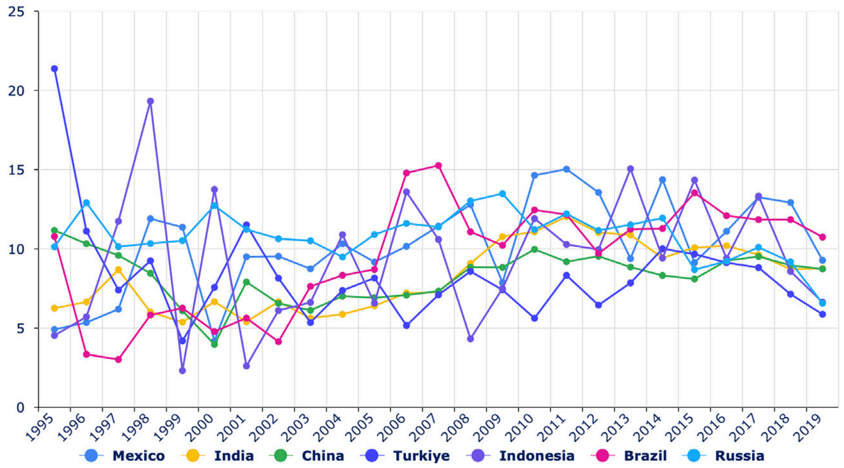

FIGURE 2
Tend of patents in E-7 countries (1995–2019).

made (Kuznets, 1955). Based on these data, Kuznets established the EKC hypothesis, which states that carbon emissions are negatively associated with economic growth (as measured by GDP). Some researchers further examined the EKC theory with scientific investigations, exploring at how high-rise influences CO_2 emissions and other variables (Holtz-Eakin and Selden, 1995; Dinda and Coondoo, 2006). Conventional hypotheses for CO_2 emissions emphasize population growth, economic growth, and technological progress (Ehrlich and Holdren, 1971) The EKC, a quadratic link between pollution and income growth, provides strong evidence for the importance of economic prosperity (Doytch and Uctum, 2016; Pham et al., 2020; Balsalobre-Lorente et al., 2022). The minimum level of energy consumption during the pre-industrialization phase, the high level of emissions during modernization and manufacturing sector development, and the low level of emission levels during the deindustrialization and shift to a services-based economy are all assumed to occur as the economy expands and undergoes modernization. Energy consumption and CO_2 emissions have also been shown to exhibit a similar quadratic relationship (Baloch et al., 2021; Doytch and Ashraf, 2021; Adebayo et al., 2022).

EKC can be explained as affluence rises, people demand a better environment, while industrialization and output raise environmental pressure. This leads to legislation and technologies to improve efficiency and reduce emissions. Many EKC studies employ ecological footprints as an environmental quality proxy, and past research suggests that higher-income countries are more likely to support the EKC hypothesis (Hashmi et al., 2021). While there was some variation in findings, the EKC hypothesis was generally supported by high-income countries (Pata, 2021). The turning point (TP) was higher in countries with higher incomes than in those with lower incomes. According to the inverted U-shaped EKC hypothesis, environmental damage rises alongside economic growth until rising income inequality mitigates the impact. Further, the study's findings indicate that E7 economies' income growth has a moderating effect on their carbon emissions. The results corroborate the research of (Dong et al., 2018; Pata 2018; Gyamfi et al., 2021a; Pata, and Caglar. 2021; Ali Talib et el. 2022; Yang et al., 2022), showing that an increase in national income, as a result of economic growth, is likely to help drive these economies toward environmental sustainability. The E-7 economies are mostly low-middle-income countries and the low-middle-income countries have not yet reached income levels high enough to be able to derive their turning points, which is consistent with (Dinda, 2004).

Human development (HDI) is the primary goal of economic progress, and as a result, all nations strive to improve their HDI. To achieve this goal, we need to understand what factors have an effect on HDI. The HDI has received a lot of concentration from environmentalists already. Various samples, econometric methods, and contextual factors were used. As a result of these studies, we know that both economic development (Ranis et al., 2000; Suri et al., 2011; Shah, 2016) and carbon dioxide emissions (Bedir and Yilmaz 2015) have an impact on human development. In addition to the things listed above, the HDI also looks at the energy consumption as a separate variable. In the past, it was believed that increasing fuel consumption would result in better human development. Nevertheless, as the environmental issues connected with fuel usage are rising, this perspective would be no more appropriate. The use of more fuel doesn't really inevitably result in more HDI (Tran et al., 2019). The following is a discussion of some studies that compare energy consumption and HDI. Over 200 countries were included in the study developed by (Martnez and Ebenhack, 2008), and the results indicate a correlation between fuel consumption and HDI. Furthermore, Ouedraogo (2013) evaluated 15 emerging economies from 1988 to 2008 by using Pedroni cointegration, and FMOLS analysis, which revealed an adverse and one-way Granger causality association between CO_2 emissions and HDI. In contrast to the previous study, Tran et al. (2019) examined the link for 93 economies using 1990–2014 statistics by utilizing the GMM (generalized method of moments) and found fuel consumption doesn't affect HD improvement in emerging and developed nations. Martnez and Ebenhack, 2008 discovered a statistically significant relationship between HDI and *per capita* energy use. Low-HDI countries that are energy-poor can benefit greatly from even a moderate quantity of energy support. Low-HDI countries should be provided the most attention in consultation about global atmospheric variations to protect their human development rights (Pan, 2002).

One of the most environmentally and economically sustainable measures is the proportion of energy consumed that comes from alternative sources. Multiple analyses of this situation have identified fossil fuel-based energy as a major source of environmental degradation. In the case of Nigeria, Ali et al. (2018) examined that energy use significantly posits a slew of environmental and health issues. Contrarily, a number of reports showed that replenishing energy supplies contributed to environmental dominance. The AMG method was used by (Saqib et al., 2022) and others to investigate how advances in renewable energy and technology have affected the environmental impact of the G-7 economies. The empirical research looked into how renewable energy considerably enhances environmental eminence. The earlier literature by (Wu et al., 2022; Yang Q. et al., 2022; Zhang et al., 2022; Wang et al., 2023) finds similar conclusions, stating that cleaner energy and technological innovation have a substantial influence on carbon emissions.

Studies typically ignore the development of environmental patents, despite their value in reducing CO_2 emissions. Only a significant handful of empirical research uses econometric tools to investigate how environmental patents affect CO_2 emissions. The influence of technological development on reducing energy intensity has been researched and the role of environmental patents in eliminating carbon emissions has been investigated and found that patents are significant indicators of innovation and industrial transformation, which is consistent with the conclusion of an empirical study (Mendonça et al., 2004; Wurlod and Noailly, 2018). In a similar vein, this paper aims to assess the impact of patents on environmental pollution levels to fill in the voids in our knowledge of how patents in environmental technology might spur unique, sophisticated technology that minimizes CO_2 emissions. Environmental pollution can be minimized by the use of environmentally friendly technologies. In many fields, including environmental protection, it is crucial to employ the most appropriate innovative deployment channel. It is important to invent new ideas and discover new methods for creating them. According to empirical research, innovation affects CO_2 emissions through several channels. Innovation affects CO_2 emissions through productivity gains. Patenting global inventions and innovations boosts technological innovation. Efficiency in resource use can accelerate technological progress. In order to reduce CO_2 emissions, industries, organizations, and employees must adopt innovative technologies. Instead of developing carbon-reducing products and services, firms can duplicate a successful idea, industry, or corporation. Global concerns can slow environmental technology development. Patents on environmental innovation technology reveal its technical knowledge, which can be used to analyze its progress. To address global needs, new technologies must be developed and adopted. Patents show how far an invention has come, who invented it, and who wants to use it. This can help develop new technologies.

Research and development (R&D) spending is often applied as a surrogate for innovation in existing research that aims to capture its environmental consequences. Macro investigations have yielded contradictory findings (Churchill et al., 2018), and (Petrovi and Lobanov, 2020) discover contradictory findings for dissimilar spans and countries, whereas (Fernández Fernández et al., 2018) find that R&D expenses lead to reduce the level of environmental pollution. This study reveals that the CO_2-lowering effect depends on country-specific factors (Acemoglu et al., 2012) and that this effect tends to recover over time, which stops long-run ecological eminence increase from green technological innovations (Braungardt et al., 2016; Sharif el al. 2022). The effect of environmentally friendly technologies on global emissions of CO_2 is the subject of research. For green innovations to begin significantly lowering CO_2 emissions, they must discover a critical income level at which to do so. Du et al. (2019) evaluated that the high costs of spreading new green technology make this a somewhat high-income threshold, especially for people who live in underdeveloped countries. This conclusion is corroborated by the research (Popp, 2012), which notes that organizations in undeveloped countries cannot afford the high start-up fixed costs associated with green technology discoveries. Carbon capture technologies have been studied and documented in recent times (Luis Mguez et al., 2018). Some analyses compare alternative and cleaner energy and ecological patents for carbon emissions reduction purposes (Cheng et al., 2018). A small number of studies suggest that CO_2 emissions can stimulate green patent filings and R&D investment (Cho and Sohn, 2018).

TABLE 1 Data variables and sources (1995–2019).

Variables	Symbol	Measurement	Data sources
CO_2 emissions	CO_2	Million tons per person	WDI
Gross domestic product	Y	GDP *per capita*	WDI
Human development Index	HDI	Three main tenets of HDI are life expectancy, education quality, and standard of living	UNDP
Renewable energy	RE	% of final energy use	WDI
Environmental patents	TECH	% of total patents on environment technologies	OECD

When applied to the context of the EKC hypothesis, the literature fails to provide evidence of a connection between human development, technological innovation, renewable energy, and ecological footprint. This research aims to close that gap in the existing literature. Further, this link must be examined from the SDGs' point of view, as E-7 countries are currently experiencing difficulties achieving the SDG targets, and the findings of this study may help close the policy-level gaps that now exist in E-7 countries. The study's significance at this level of policymaking is contained therein.

3 Data description and econometric models

This study utilizes the data from the World Bank compiled by WDI, the UNDP, and the OECD environment database from 1995 to 2019 for the E-7 economies. This allows the authors to examine the influence of environmental patents, renewable energy, and human development on CO_2 emissions. Table 1 reports a summary of the panel-selected variables that were used in this investigation. These variables were the amount of carbon dioxide released per person, the gross domestic product (Y), the human development index (HDI), renewable energy (RE), and technological progress in areas related to the environment (TECH). The mathematical expressions of the econometric function are presented in Eqss (1), (2) as follows:

CO_2 emission = f (Economic growth, Human development, Renewable energy, Technological innovations)

$$CO_{2,it} = f\left(\ln Y_{it},\ \ln Y_{it}^2,\ \ln HDI_{it},\ \ln RE_{it}, \ln TECH_{it}\right) \quad (1)$$

CO_2 Emission = f [Economic Growth, Human Development, Renewable Energy, Technological Innovations (Renewable Energy Consumption* Technological Innovations)]

$$\ln CO_{2,it} = \ln Y_{it}, \ln Y_{it}^2, \ln HDI_{it},\ \ln RE_{it}, \ln TECH_{it},\ (\ln RE * \ln TECH)_{it} \quad (2)$$

4 Econometric modelling strategy

4.1 Cross-sectional dependence tests

Five econometric steps estimate reliable and robust findings. First, this paper applies four cross-sectional dependence (CSD) approaches. The CSD is a major issue in longitudinal data analysis, causing issues with stationarity, long-run cointegration tests, and dimensional deformation. Panel data model disruptions are usually cross-sectionally independent when the number of observations (N) is large as compared to the time period (T). Breusch and Pagan, (1980), Pesaran, (2020) scaled LM; bias-corrected scaled LM, and (Pesaran, 2020) CSD are applied in the current research to test for cross-sectional dependency. Where, the null and alternative hypotheses can be tested by considering Eqs 3, 4 respectively.

$$H_0\colon \rho_{ij} = Cov\left(\mu_{it}, \mu_{jt}\right) = 0, \quad \text{no cross} - \text{sectional dependence} \quad (3)$$

$$H_1\colon \rho_{ij} = Cov\left(\mu_{it}, \mu_{jt}\right) \neq 0, \quad \text{cross} - \text{sectional dependence} \quad (4)$$

CSD test proved by (Pesaran, 2020) developed a customized description, which is provided Eqs 5, 6:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij}\right) \sim N(0,1)i, j \quad (5)$$

$$R = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right)\left[(M-k)\frac{\hat{\rho}_{ij}^2 - (T-k)\hat{\rho}_{ij}^2}{\text{Var}\ (T-k)\hat{\rho}_{ij}^2}\right] \quad (6)$$

Where the current research estimated the model using cross-sectional fixed effects for the E-7 nations, the biased corrected LM test statistic was also estimated. The LM test statistic is the most developed CD diagnostic proposed by Breusch and Pagan (1980) in null hypothesis in Eq. 7:

$$CSD_{LM} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1 j=i+1}^{N-1}\sum_{ij}\left(M_{ij}\hat{\rho}_{ij}^2 - 1\right) \to N(0,1) \quad (7)$$

Where CD_{BP} denotes the CSD test as demonstrated in Eq. 8:

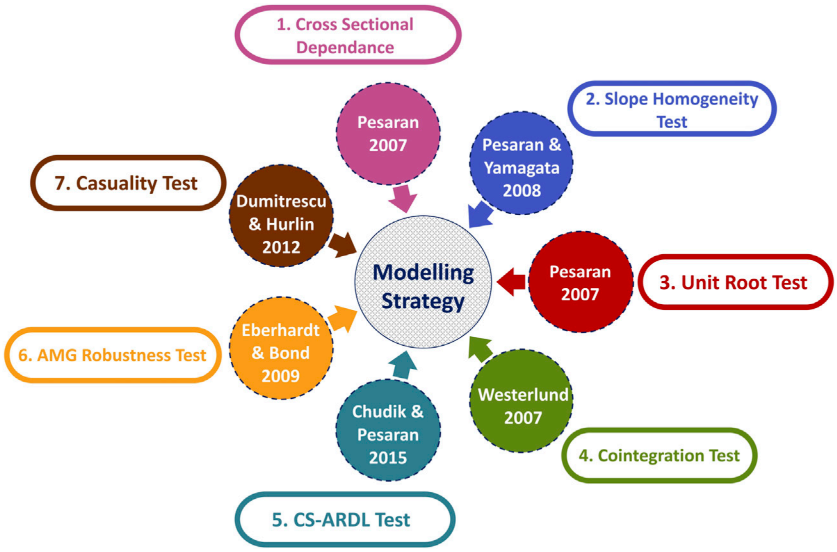

FIGURE 3
Econometric modelling strategy.

$$CSD_{BP} = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \hat{\rho}_{ij}^{2} \rightarrow \chi^{2}\frac{N(N-1)}{2} \tag{8}$$

However, another CSD test developed by Baltagi et al. (2012) provide a undemanding asymptotic bias alteration for the scaled LM approach (CD_{BC}) as reported in Eq. 9:

$$CSD_{BC} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T_{ij}\hat{\rho}_{ij}^{2} - 1\right) - \frac{N}{2(T-1)} \rightarrow N(0,1) \tag{9}$$

The $\hat{\rho}_{ij}^{2}$ terms denoted in Eqs. 5, 7, 8 and 9 denotes pairwise cross-sectional correlations by employing a simple linear regression. The methodological presentation in graphical form is represented in Figure 3.

4.2 Slope homogeneity tests

The stability of panel estimators could be impacted by the non-existence or existence of slope homogeneity or heterogeneity in the underlying panel data. By default, conventional estimators assume that all models have the same slope. Therefore, the slope heterogeneity of the model needs to be investigated first, before moving on to the experimental approximation. Due to these considerations, the slope heterogeneity test created is applied in this study (Pesaran and Yamagata, 2008). The test mathematical expression of the delta tilde $(\tilde{\Delta}_{HS})$ and adjusted delta tilde $(\tilde{\Delta}_{HS})$ of the slope heterogeneity method are provided in Eqs 10, 11 respectively:

$$\tilde{\Delta}_{,HT} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - k\right) \tag{10}$$

$$\tilde{\Delta}_{AHS} = (N)^{\frac{1}{2}}\frac{2k(T-k-1}{T+1}^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - 2k\right) \tag{11}$$

4.3 Unit root tests

Traditional unit root tests assume model slope homogeneity and cross-section independence, which may lead to inaccurate results (Pesaran, 2007, 2020). The test tackles CSD and slope heterogeneity. CIPS and CADF applied in Eqs. 12, 13, 14:

$$\Delta F_{i,t} = \alpha_i + \alpha_i Z_{i,t-1} + \alpha_i F_{t-1} + \sum_{l=0}^{p} \alpha_{il}\Delta\bar{F}_{t-1} + \sum_{i=1}^{p} \alpha_{il}\Delta F_{i,t-1} + \mu_{it} \tag{12}$$

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T) \tag{13}$$

$$\widehat{CSAIPS} = \frac{1}{N}\sum_{i=1}^{n} CADF_i \tag{14}$$

4.4 Long-run cointegration test

This study examines the long-run Cointegration among the selected series in both functions using cointegration tests (Westerlund, 2007). Westerlund's cointegration method is significant since it can be applied to slope heterogeneous models. The test also considers cross-section dependency. In Eq. 15, Eq. 16, Eq. 17, and Eq. 18, Westerlund's test employs the different four statistics: two-group test statistics (G_t and G_a) and two panel statistics (P_t and P_a).

$$G\tau = \frac{1}{N}\sum_{i=1}^{N}\frac{\hat{\alpha}i}{SE(\hat{\alpha}i)} \tag{15}$$

$$G\alpha = \frac{1}{N}\sum_{i=1}^{N}\frac{T\hat{\alpha}i}{\hat{\alpha}i(1)} \tag{16}$$

$$P\tau = \frac{\hat{\alpha}i}{SE(\propto i)} \tag{17}$$

$$P\alpha = T\hat{\alpha} \tag{18}$$

where, $\hat{\alpha}i$ is shown by $SE(\hat{\alpha}i)$ as the standard random error. The semi-parametric kernel approach of $\propto i(1)$ is $\hat{\alpha}i(1)$.

4.5 Cross-section augmented autoregressive distributed lag test

In order to test the effect of technological innovation on carbon emissions in the context of control factors, because it takes into consideration the slope heterogeneity, CSD, and endogeneity concerns, this strategy is more effective than others (Chudik and Pesaran, 2013). Additionally, this approach produces reliable outcomes even when there are only a small number of economies available to serve as the sample, the CS-ARDL strategy is the one that we chose to implement as indicated in CS-ARDL Eq. 19:

$$\Delta EFP_{2,i,t} = \emptyset_i + \sum_{l=1}^{p}\theta_{il}\Delta CO_{2,i,t-l} + \sum_{l=0}^{p}\theta'_{il}X_{i,t-l} + \sum_{l=0}^{1}\theta'_{il}\bar{Z}_{i,t-l} + \mu_{i,t} \tag{19}$$

Where

$$\bar{Z}t = (\Delta C\bar{O}2t, \bar{X}t')' \text{ and}$$
$$\text{Xit} = GDP_{it}, GDP^2_{it}, HDI_{it}, REC_{it}, TECH_{it})' \tag{20}$$

4.6 Augmented mean group robustness test

The cointegration correlation testing in the demonstration is a prelude to model estimation. The current paper employs the augmented mean group (AMG) test, proposed by (Eberhardt and Bond, 2009). The CSD, non-stationarity, endogeneity, and slope heterogeneity are all features of longitudinal data that the AMG technique can help remedy. The first and second stage AMG implication, expressed by Eq. (21) and Eq. 22) as:

$$\Delta X_{it} = \delta_i + \beta_i\Delta Y_{it} + \gamma_i A_t + \sum_{t=2}^{T}\delta_i\Delta D_t + \varepsilon_{it} \tag{21}$$

$$\hat{\beta}_{AMG} = N^{-1}\sum_{i=1}^{N}\hat{\beta}_i \tag{22}$$

4.7 Panel causality test

Stepping back and trying to figure out which variable caused the other is the econometric procedure's end objective. A panel causality test developed by Dumitrescu and Hurlin (2012) was used to arrive at this conclusion. In order to present a test for the causality hypothesis (Dumitrescu and Hurlin, 2012), modified the causality test proposed by (Granger, 1969), as shown in Eq. 22.

$$Y_{i,t} = \alpha_i + \sum_{k=1}^{K}\gamma_i^{(k)}Y_{i,t-k} + \sum_{k=1}^{K}\beta_i^{(k)}X_{i,t-k} + \varepsilon_{i,t} \tag{23}$$

Wald statistics provides a reliable way of analysis. Eq. 24 presents Wald statistics:

$$W_{N.T}^{HNC} = N^{-1}\sum_{i=1}^{N}W_{i,T} \tag{24}$$

The z-test test statistic provided in Eq. 25 proposed by (Dumitrescu and Hurlin, 2012) for large time (T) instead of cross-sections (N):

$$Z_{N,T}^{HNC} = \sqrt{\frac{N}{2K}}\left(W_{N,T}^{HNC}\right) - K. \tag{25}$$

5 Results and discussion

5.1 Descriptive and correlation matrix information

Table 2 describes the findings of descriptive and correlation matrix information. In the first strand of Table 2, the authors calculate the average, lowest, highest, standard deviation, skewness, kurtosis, and their respective probabilities distribution values. The average values of selected time series like CO_2, Y, HDI, RE, and TECH are 2.9587, 11.8273, 0.7954, 1.0351, and 1.1132 respectively. The standard deviations for CO_2, Y, HDI, RE, and TECH are impressive as 0.5987, 1.7554, 0.1067, 1.0277, and 1.0102 respectively. The selected variables such as Y, HDI, RE, and TECH all have a strong correlation with CO_2 emissions. However, HDI, RE, and TECH are negatively linked whereas Y is found to have a positive linear association with CO_2 emissions. The correlation matrix of the variables demonstrates the positive correlation in between income and CO2 emissions but negative correlation with human development index, renewable energy and technological innovation. We also investigate the degree of multicollinearity that exists between

TABLE 2 Descriptive statistics and pairwise correlation matrix.

Descriptive statistics							
Variables	Mean	Min	Max	Std. Dev	Skew	Kurt	Prob
CO2	2.9587	1.2865	3.5869	0.5987	0.4527	3.0041	0.0000
Y	11.8273	7.7998	12.8612	1.7554	−1.5781	3.9993	0.0000
HDI	0.7954	1.0002	2.6894	0.1067	−0.4157	2.7448	0.0000
RE	1.0351	0.0127	2.0285	1.0277	0.2014	2.3279	0.0000
TECH	1.1132	0.2054	2.5175	1.0102	0.4577	2.1347	0.0000
Pairwise correlation matrix							
Parameters	CO2	Y	HDI	RE	TECH		
CO2	1.0000						
Y	0.3714*	1.0000					
HDI	−0.0718*	1.3211*	1.0000				
RE	−0.1946*	0.1966*	0.1618*	1.0000			
TECH	−0.5433*	0.7451*	0.7451*	0.9562*	1.0000		
VIF		0.5841	0.4875	0.5227	0.7541		

Note: * designates the significance level at 1%.

TABLE 3 CSD test results.

Variables	Breusch-Pagan LM		Pesaran scaled LM		Bias-corrected scaled LM		Pesaran CSD	
	Stat	Prob	Stat	Prob	Stat	Prob	Stat	Prob
CO2	490.5670*	0.000	45.2578*	0.000	39.2250*	0.000	16.2581*	0.000
Y	1965.3598*	0.000	218.2261*	0.000	162.3352*	0.000	59.2591*	0.000
HDI	389.3357*	0.000	49.1031*	0.000	38.3369*	0.000	15.0036*	0.000
RE	583.0378*	0.000	77.2289*	0.000	75.3942*	0.000	38.5680*	0.000
TECH	1168.0334*	0.000	85.2293*	0.000	77.3277*	0.000	49.9960*	0.000
RE*TECH	1227.967*	0.000	98.5021*	0.000	97.1220*	0.000	32.6943*	0.000

Note: * designates the significance level at 1%.

the variables, and the VIF coefficients indicate that this does not pose a challenge to the estimate process.

5.2 Findings of cross-sectional dependence tests

In study utilized CSD tests to look at the possibility of CSD. Table 3 contains the results of the four CSD tests. Statistically significant *p*-values in the outcomes of the cross-sectional CSD tests indicate the presence of the CSD. Accordingly, it is necessary to move on to creating a stationarity test of the second generation that can address the CSD problem.

5.3 Findings of slope homogeneity test

The Pesaran and Yamagata (2008) method is useful for examining the scatter in slope coefficients. Slope heterogeneity testing explores that both functions are suffering from this issue. The massive delta and the adjusted delta amount both make this very evident. Slope heterogeneity is demonstrated in both models 1 and 2 as indicated in Table 4:

5.4 Findings of panel unit root test

This research employs a CIPS unit root test of the second generation to handle the panel data difficulties brought on by the

TABLE 4 Slope-homogeneity test results.

Model 1: $CO_{2,it} = f(\ln Y_{it}, lnY^2_{it}, \ln HDI_{it}, \ln RE_{it}, \text{lnTECH}_{it})$			
$\tilde{\Delta}_{HS}$		$\tilde{\Delta}_{AHS}$	
Stat	Prob	Stat	Prob
11.5271*	0.0000	13.0296*	0.0000
Model 2: $CO_{2,it} = f[\ln Y_{it}, \ln Y^2_{it}, \ln HDI_{it}, \ln RE_{it}, \text{lnTECH}_{it}, (\ln RE{*}\text{lnTECH})_{it}]$			
$\tilde{\Delta}_{HS}$		$\tilde{\Delta}_{AHS}$	
Stat	Prob	Stat	Prob
9.2223*	0.0000	10.2550*	0.0000

Note: * designates the significance level at 1%.

CSD and slope variability. The alternative hypothesis is valid at their first integration order such as I (1), as shown by the results of the CIPS unit root test, which show that all variables having no unit root at that level. Mean and standard deviation values for both models are shown to fluctuate over time in Table 5.

5.5 Findings of panel long-run cointegration test

Based on the evidence of the cointegration test reported in Table 6, there seems to be a connection that lasts over a longer period of time between the variables in models 1 and 2. This is valid, as demonstrated by the group and panel statistics compiled by Westerlund. Since these tests are meant to handle cross-sectional dependency in a panel investigation, their use has been extensively reported in the scholarly literature (Chudik et al., 2016; Baloch et al., 2021; Nathaniel et al., 2021).

5.6 CS-ARDL test results

This research makes use of the CS-ARDL methodology to investigate how eco-friendly technological innovation affects carbon emissions when certain variables are held constant. Table 7 displays the outcomes of applying the CS-ARDL method. It is not surprising that the Y, Y^2, HDI, REN, and TECH of the E-7 economies all play significant functions in formative planet health. With the exception of GDP, every other variable has an adverse influence on the pollution levels in the region. The negative value of the ECM coefficient provides support for the hypothesis that there is a long-run link between the candidate time series variables. It is encouraging to see the E-7 countries working to lessen their pollution levels. However, the E-7 countries collectively contribute a lot more CO_2 to the atmosphere than the rest of the world combined. The E-7 countries' carbon footprints might be significantly reduced if they adopted a renewable energy policy and technological innovation. Similar findings are found (Mehmood, 2022) regarding the importance of increasing the HDI, and the share of energy that comes from alternative and renewable energy sources, in South Asian nations in order to reduce pollution, and (Umar et al., 2020) agree that technological advancements have helped lower pollution rates by increasing the use of greener, more energy-efficient methods. Further evidence that human capital can reduce an organization's CO2 emission is provided by Huang et al. (2022) and Usman and Radulescu. (2022).

The positive and adverse signs of the coefficient for Y and Y2 relative to CO_2 emissions articulate the impression of the EKC hypothesis. More precisely, when real income rises by 1%, carbon emissions will lead to a boost of 0.9531% in the long run, alternatively, a 1% augmentation in Y^2 reduces the pollution level by 0.0192% in the region. These associations recommend that in initial phases, high/lofted real income growth in E-7 economies will boost the pollution level to a threshold point (in this case it is 0.9531%) however after reaching this point, carbon emissions levels will initiate reducing with the more enhancement in income growth. This empirical outcome carries the EKC relationship in the E-7 economies. The primary reason behind this phenomenon is that in starting phase of income growth, economies are first and foremost anxious about their economic development, and the candidate economies overlook the environmental consequences, spotlighting the enhancement of their trade pattern with other economies and communications expansion in the course of financial development, and globalization. Overall investment level augments and *per capita* income increases, consequently, the demand for primary energy boosts and ecological damages rises. Ultimately, the increase in economic growth levels carries environmental, economic, and social consciousness that assists to decrease ecological contamination (Huang et al., 2022). At this phase, countries are additionally increased when more foreign investment inflows, with the least harm to the atmosphere. This

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TABLE 5 Unit root test results.

Variables	CIPS		CADF	
	I (0)	I (1)	I (0)	I (1)
CO2	−2.9525	−5.0035*	−4.0028	−5.0368*
Y	−6.9317	−7.2543*	−5.5258	−6.6380*
HDI	−2.5214	−2.6747*	−2.9723	−3.0934**
RE	−2.3978	−4.2163*	−3.5880	−5.5897*
TECH	−2.1882	−4.2377*	−3.2187	−5.2301*
RE*TECH	−2.2981	−4.8230*	−2.9679	−4.3368*

Note: * and ** designate the significance level at 1%, and 5% respectively.

EKC influence develops due to the large-scale productivity with superior technologies and demand for ecological eminence from the populace. This study's outcomes are in line with those of Gyamfi et al. (2022), Nosheen et al. (2021), Dogan and Turkekul, (2016), Balsalobre-Lorente et al. (2022).

The econometric estimated results declare with confirmation that a superior level of human development is painstaking to be vital in mitigating carbon emissions in the region. Particularly, for each percentage augment in human development level, there is descending environmental contamination by 0.6954% and 0.1689% in the long- and short-run respectively. The analogous proposition is provided by Huang et al. (2022) and Hao et al. (2021). This defends the squabble that humanizing the human development eminence with facilitates education and related other ventures could enhance society's awareness towards the utilization of modern and new technologies and power resources that have an inferior ecological collision. As a result, such innovations can significantly assist in curbing environmental deficits. Several earlier articles have justified the negative effect of human development on environmental pollution (Huang et al., 2022, Zhongwei and Liu, (2022), Saqib et al. (2022). Moreover, under the umbrella of both short-run and long-run findings, the influence of human development on CO2 emission is established towards mitigating pollution levels and also it deals with many sustainability problems. In this pursuit, Sarkodie et al. (2020) observed that the enhancement in human development figures is favorable in commencing with ecological contamination and acceleration of the overall emissions, particularly in the context of E-7 economies.

Renewable energy has an adverse effect on carbon emissions in the E-7 countries. By inference, alternative and renewable energy sources can play a significant role in achieving the carbon neutrality arrangement in these economies. For that reason, cleaner energy utilization has a lot of potentials to diminish carbon emissions in these countries. This finding is usually accurate transversely to all the stipulations, both for the long-run and short-run. Following the newly developed studies developed by Gyamfi et al. (2022) and Usman and Radulescu (2022), who had analogous results for the E-7 and top nuclear energy-producing countries, increase and investment in the proportion of alternative energy use will assist to reduce the environmental consequences and, in sequence, protect environmental quality in the mounting efforts in the block.

Finally, this study analyzes how renewable energy and technological advancement (RE*TECH) in model 2 mitigate the impact on CO_2 emissions. It can be observed in Table 7, when (RE*TECH) increased, CO_2 emissions diminished. Indeed, data showed that RE and TECH interacted in a substantial manner. At the 5% significance level, this

TABLE 6 Cointegration test results.

Model 1: $CO_{2,it} = f(\ln Y_{it}, lnY_{it}^2, \ln HDI_{it}, \ln RE_{it}, \ln TECH_{it})$				
Statistics	Values	Z-values	*p*-values	Robust p-values
$G\tau$	−5.5580*	−4.9652	0.0000	0.0000
$G\alpha$	−14.2562***	1.6952	0.0640	0.0000
$P\tau$	−16.0356*	−4.5348	0.0000	0.0000
$P\alpha$	−18.3055*	−1.5251	0.0090	0.0000
Model 2: $CO_{2,it} = f(\ln Y_{it}, \ln Y_{it}^2, \ln HDI_{it}, \ln RE_{it}, \ln TECH_{it}, (\ln RE*\ln TECH)_{it})$				
Statistics	Values	Z-values	*p*-values	Robust *p*-values
$G\tau$	−3.7435*	−2.5688	0.0000	0.0000
$G\alpha$	−9.3352*	4.5821	0.0510	0.0000
$P\tau$	13.0052**	−2.5247	0.0000	0.0000
$P\alpha$	16.0005**	−1.8534	0.0091	0.0000

Note: *, ** and *** designate the significance level at 1%, 5%, and 10% respectively.

TABLE 7 Findings of CS-ARDL test.

Model 1: $CO_{2,it} = f\,(\ln Y_{it}, \ln Y_{it}^2, \ln HDI_{it}, \ln RE_{it}, \text{lnTECH}_{it})$				
Variables	Short-run		Long-run	
	Coeff	Prob	Coeff	Prob
Y	0.7950	0.1410	0.9531*	0.0000
Y^2	−0.0336*	0.0022	−0.0192*	0.0000
HDI	−0.1689***	0.0620	−0.6954*	0.0005
REN	−0.0952**	0.0100	−0.1312*	0.0161
TECH	−0.00421**	0.0110	−0.0051*	0.0050
ECM (-1)	−0.5221*	0.0001	—	—
Model 2: $CO_{2,it} = f\,[\ln Y_{it}, \ln Y_{it}^2, \ln HDI_{it}, \ln RE_{it}, \text{lnTECH}_{it}, (\ln RE^*\text{lnTECH})_{it}]$				
	Coeff	Prob	Coeff	Prob
Y	0.5241***	0.0550	0.2501*	0.0000
Y^2	−0.07450***	0.08120	−0.0591*	0.0001
HDI	−0.2224***	0.0510	−0.4027*	0.0000
RE	−0.05210**	0.0311	−0.1425**	0.0114
TECH	−0.03439**	0.0210	−0.0351*	0.0029
RE* TECH	−0.06872**	−0.0101	−0.0550*	0.0018
ECM (-1)	−0.4262**	0.0200	—	—

Note: *, **, and *** designate the significance level at 1%, 5%, and 10% respectively.

interaction shows that the E-7 economies can expect a large reduction in carbon pressure from the mixture of renewable energy and technological innovation. Dahmani et al. (2022) came to similar conclusions on how technological innovation and the use of renewable energy sources can be seen as major factors in achieving better standards of environmental sustainability.

5.7 Robustness analysis results

The CS-ARDL method robustness was also evaluated using the AMG method. The AMG and CS-ARDL long-term estimates have identical signals. With these exceptions, the dimensions are virtually comparable. When comparing the CS-ARDL technique to the AMG method, the magnitude of the coefficients in the CS-ARDL approach is larger. Zhongwei and Liu (2022) also used the CS-ARDL method to determine the association between variables in the short run and the long run, and they used the AMG method to determine the robustness of their findings.

The econometric findings of the AMG technique suggest that a wide range of factors may impact CO_2 emissions in the E-7 economies. Reliable and consistent with the results from the CS-ARDL method, Table 8 demonstrates that all variables except of Y have an adverse effect on pollution levels. The other variables like Y^2, HDI, RE, and TECH are all shown to have a substantial impact on shifts in CO_2 emissions by the causality test. Invention, alternative energy sources, and human development can all benefit greatly from improved environmental conditions and the outcomes confirm the study (Tran et al., 2019; Gyamfi et al., 2021b). AMG Robustness test results for the study in Table 8, while interpreted graphical schema presentation of the overall empirical findings, relied on the applied econometric results are reported in Figure 4 accordingly.

5.8 Panel causality test results

Table 9 presents the Granger causality outcomes of this paper. In this regard, to account for the fact that the panel estimators used in the study may produce estimates that may not accurately imitate the causality direction between the selected panel series, the authors present causality test results for the variables in the present study (Onifade et al., 2020). The D–H causality approach is reliable and robust adjacent to CSD applied to establish the causal association between technological development, income growth, human development, renewable energy, and carbon emissions. The findings of the D–H causality

TABLE 8 AMG test results.

Model 1: $CO_{2,it} = f(\ln Y_{it}, \ln Y_{it}^2, \ln HDI_{it}, \ln RE_{it}, \ln TECH_{it})$		
Variables	AMG estimator	
	Coeff	Prob
Y	0.8235*	0.000
Y^2	-0.0312*	0.000
HDI	-0.2958*	0.000
RE	-0.1952*	0.000
TECH	-0.1751*	0.000
Constant	1.8643*	0.000
Model 2: $CO_{2,it} = f[\ln Y_{it}, \ln Y_{it}^2, \ln HDI_{it}, \ln RE_{it}, \ln TECH_{it}, (\ln RE*\ln TECH)_{it}]$		
Variables	AMG	
	Coeff	Prob
Y	0.6589*	0.0000
Y2	-0.0211*	0.0000
HDI	-0.3823*	0.0000
RE	-0.2742*	0.0000
TECH	-0.1884*	0.0000
RE*TECH	-0.2003	0.0000
Constant	1.8522***	0.0510

Note: * and *** designate the significance level at 1%, and 10% respectively.

approach shown in Table 9 discover that two-way causality presents between human development, renewable energy, and technological innovations with CO_2 emissions, while one-way causality is observed from income growth to carbon emissions, human development, renewable energy, and technological innovations. The causality tests findings explore that a two-way causality link between the renewable energy use and technological innovation with carbon emission. This implies that these indicators cause the carbon emission. These results are in line with the previous literature proposed by Raza et al. (2015), and Usman and Radulescu (2022). All declared causality findings have policy suggestions as technological innovations are seen to encourage the protection of environmental sustainability without hindering the pace of economic growth trajectory. This relationship (between CO_2 emission and GDP growth) is evidenced by (Apergis and Payne 2015; Dogan and Turkekul 2016). This theory is supported by the literature, and it is crucial to highlight the fact that renewable energy and technological innovations are increasing ecological integrity in E-7 economies (Kasman and Duman 2015; Jiang at. el., 2022). Even though such findings have many ecological implications, as vigilance is recommended for the G-7 policymakers and their respective government officials, there is require to coast from non-renewable intensive energy blends to cleaner and alternatives that are presumed to be greener and eco-friendly.

6 Conclusion and policy options

6.1 Conclusion

This paper investigates the impact of renewables and technology innovation in the EKC framework for E-7 nations spanning from 1995 to 2019 from the perspective of the SDG 13 campaigns to mitigate the influence of climate change. This paper applies a battery of second-generation modeling estimators that tackle the issue of CSD and heterogeneity in order to produce credible empirical results. This research employs the CS-ARDL method, as well as the AMG method, and the D-H causality test. The level of environmental degradation in E-7 economies is explained by a number of interrelated factors, and a Westerlund long-run relationship test validates the existence of a long-run link between these factors. The findings from this study

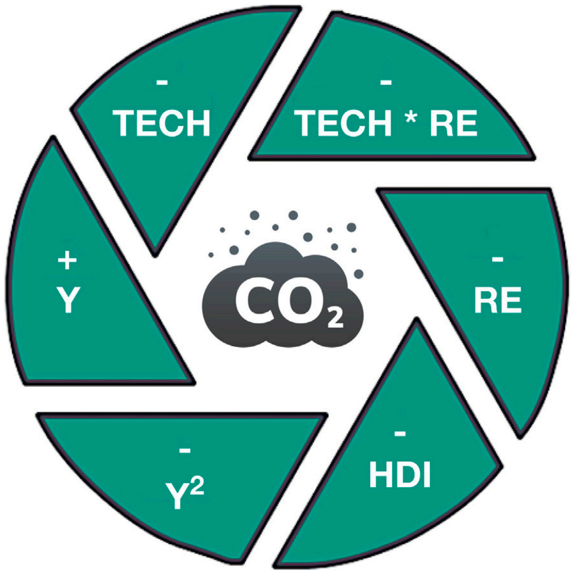

FIGURE 4
AMG-based empirical scheme.

provide further evidence of the EKC phenomena in E-7 economies. This finding is consistent with the group's understanding of emerging and industrialized nations as places where economic activities are carried out without regard to a sustainable environmental. Economic growth appears to be prioritized in comparison to environmental quality in this bloc. The empirical findings also showed that renewables and technological advancements enhance environmental quality. This suggests that within the tide of global and economic interconnectedness, a consciousness of environmental issues is making its way into the blocs. We must make a concerted effort to switch to renewable energy sources like biomass, hydro and solar power because of their proven environmental benefits.

6.2 Policy recommendations

Furthermore, the results of this study provided additional sustain for the importance of implementing the recommended policies. The recommendation for action comprises the following:

The EKC proposition in E-7 economies needs to diminish pollution levels on its course for boosts real income growth levels in the region. The benefits of a cleaner environment make it imperative that we make the switch to renewable energy sources. Therefore, all people concerned, including public officials, should work toward a new paradigm of clean energy technology by shifting the bloc's energy balance away from conventional energy sources like fossil fuels. Tree-planting initiatives, for example, can help lessen the impact of deforestation and are one way in which the blocs might work to prevent environmental degradation. The results acquired in this paper are in line with predictable findings. Comparable to this research, the empirical outcomes of various research papers explore that technological innovation significantly diminishes energy deployment and the level of environmental pollution level by saving energy.

Increasing R&D expenses and supporting scientific investigation in E-7 economies contribute to the expansion of new and modern technologies and the perfection of accessible technologies. In this pursuit, technological advancement also enhances production levels and diminishes environmental deficit influences on real GDP growth. The installment of technological progress at the sectoral level (i.e., agriculture, services, and industrial) offers the prospect to get hold of higher productivity with less ecological cost employing the identical input. Furthermore, the deployment of energy-saving modern technology commonalities at all phases of each sector's life cycle resources a lessening in total pollution level. The support for the adoption of environmental legislation and the impediments that prevent patents from being completely utilized in the related industries should be decomposed by environmental regulations that the E-7 economies should adopt. The E-7 economies should also implement various policies to spur the development of environmental patents and promote their dissemination. Moreover, the government of these economies should also redesign strategies to enhance the proportion of renewable and alternative energy deployment in the total energy mix, progressively reinstating fossil fuel energy sources with alternative and renewable/cleaner energy sources. The central authorities of E-7 economies should reduce the utilization of fossil fuels and non-renewable power sources and search to develop the impending of cleaner and alternative power sources. Developing responsiveness and awareness of these alternative power sources, supporting the deployment of renewable energy, escalating investment levels in the cleaner and alternative power sector, and exempting the preliminary tax for renewable energy schemes should be put into practice.

As a future line of inquiry, this study examined the EKC phenomenon's applicability for E-7 economies; other scholars can broaden the EKC argument by taking into account covariates like population and urbanization in an asymmetric frame-work for other blocs like G-20, ASEAN, BRICS, and others. Moreover, this research can be comprehensively extended by examining the influences of financial development, population, green growth, and some other technological, and socio-economic determining of resources management and environmental sustainability on dissimilar proxies of environmental pollution. In addition, a country and sector-wise analysis can also be performed for redesigning specific policy-making objectives. Besides, the indirect influences of technological development on carbon

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TABLE 9 Findings of D-H causality test.

Hypothesis	W-Stat	Stats	Prob	Remarks
Y ⇏ CO_2	6.2162*	4.9782	0.0000	Y ⇨ CO_2
CO_2 ⇏ Y	4.0172*	4.2281	0.0000	
HDI ⇏ CO_2	5.9562**	5.1272	0.0310	HDI ⇐ ⇒ CO_2
CO_2 ⇏ HDI	4.1119*	4.0091	0.0020	
RE ⇏ CO_2	10.2836**	9.0002	0.0400	RE ⇐ ⇒ CO_2
CO_2 ⇏ RE	5.3921***	5.209	0.0510	
TECH ⇏ CO_2	3.9962**	3.7621	0.0492	TECH ⇐ ⇒ CO_2
CO_2 ⇏ TECH	4.6823*	3.9943	0.000	
Y ⇏ HDI	4.3628*	6.8332	0.000	Y ⇨ HDI
HDI ⇏ Y	1.7634	1.2891	0.1072	
Y ⇏ RE	4.9821*	3.7921	0.0030	Y ⇨ RE
RE ⇏ Y	4.1982	1.6234	0.0812	
Y ⇏ TECH	7.0018*	6.9825	0.0000	Y ⇨ TECH
TECH ⇏Y	3.3982	0.9886	0.6732	
RE ⇏ HDI	4.1811*	5.0888	0.0000	RE ⇐ ⇒ HDI
HDI ⇏ RE	6.9723*	8.7632	0.0000	
TECH ⇏ HDI	9.3216*	12.9853	0.0000	HDI ⇐ ⇒ TECH
HDI ⇏ TECH	5.6964**	8.5683	0.0000	
TECH ⇏ RE	5.9745*	7.0321	0.0001	TECH ⇨ RE
RE ⇏ TECH	5.3561*	5.9542	0.0000	

Note: *, ** and *** designate the significance level at 1%, 5%, and 10% respectively. The symbols ⇨ and ⇐ ⇒ represent one-way and two-way causality relationship, respectively.

emissions in the E-7 economies can be investigated within the model.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.databank.worldbank.org/indicator/NY.GDP.PCAP.CD/1ff4a498/PopularIndicators. Accessed date: (02 September 2022).

Author contributions

NS: conceptualization, software, methodology, interpreted results, and writing-original draft preparation. MU: conceptualization, formal analysis, validation, project administration. MR: abstract, supervision, conclusion, and review and editing. CS: literature review, review, and editing; CS: introduction, visualization, and review and editing CT: results improvement, data curation, review, and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The prominence of fossil energy resources in ecological sustainability of BRICS: The key role of institutional worth

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Introduction: The relationship between fossil fuel energy resources and environmental degradation has been quantified from theoretical and empirical perspectives. However, none of these studies has considered the conditioning role played by institutions in the nexus, especially for BRICS countries. Therefore, the current study examines the moderating role of institutional quality using annual data from 1996–2018 for BRICS countries.

Method: The study employs the novel cross-sectional augmented autoregressive distributed lags (CS-ARDL) estimator, robust to cross-sectional dependency and heterogeneity, for short-run and long-run estimation. Moreover, augmented mean group (AMG) and common correlated effects mean group (CCEMG) estimators are used for robustness analysis.

Results: The finding reveals that fossil fuel energy resources, globalization, and growth significantly positively affect the ecological footprint, whereas the institutional quality significantly negatively effects the ecological footprint in BRICS countries. Furthermore, the interaction term of institutional quality with fossil fuel energy resources significantly negatively moderates the fossil fuel energy-EFP nexus. Finally, we performed the Dumitrescu and Hurlin (DH) panel causality analysis to determine the causality direction between the variables. Except for intuitions quality and growth, we found a unidirectional causality for explanatory variables and EFP.

Discussion: The study provides novel empirical evidence and recommends the importance of institutional quality for environmental sustainability.

KEYWORDS

fossil fuel, ecological footprint, institutions, CS-ARDL, BRICS

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1 Introduction

The intensity of globalization, development, energy use and environmental degradation have constantly grown globally and are expected to rise more in the upcoming time (Rafique et al., 2021; Ullah I. et al., 2022). Many countries' energy infrastructures, whether industrialized or emerging, depend on fossil fuel sources (coal, oil, natural gas) (Ali et al., 2021). Countries are speeding up economic progress, raising living conditions that raise fossil fuel usage in manufacturing and activities associated with fostering economic development, consequently degrading the environmental condition of emerging economies (Saidi et al., 2020). Using fossil fuel resources has several concerns, including environmental repercussions, shortage, supply risk, and price uncertainty, which place them in the core of change to carbon-free economies. Furthermore, greenhouse gas (GHG) emissions are the crucial contributing element, causing global warming and, therefore, environmental impacts; out of that, carbon dioxide (CO_2) emissions constitute 76 percent of the overall GHG emissions (Caglar et al., 2022; Shah et al., 2022). Most CO_2 emissions stem from combusting fossil fuel resources, like coal, oil, and natural gas, that comprise over 80 percent of the global energy needs (Khan K. et al., 2022; Ullah et al., 2022d).

The BRICS (Brazil, Russia, India, China, South Africa) is a group of emerging economies regarded for about 40 percent of the world's population, contributes 21 percent of the GDP, conserves nearly 40 percent of the world's energy, and emits 42 percent of worldwide CO_2 emissions from fossil fuel burning (Ummalla and Goyari, 2021). The economic growth of the BRICS is always expanding as they progress to become industrial economies. As an outcome, the energy demand has increased to accommodate the demand of numerous sectors, such as the industrial, transport, economic, and residential sectors (Adedoyin et al., 2021). Fossil fuels monopolize the aggregate primary energy output in the BRICS economies; however, Brazil consumes a large amount of biofuel in transportation and India consumes a considerable amount of biomass in residential consumption. Hence the percentage of fossil energy resources in primary energy supply fluctuates from 55 percent in Brazil to 75 percent in India and about 90 percent in China, Russia and South Africa, although the world's average is approximately 80 percent (IEA, 2021).

Consequently, the importance of the BRICS nations in the global consumption pattern of natural resources and energy production is expanding substantially. As per British Petroleum (BP) Statistical Review of World Energy (2021), the primary power source of Russia is natural gas and the proportion of gas in its structure of energy consumption in 2021 was 53.6 percent; China, India, and South Africa rely on coal; 61.2%, 57.3%, and 65.4%; however, Brazil relies on oil, 56.3 percent. There is a rise in the proportion of oil in the primary energy usage structure in the BRICS, except for China, whose statistics are inclined to fall from 20.5 percent in 2006 to 18.4 percent in 2021. Whereas the percentage of coal decreased dramatically in all economies apart from India, in which it nearly maintained its 2006–2019 level of 54.9%. Some countries in this group are net importers or exporters of particular fossil resources due to the interrelationship between local consumption and production. China is the world's largest supplier of coal and a substantial producer of petroleum but is also the biggest importer of fossil resources to meet its domestic demand. Russia is a major exporter and producer of fossil fuels of all forms. India generates some local coal, oil, and gas but is a net importer of coal, oil, and gas. Yet, India refines crude oil in surplus of its national requirements and exports it as a refined product. South Africa imports oil and gas while exporting coal, whereas Brazil imports coal and gas and exports oil (IEA, 2021).

Institutions can be regarded as a set of rules, principles, and decision-making mechanisms that operate at the stages of public entities that focus primarily on environmental situations and resource regulations (Nadeem et al., 2022). Individuals and society achieve maximum social protection when they strive to decrease risks to people's lives and advance environmental and social concerns. Sound and high environmental regulations implemented by government entities in a country are among the most important drivers of environmental quality improvement (Jianguo et al., 2022). Thereby, quality institutions must be presumed as inputs for offering valuable laws which, once applied effectively, will assist in reducing environmental threats in the world economy, thereby accelerating the intended level of sustainable development (Saidi et al., 2020). Moreover, robust institutions can impact economic development and ecological deterioration by ensuring polluting companies' locations and limiting pollution havens. In addition, the involvement of institutions could stimulate sustainable development, which might lead to an upsurge in environmental deterioration in the absence of appropriate rules and regulations. According to Azam et al. (2021), improved institutions are required for environmental preservation and sustainable natural resource management. Nevertheless, the function of institutions in environmental sustainability has not been examined thoroughly in the literature, particularly in BRICS economies.

Due to the lack of evidence in prior research and the absence of studies for BRICS, it is essential to conduct more empirical research to recognize the role of institutions and fossil energy resources in environmental sustainability. By evaluating the significance of fossil energy resources and institutional quality in environmental sustainability, this study adds value to the worldwide discussion on environmental sustainability in the BRICS. In addition, the role of institutions in addressing the effects of fossil energy resources on environmental sustainability is estimated to design policies that offset the negative environmental effects of fossil fuels. Given the importance of environmental sustainability, an examination of the importance of institutions in BRICS countries will assist with the development of a better knowledge of the impact of institutional quality and bring new perspectives to environmental quality. Due to a potential heterogeneity among BRICS countries, robust and more contemporary econometric panel methods are used in this study to produce efficient results, which is an additional innovation.

2 Literature review

2.1 Fossil fuels and environment quality

The relationship between ecological sustainability and primary energy usage (energy derived from fossil fuel resources such as coal, oil and gas) is a topic of intense discussion in energy-environment research. Using carbon dioxide (CO_2) emission as a measure of environmental sustainability, numerous studies demonstrate a long-term, unidirectional relationship between CO_2 and primary energy consumption (Caglar et al., 2022; Kanat et al., 2022; Ullah et al., 2022d). Global environmental authorities and prominent environmentalists have identified energy usage as the primary source of environmental contamination (Ullah et al., 2022b). Even so, industrialized nations continue to consume energy and degrade the atmosphere; however, they are willing to accept a carbon price and support the use of renewable energy (Rafique et al., 2021). Numerous studies from the past substantiated energy-use-driven pollution and ecological degradation (Adedoyin et al., 2021; Gyamfi et al., 2021; Ummalla and Goyari, 2021). Luo et al. (2021) examined the impact of energy consumption, green investment, and technological innovations on CO_2 emission in selected Asian countries. The authors found that green investment and innovation are helpful in reducing CO_2 emission, while conventional energy resources such as coal, gas and oil increases the CO_2 emission in selected economies, and hence, damaging the envionomental quality.

Using the novel autoregressive distributed lag approach, Adedoyin et al. (2021) analyzed the effect of energy usage on CO_2 emissions. They revealed that increasing energy usage has a positive effect on CO_2 emissions. Awodumi and Adewuyi (2020) studied the influence of non-renewable energy and economic growth on CO_2 emission for a group of African oil-producing countries by incorporating other factors like trade openness, urbanization and income disparity. The results show that urbanization and income disparity significantly minimize environmental deterioration. In contrast, oil and gas consumption and trade openness degraded the environmental condition in most African countries. Khan et al. (2020) studied the relationship between economic growth, energy consumption, and CO_2 emission in Pakistan from 1965 to 2015 using annual data set. They indicated that long-term and short-term energy use increases CO_2 emissions in Pakistan. In addition, as conventional forms of energy usage, oil and coal raise CO_2 emissions, whereas natural gas usage decreases CO_2 emissions, preserving the health of Pakistan's ecosystem. According to (Munir and Riaz, 2020), a growth in coal, gas, and oil adds to a spike in CO_2 emissions and *vice versa*. However, the emission patterns are not equally applicable to the sample countries.

Ullah I. et al. (2022a) utilized data from low and high globalized OECD nations from 1996 to 2019 to examine the relationship between globalization, financial inclusion, economic complexity, economic growth, energy consumption, and carbon emissions. The authors reported that using fossil energy resources negatively impacts the sustainability of the environment *via* increasing CO_2 emissions in both low and high globalized OECD countries. In contrast, Ozcan et al. (2020) examined the dynamic relationship among energy use, economic growth, and ecological deterioration for 35 OECD economies from 2000 to 2014. The outcomes of the study reported the improvement in environmental quality driven by the energy usage trend and economic growth in these nations. Thus, growth policies and energy usage trends have evolved to align with the environmental strategies of the countries. Likewise, Arminen and Menegaki (2019) found no correlation between high-income countries' energy usage and CO_2 emissions. According to Ullah et al. (2022b)'s analysis, the usage of fossil fuels is the primary cause of Vietnam's rising CO_2 emissions. They also advocate switching from fossil fuels to renewable alternatives to improve environmental sustainability. Ali et al. (2021) reached similar conclusions for Vietnam, concluding that fossil fuel consumption is a major contributor to CO_2 emissions. By using the data of European union countries for the period 1980 to 2018, Zhen et al. (2022) also concluded that conventional energy resources have adverse impact on environmental quality.

2.2 Institutions and environment quality

The link between institutional quality and environmental sustainability has attracted considerable interest in recent years. Current research has highlighted energy consumption, economic growth, trade openness, financial development and foreign direct investment as the main channels by which institutions influence the quality of the environment (Tamazian and Bhaskara Rao, 2010; Adams and Acheampong, 2019; Khan et al., 2019; Saidi et al., 2020; Azam et al., 2021; Ullah et al., 2022b; Jianguo et al., 2022). Dasgupta and De Cian (2018) explained that governance, economic, and social preparedness, institutional quality impacts pollution mitigation. They further indicated that institutions have a key role in creating renewable technology and minimizing environmental deterioration in every economy since they assist policymakers in successfully enforcing and managing environmental regulations.

Abid (2016) investigated the effect of institutional quality on CO_2 emission in African nations and found that effective institutions aid in decreasing CO_2; supported by the data, they concluded that regulations linked with law contribute to improving the environmental quality in Africa. Analyzed by Ibrahim and Law (2016), the same conclusions were reached for African nations. Wang et al. (2018) opted for linear regression instead of a nonlinear one and evaluated corruption's interaction with other factors such as trade, population growth, GDP, and urbanization. The results demonstrated that corruption control directly impacts lowering CO_2 emissions. Yet, the effect varies when incorporating CO_2 and GDP interaction terms. Furthermore, corruption has the indirect influence of delaying the turning point of the EKC curve. Sarkodie and Adams (2018) investigated the effects of renewable and non-renewable energy, institutional quality and CO_2 emissions in South African nations. The results demonstrated that institutions' quality and renewable energy reduce CO_2 emissions in South African countries, whereas non-renewable energy increases CO_2 emissions. Egbetokun et al. (2020) evaluated the impact of institution efficiency on six different indicators of environmental pollutants in Nigeria from 1990 to 2016 using the ARDL model. They found that strong institutions considerably decrease CO_2 emissions. Khan et al. (2019) used Driscoll-Kraay standard error regression analysis to validate the EKC hypothesis for the BRICS countries from 1996 to 2017 and confirmed the EKC association while controlling governance variables.

Nadeem et al. (2022) highlighted the significance of institutions for environmental quality and suggested that effective instituions are important for preserving efficient resource allocation and enhancing the environmental quality. Wang et al. (2018) explained that corruption has direct and indirect effects on environmental quality since it undermines the effectiveness of institutions, encourages rent-seeking activities, and impedes the effectual execution of environmental legislation; however, corruption control assists in reducing emissions. By using the data from 1995 to 2018 and applying modern estimation techniques, Ullah et al. (2022b) explained in case of China that effective regulations significantly promote the environmental quality. Zhang et al. (2016) also indicated that control of corruption decreases carbon emissions indirectly *via* a mediation effect. Employing data from developing nations, Azam et al. (2021) have evaluated the impact of institutional quality on energy usage and environmental sustainability. They discovered that quality institutions positively affect the ecological variables CH4, CO_2, and forest land. Furthermore, they indicated that energy use is also positively affected by institutions' quality.

Another study conducted by (Godil et al., 2020) examined the impact of institutions' quality, economic growth, ICT, and financial openness on Pakistan's CO_2 emissions. According to the study, long-term economic expansion positively impacts CO_2 emissions, whereas institutional quality contributes to limiting CO_2. On the contrary, Hassan et al. (2020) found that the quality of institutions favorably influences CO_2 emission in Pakistan. According to (Asongu and Odhiambo, 2019), implementing environmental regulations reduces CO_2 emissions and improves the quality of the environment.

Salman et al. (2019) likewise found that institutional quality has a favorable impact on CO_2 reduction. Based on their findings, the authors concluded that efficiency institutions are crucial aspects of policies that will aid in reducing CO_2 emissions and boosting economic growth. Ahmed et al. (2020) examined Pakistan's financial growth, institutional quality, and ecological sustainability. According to the findings, there is a long-term symmetric and asymmetric relationship between institutional quality and financial growth, whereas institutional quality has an insignificant effect on ecological sustainability. Le and Ozturk (2020) analyzed the effect of institutional quality, government spending, and financial development on CO_2 emissions in emerging economies. According to the findings, governance, financial growth and energy use enhance CO_2 emissions. Jianguo et al. (2022) assessed the impact of institutional quality on the environmental sustainability of OECD economies and confirmed that CO_2 emission reduction strategies are effective. In addition, the authors indicated that strong institutions significantly moderate the impact of financial development on CO_2 emission reduction in OECD nations. In contrast, Khan H. et al. (2022) estimated the global data for the time 2002 to 2019 and concluded the adverse impact of institutional quality on environmental sustainability. Similarly (Obobisa et al., 2022), used data of 25 African countries for the period 2000–2018, and their results also suggest that promoting institutional quality lead to increase the CO_2 emission and impede the environmental quality.

All of the preceding discussion leads us to conclude that fossil fuel energy resources and institutions directly impact ecological sustainability. Moreover, institutions' effects on environmental quality can also manifest through indirect channels such as energy use, trade, FDI, and financial development. Nevertheless, the effects of fossil fuel energy resources and institutional quality on ecological sustainability are varied and contradictory. In addition, the relative importance of institutions might vary across countries, which can have different policy-related repercussions for the respective countries. Our study explores the dynamic linkages of fossil fuel energy resources and institutional quality in the ecological sustainability of BRICS.

3 Methodology

3.1 Theoretical framework and model

The ecological footprint (EFP) was first established by (Rees, 1996). The EFP measures human demands for natural recourses and comprises six sub-components: carbon footprint, cropland, grazing land, developed land, fishing grounds, and forest products. By integrating these six sub-components, the EFP reacts to the amount of nature nations possess and the extent to which they utilize productive natural resources (Ulucak and Bilgili, 2018). The EFP evaluates environmental deterioration as the use of resources by humans, while overall, earth utilization is a suitable measure of the influence of humans over natural resources. Nonetheless, EFP has arisen as a significant indicator of environmental damage. In addition, a rise in demand and supply of commodities results in increased usage of environmental resources and energy. A country's ecological footprint is growing due to its large demand for conventional fuels (Wang et al., 2020). Therefore, EFP is a comprehensive metric for ecological sustainability and has been used in many studies (Dogan et al., 2020).

Coal, oil, and natural gas are essential resources for a nation's energy output and governmental policies. While seeking sustainable growth, numerous developing nations have enacted different energy-saving and emissions-control legislation. However, owing to rising energy requirements in developing nations, their reliance on fossil energy sources cannot be alleviated in a short time; therefore, fossil fuels have become crucial to meeting energy needs. Fossil fuel energy is not only relevant to a country's national policy and energy sovereignty but also accountable for worldwide greenhouse gas emissions; thus, prior research has concentrated substantially on the consequences of fossil energy use on CO_2 emissions (Pao and Chen, 2019; Ullah et al., 2022d). Jonek-Kowalska (2022) demonstrates that during the energy transition procedure, the proportion of clean energy in the energy balance develops gradually, whereby the decline in the proportion of coal is countered by a rise in the percentage of natural gas. Therefore, developing economies cannot substitute oil and coal with biofuels by trade (Ali et al., 2021). Consequently, natural gas remains the favored alternative source, and fossil energy stays unchangeable. In the setting of a growing disparity between energy demand and supply, fossil resources are essential for developing economies to attain energy equilibrium. The dramatic surge in energy use will ultimately result in a rise in resource utilization and impact ecological sustainability. To promote sustainable growth, it is crucial to understand the impact of fossil-based energy sources on ecological sustainability in one of the fast-developing groups such as the BRICS.

Since the pioneering work of North (1990), this key role of institutions has been widely recognized in the literature. Institutions stimulate the private sector, enhance the efficiency of contract implementation, safeguard property ownership, and ensure the rule of law, and their freedom from political interference makes the execution of policy initiatives more effective (Salman et al., 2019). However, poor institutions present opportunities for corruption, an ineffective bureaucratic structure, rent-seeking by investors, and the absence of comprehensive environmental policy legislation (Khan et al., 2019). Institutions play a vital part in a country's growth also in environmental quality, and they can either improve or degrade ecological sustainability (Hassan et al., 2020). A strong institutional structure can enhance the government's abilities to properly manage environmental policy and combat corruption that may directly or indirectly affect the quality of the environment (Wang et al., 2018). Similarly, it is anticipated that institutional quality would play a significant influence on the social, political, and economic readiness to minimize environmental damage since institutions may contribute to the equal allocation of resources and power, hence improving environmental sustainability (Zhang et al., 2016). For the application of environmental laws, however, the importance of institutions soundness cannot be overstated, as institutional arrangements combat corruption and pave the way for strict environmental regulations necessary for a safe environment (Khan H. et al., 2022).

Given this theoretical context, it is clear that fossil energy resources and institutions' quality significantly impact ecological sustainability. Meanwhile, EFP's rise as a broader indicator of environmental sustainability gained prominence. The investigation of the influence of fossil fuel energy resources and institutions quality on EFP has received the least focus to date, particularly for BRICS. Eq. 1 gives the statistical means to demonstrate the model hypothesis:

$$\ln EFP_{it} = \beta_1 lnOil_{it} + \beta_2 lnGas_{it} + \beta_3 lnCoal_{it} + \beta_4 lnINQ_{it} + \beta_5 lnGLB_{it} + \beta_6 lnGDP_{it} + \varepsilon_{it} \quad (1)$$

In Eq. 1, EFP denotes ecological footprint *per capita* (hectares *per capita*), Oil, Gas, and Coal are the production of oil, gas, and coal. INQ is the composite index of institutional quality, GLB and GDP are the control variables, respectively denoting the level of globalization and gross domestic product *per capita*.

Furthermore, to empirically access the role of institutional quality in fossil energy resources and ecological sustainability nexus, the following Eq. 2 is estimated

$$\ln EFP_{it} = \beta_1 lnOil_{it} + \beta_2 lnGas_{it} + \beta_3 lnCoal_{it} + \beta_4 lnINQ_{it} + \beta_5 lnOil{*}INQ_{it} + \beta_6 lnGas{*}INQ_{it} + \beta_7 lnCoal{*}INQ_{it} + \beta_8 lnGLB_{it} + \beta_9 lnGDP_{it} + \varepsilon_{it} \quad (2)$$

3.2 Data

The study employed the data of BRICS economies from 1996 to 2018, which consists of the longest available data for all the sample countries. The ecological footprint *per capita* (global hectares) is used to proxy EFP and obtained from Global Footprint Network. The data on fossil fuel energy resources, including coal, oil, and gas (consumption), is taken from BP statistics. The World Governance Indicators are used to proxy institutional quality. We considered all six components of WGI: corruption control, government effectiveness, rule of law, voice and accountability, political stability and regulatory quality. Then, a single index for institutional quality (INQ) is calculated by taking the average of these six components.

Finally, the data of control variable economic growth (GDP *per capita*) is taken from World Development Indicators (WDI) and the KOF globalization index is used to proxy the level of globalization.

3.3 Estimation method

3.3.1 CD and slope homogeneity

The suggested model must be supported by empirical evidence. Consequently, the most recent econometric approaches are employed for this goal, with panel data concerns. For instance, cultural, economic, and geographical linkages among the sampled countries may lead to cross-sectional dependence (CD), a critical element of panel data analysis. Driven by economic linkages, the BRICS countries are likely to be cross-sectionally dependent. Consequently, it is essential to assess the possibility of CD, as ignoring CD issue would lead to inappropriate and unreliable assessments of cointegration and stationarity characteristics (Adedoyin et al., 2021; Luo et al., 2021). The Pesaran (2015) CD check is performed to determine the dependence of cross-sections using the following equation.

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=0}^{N-1}\sum_{j=i+1}^{N} p_{ij}\right) \tag{3}$$

In Eq. 3, *CSD* and *N* represent cross-sectional dependency and number of cross-sections, respectively, term *T* shows time, and *p* indicates error correlation among *j* and *i*.

In addition to cross-section dependency, it is essential to investigate slope heterogeneity issues, as regression coefficients are expected to vary across cross-sections. This is asserted that neglecting slope heterogeneity concerns results in ambiguous estimates. Although chosen BRICS countries are interconnected in various respects, there are substantial differences among them regarding this study. For instance, they vary n terms of EFP *per capita*, energy resource use, globalization, and other macroeconomic aspects. Consequently, the slope homogeneity test developed by Hashem Pesaran and Yamagata (2008) has been adopted. Eqs 4, 5 illustrate the standard mathematical form of SHT.

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - k\right) \tag{4}$$

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - 2k\right) \tag{5}$$

3.3.2 Panel unit root test (CADF, CIPS)

Identifying the stationary levels of the variables has been a vital part of empirical estimates in the literature on environmental economics, particularly when the dataset does include multiple economic indicators (Wang et al., 2018; Khan et al., 2019). Although it is important to determine the integration order to obtain dynamic parameters, the literature suggests several tests for panel units' roots. This study focuses on the BRICS economies, each with its own fossil resources and ecological footprint levels. Therefore, the conventional panel unit root tests would generate inaccurate and skewed results. To overcome this, we employ robust panel estimate approaches, such as CIPS and CADF, proposed by (Pesaran, 2007). CIPS is an enhanced form of IPS that determines CADF statistics for the whole panel using the average of each CADF test result. In the context of a cross-section dependency problem and heterogeneity, both CIPS and CADF tests are efficient and provide reliable results. The following Eq. 6 is used to calculate CIPS statistics.

$$\widehat{CIPS} = \frac{1}{N}\sum_{i=1}^{n} CADF_i \tag{6}$$

3.3.3 Westerlund cointegration

Considering both CD and heterogeneity issues, the panel cointegration method gives more accurate and efficient results. Possibly, the panel cointegration approach is essential that is generally appropriate for the shorter cross-sectional's time-series elements. Recent research (Jianguo et al., 2022; Zhen et al., 2022) has attempted to apply (Westerlund, 2007) the panel cointegration method, which is based on the assumption of CSD. The Westerlund test for panel cointegration accounts for CSD and SLH, which are the critical aspect in panel data estimation (Zhen et al., 2022). The approach consists of four statistical tests, including Gt, Ga, Pt, and Pa. The Gt and Ga are group statistics that are autonomous of the information aggregated by the error correction technique. The calculation conditions for the cointegration test of Westerlund are represented in Eq. 7.

$$\Delta y_{it} = \sigma_i d_t + \delta_i\left(y_{i(t-1)} + \varnothing_i x_{i(t-1)}\right) + \sum_{j=1}^{m}\delta_{ij}\Delta z_{i(t-1)} + \sum_{j=1}^{m}\theta_{ij}\Delta x_{i(t-1)} + \epsilon_{it} \tag{7}$$

3.3.4 CS-ARDL

Finally, the cross-section's dependency is addressed by employing a recently developed CS-ARDL approach. Unlike other standard and pooled mean group techniques, the CS-ARDL is an effective and reliable method for estimating long-term effects (Zhen et al., 2022). In addition, the CS-ARDL method is effective against slope heterogeneity and cross-sectional dependency problems but also for a number of other concerns, such as non-stationarity, endogeneity, and unknown variances, which omission may lead to misleading and erroneous outcomes (Wang et al., 2018). The mathematical form of the CS-ARDL model can be represented as:

TABLE 1 CSD and slope homogeneity results.

Variables	Test-statistics
EFP	17.514*** (0.0000)
Oil	19.712*** (0.0000)
Gas	22.367*** (0.0000)
Coal	28.637*** (0.0000)
INQ	31.367*** (0.0000)
GLB	27.374*** (0.0000)
GDP	21.672*** (0.0000)
Slope homogeneity test	
Statistics	Values
Delta-tilde	28.357*** (0.0000)
Delta-tilde Adjusted	23.822*** (0.0000)

Note: *** explicate 1% significance level; values in ( ) are *p*-values.

$$\Delta EFP_{it} = \sigma_0 + \sum_{j=1}^{p} \pi_{it} \Delta \mathrm{EFP}_{it-j} + \sum_{j=0}^{p} \gamma_{it} Z_{it-j} + \sum_{j=0}^{p} \delta \bar{X}_{it,t-j} + \mu_{it} \quad (8)$$

Where in Eq. 8 $\bar{X}_t = (\Delta\overline{EFP}_t, \bar{Z}_t)$, Whereas $\Delta\overline{EFP}_t$ and $\bar{Z}_t$ are, respectively averages of the dependent and independent variables. The term p shows lags of respective variables in the model. Furthermore, $\Delta\mathrm{EFP}_{\mathrm{it}}$ is the dependent variable, and Z_{it} denotes all explanatory variables, including oil, gas, coal, INQ, GDP, and GLB. To confirm the stability of CS-ARDL results, we applied AMG and CCEMG tests for robustness. The AMG and CCEMG tests are efficient in handling heterogeneity and cross-sectional dependence problem by using a common dynamic process (Pesaran, 2007; Luo et al., 2021).

3.3.5 Causality DH

The CS-ARDL estimate approach gives long-run coefficients and cannot identify the causal direction among covariates, while causality is vital for making policy direction. Parallel to the study of (Khan et al., 2019), we also perform the panel causality analysis developed by Dumitrescu and Hurlin (2012) to determine the relationship among fossil fuel resources, institutional quality, globalization, GDP, and EFP. The Dumitrescu and Hurlin (DH) causality method qualifies for heterogeneity and conditional dependence (CD) in the panel data, whereas the vector error correction model (VECM) granger causality test does not. Furthermore, the DH method effectively gives consistent results for limited data. The following Eq. 9 is estimated to examine the causal relationship among variables.

$$y_{it} = \sigma_i + \sum_{i=1}^{p} \gamma_i^p y_{it-n} + \sum_{i=1}^{p} \varphi_i^p x_{it-1} + \varepsilon_{it} \quad (9)$$

Where x and y are underlying variables for n cross-sections in t time. The terms γ_i^p and φ_i^p indicate the autoregressive parameters and regression coefficient across countries, respectively.

4 Results and discussion

We begin our analysis by examining the cross-sectional dependency (CSD) and slope homogeneity (SLH) tests to select the appropriate regression method. As confirmed by Luo et al. (2021), the first-generation tests give inconsistent results in the presence of CSD. Table 1 represents the results of CSD test proposed by (Pesaran, 2015), which confirms the rejection of the null hypothesis (no CSD) for each selected variable, as the *p*-values are significant at 1% level. This indicates that a shock in any variable in one sample country will also affect the other sample countries. Similarly, the lower panel of Table 1 also confirms the rejection of the null hypothesis that the slope is homogeneous and confirms the slope heterogeneity.

The confirmation of CSD and slope heterogeneity indicates that further analysis should be carried out using second-generation econometric techniques. Consequently, the next important step is to check the stationarity level of the

TABLE 2 Stationarity results.

Variables	Level		First-difference		Order of integration
	CADF	CIPS	CADF	CIPS	
EFP	−2.432	−2.121	−3.536***	−4.546***	I (1)
Oil	−1.475	−1.474	−3.473***	−4.373***	I (1)
Gas	−2.138	−1.574	−4.271***	−4.537***	I (1)
Coal	−1.433	−1.574	−4.647***	−4.182***	I (1)
INQ	−1.485	−2.462	−4.546***	−4.456***	I (1)
GLB	−1.474	−1.548	−3.467***	−4.372***	I (1)
GDP	−2.374	−1.647	−3.536***	−4.812***	I (1)

Note: *** explicate 1% significance level.

TABLE 3 Cointegration results.

Statistic	Values	Z-values	*p*-values	Robust *p*-values
Gt	−5.647	−3.372	0.039	0.018
Ga	−9.281	−4.372	0.000	0.000
Pt	−14.356	−3.811	0.000	0.000
Pa	−11.893	−4.219	0.001	0.001

TABLE 4 CS-ARDL results.

Explanatory variable	Coefficients	t-stats	*p*-values
Long-run estimates			
Oil	0.241**	2.327	0.028
Gas	0.129**	2.738	0.019
Coal	0.211***	4.384	0.000
INQ	−0.091***	−3.833	0.000
Oil*INQ	−0.117*	−1.738	0.049
Gas*INQ	−0.098**	−2.829	0.015
Coal*INQ	−0.081***	−3.948	0.000
GLB	0.078**	−2.882	0.015
GDP	0.251***	4.532	0.000
Short-run estimates			
ECM	−0.319***	−3.564	0.000
Δ Oil	0.201*	−1.814	0.049
Δ Gas	0.181**	2.135	0.038
Δ Coal	0.092**	2.347	0.028
Δ INQ	−0.051*	−1.911	0.046
Δ Oil*INQ	−0.073**	−2.711	0.020
Δ Gas*INQ	−0.081	−1.397	0.611
Δ Coal*INQ	−0.067***	−4.728	0.000
Δ GLB	0.026***	4.382	0.000
Δ GDP	0.118***	5.291	0.000

Note: "***," "**," and "*" explicate 1%, 5%, and 10% significance level.

variables. Considering the CSD, the second-generation unit root tests CADF and CIPS are applied and results are given in Table 2 The stationarity results in Table 2 indicate that all the variables are stationary at the first difference by both tests at 1% significance level.

The long-run relationship among variables is confirmed by employing (Westerlund, 2007) cointegration, as it is considered a robust approach in the presence of CSD (Jianguo et al., 2022). Table 3 reports the cointegration results. The *p*-values of all four

TABLE 5 AMG and CCEMG results.

Explanatory variable	AMG	CCEMG
Oil	0.323** (.003)	0.273*** (0.001)
Gas	0.183*** (.000)	0.093*** (0.001)
Coal	0.217*** (.001)	0.219*** (0.001)
INQ	−0.072*** (.001)	−0.087*** (0.000)
Oil*INQ	−0.083** (.041)	−0.171** (0.021)
Gas*INQ	−0.112*** (.002)	−0.067*** (0.000)
Coal*INQ	−0.091* (.0521)	−0.129** (0.011)
GLB	−0.213*** (.000)	−0.189*** (0.000)
GDP	0.327*** (.000)	0.278*** (0.000)
RMSE	0.0073	.0071
Wald	45.237	35.758
Prob	(0.000)	(0.000)

Note: "***," "**," and "*" explicate 1%, 5%, and 10% significance level.

statistics Gt, Ga, Pt, and Pa are found significant, hence, rejecting the null hypothesis of no cointegration and confirming the long-run relationship among the selected variables.

After confirming the long-run relationship among variables, the long and short-term parameters are estimated through the CS-ARDL method. The CS-ARDL results in Table 4 revealed that oil, gas, and coal significantly contribute to the ecological footprint in BRICS, both in the long and short run. A 1% increase in oil, gas, and coal upsurge the ecological footprint by .241%, .129%, and .211% in long run, while .201%, .181%, and .092% in short run, respectively. This indicates that fossil fuel energy resources are the substantial cause of environmental degradation in BRICS, as evident by the positive impact of oil, gas and coal on the ecological footprint. The larger environmental damage is done by oil as compared to gas and coal. Overall, the findings are consistent with outcomes of some previous studies carried out in BRICS economies (Dogan et al., 2020; Ummalla and Goyari, 2021; Caglar et al., 2022) and reinforce that fossil fuel energy resources are responsible for a high ecological footprint in BRICS. For institutions' quality, the results indicate that 1% rise in INQ condenses the ecological footprint by .091% in the long run, whereas .051% in the short run. Our findings are similar to those of (Dogan et al., 2020; Saidi et al., 2020), who investigated the institution's quality-environment nexus and contradict those of (Khan H. et al., 2022; Obobisa et al., 2022). The mixed empirical results in the literature indicate that institutional quality could play a moderating role as bad institutions result in inefficiencies and environmental degradation, whereas good institutions improve environmental quality. We, therefore, introduced the interactive term between institutions' quality and fossil fuel energy resources

TABLE 6 DH causality results.

Null hypothesis	W-stats	Z bar-stats	Prob	Result
Oil –» EFP	5.748	2.923	0.002	Unidirectional causality
EFP –» Oil	3.575	1.525	0.398	
Gas –» EFP	4.857	2.273	0.021	Unidirectional causality
EFP –» Gas	2.811	.489	0.631	
Coal –» EFP	5.914	3.092	0.001	Unidirectional causality
EFP –» Coal	3.793	1.281	0.211	
INQ –» EFP	6.578	3.759	0.000	Bidirectional causality
EFP –» INQ	6.649	3.818	0.000	
GLB –» EFP	5.684	2.763	0.002	Unidirectional causality
EFP –» GLB	2.792	.483	0.629	
GDP –» EFP	5.858	3.083	0.001	Bidirectional causality
EFP –» GDP	5.499	2.685	0.003	

to investigate whether INQ can moderate the resources-environment nexus. Our estimates show that the interaction of INQ with all fossil resources, including oil, gas, and coal, negatively affects the ecological footprint in both the long and short run. The results are statistically significant for all interaction terms except the interaction of (Gas*INQ), which is insignificant; yet carries a negative sign. Therefore, the moderating influence of INQ indicates that the adverse impact of fossil fuel energy resources can be mitigated with the sound quality of institutions in BRICS. The result supports the arguments found in the literature that good institutions are critical to the transformation of fossil fuels sources into sustainable environmental outcomes through appropriate technology, improved policy-making and execution (Saidi et al., 2020; Azam et al., 2021). Rules aimed at improving environmental quality are more likely to be enforced in a setting with high institutional quality than in one with low institutional quality (Khan et al., 2019).

Turning to the effect of control variables, we found that globalization (GLB) significantly contributes to the ecological footprint (EFP). A 1% increase in GLB increases the EFP by .078% and .026%, respectively, in the long and short run. Le and Ozturk (2020) assert that increased globalization as a result of greater trade, urbanization, and industrialization leads to environmental quality degredation because of the heavy reliance on primarily fossil fuel-based energy sources. Finally, we found that economic growth (GDP) also has an augmenting effect on EFP. A 1% increase in GDP uplift the EFP by .251% in the long run and .118% in the short run. The results are in line with recent literature suggesting that countries at their early stage of development pay less attention to the quality of their environment while striving to achieve more growth (Salman et al., 2019; Saidi et al., 2020; Ullah et al., 2022d; Jianguo et al., 2022).

The robustness of the CS-ARDL results is confirmed by employing AMG and CCEMG methods. The AMG and CCEMG test results in Table 5 show that all the explanatory variables are statistically significant and consistent with the CS-ARDL results given in Table 4, thus ensuring the robustness of long-run results.

Finally, the results of the causal association between explanatory variables and ecological footprint (EFP) are given in Table 6. Accordingly, there is unidirectional causality between oil and EFP, gas and EFP, coal and EFP, and, GLB and EFP. It shows that fossil fuel resources are not sustainable for BRICS since natural resources cannot regenerate (Nathaniel et al., 2021). Thus, this leads to lose the biocapacity and causes EFP. These findings are consistent with previous studies indicating a unidirectional relationship between fossil fuels and ecological footprint (Zafar et al., 2019; Ibrahiem and Hanafy, 2020). However, there is bidirectional causality between INQ-EFP and GDP-EFP. The rapid economic growth in BRICS countries prompted the high use of natural resources and increased the dependency on fossil energy resources, consequently increasing the EFP level. Similarly, the institution's quality is significant causing factor to EFP as it endorses the setting and implementation of environmental regulations and promotes environmental quality.

5 Conclusion and policy suggestions

Our analysis focuses on empirically examining the impact of fossil energy resources and institutional worth on the environmental sustainability of BRICS for the period 1996–2018. The study employed second-generation tests to identify the long-run relationship and stationarity level of the variables, and the CS-ARDL approach to estimate the long-run coefficients, which is considered an efficient method against cross-sectional dependency and heterogeneity issues. The robustness of the findings is confirmed by AMG and CCEMG methods.

We individually estimated the impact of each fossil energy resource, i.e., coal, oil and gas, and institutional quality (INQ), on environmental sustainability, which is proxy by ecological footprint. The study findings revealed that the increase in the usage of all fossil energy resources significantly increases the ecological footprint in BRICS, causing environmental degradation. In contrast, the INQ significantly promotes environmental quality by decreasing the ecological footprint. Additionally, the results regarding the interacting effect of INQ and fossil energy resources show that all the fossil energy resources negatively and significantly affect the ecological footprint, indicating that with better environmental regulations and institutional measures, fossil energy resources can promote the environmental quality in BRICS.

Considering the negative effects of fossil fuels on the environment, we urge the BRICS countries' decision-makers to reduce their reliance on fossil fuels for the benefit of environmental quality while also putting in place policies that would ensure the responsible use of those resources. As INQ can reduce ecological footprints, thus, the quality of policy formulation and the government's credibility in implementation is also very important. The further improvement of institutions will promote environmental sustainability because better institutions entail more access to information and greater political freedom, both of which contribute to a rise in public desire for improved environmental quality and an increase in public awareness of environmental issues. As a result, people's desire for a clean environment culminates in the implementation of environmental legislation, which, in turn, leads to a decrease in emissions from fossil fuels and a reduction in the risk that these emissions would have on human health.

Like all other research studies, this particular study is not without some limitations. Firstly, the study considered BRICS countries over 1996–2018 for analysis. Secondly, due to the lack of data, the analysis is focused on specific determinants and ignores many crucial factors that influence the quality of the environment. However, the current study provides a fruitful direction for further future research. The researcher can use both times series and extensive panel framework to investigate the moderating role of institutions between fossil fuel energy resources and CO_2 emissions. The research can be expanded by considering developing countries and a comparative analysis on developed and developing countries by employing advanced methods. By covering up these research gas, the present study would be pretty practical from a policy aspect for other emerging and developing economies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Nexus between agriculture productivity and carbon emissions a moderating role of transportation; evidence from China

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This research investigates the nexus existing between agricultural productivity and CO2 emissions under the moderating effect of transportation within the context of China. The data for this study are drawn from the World Bank and cover the period 1991–2019. The data is analyzed using an autoregressive distributed lag approach (ARDL). Agricultural productivity is measured in terms of crop and livestock production. The goal of this research is to make some contributions, as crop production has a negative impact on carbon dioxide emissions in the long and short run. Carbon dioxide emissions are positively influenced by livestock production in the long run, but negatively in the short run. As for the moderation effect, the results indicate that transportation significantly impacts agricultural productivity and CO2 in both the long and short term. The study provides in-depth insights to policy makers for designing more suitable policies regarding the necessity of decreasing CO2 emissions. In addition to discussing the crucial implications, future directions are also discussed.

KEYWORDS

CO2 emission, transportation, ARDL, agriculture, productivity

1 Introduction

In China's economic development, the agriculture sector plays a vital role. As per, Zheng et al. (2019), China is one of the most growing economies in the world. China is dominant in producing vegetables, meat and different kinds of cereals. Further, China is in the first position regarding the largest population ranking. Thus, it is crucial to understand how agricultural activity affects CO2 emissions and also how transportation moderates this relationship. The main objective of this study is to determine how China's agricultural sector is affecting the environmental ecosystem.

Further, the economic development and climate change have been in line for the last two decades. As a result of economic growth, carbon dioxide emissions contribute to the worldwide climate crisis, such as floods, storms, extreme temperatures, melting glaciers

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and rising sea levels (Fei, et al., 2011). One of the greatest threats fronted by humanity on this globe is climate change (Lu et al., 2018). In many parts of the world, rising global average surface temperatures are melting glaciers and altering precipitation, severely eroding regional water supply advantages (Nie et al., 2021). In recent decades, many experimental studies have proclaimed that climate change and global warming are the causes of environmental deterioration and the researchers are highlighting the significance of sustainable environment (Lu et al., 2018).

The sustainable environment denotes securing the climate for posterity without compromising the present speed of economic flourishment. Sustainable progression is essential to form this globe into a livable space for not only the current generation but also for posterity. Minimizing carbon discharges is the major target to achieve the sustainable evolution (Barroso, 2020). Many analysts have examined the relationship between climate and sustainability, while many examined other variables that may affect this relationship from this perspective. One of the key variables in evaluating the relationship between environment and growth (Nathaniel et al., 2021), is energy consumption as it is the primary contributor to CO2 emissions.

As all economic sectors are accountable for their growth, so all have some primary or secondary influence on carbon dioxide emissions, and likely its accurate for the agricultural sector (Khan et al., 2021). The agricultural sector accounts for 14%–30% of global GHG emissions because of its reliance on fossil fuels (Zhang et al., 2020). Indeed, the use of gasoline-powered farm equipment, pumping water for irrigation, indoor livestock care, and the use of nitrogen-rich fertilizers all contribute to agriculture's extraordinary greenhouse gas emissions. According to the Food and Agriculture Organization of the United Nations (FAO), agricultural sector CO2 emissions will likely to decrease by almost 80%–88% between now and 2020 (Zhang et al., 2020). Indeed, it can be attained by replacing the agronomics sector's layout and alternating the energy mix utilized in the agricultural zone by using sustainable sources. This also highlights the significance of the agricultural sector that it is a dominant root of earnings, especially in growing countries (Jebli et al., 2020). Further, agriculture is also in charge of supplying food to masses of humans all over the world. Chien et al. (2022) stated that agronomy could have a constructive or obstructive influence on the standard of the environment. Thus, through energy, and utilization, agriculture can influence the environment adversely.

One of the major causes behind CO2 emissions is energy consumption which is increasing due to the utilization of machinery in production and transport activities, agricultural igniting procedure, soared demand for unprocessed materials, raised use of land along with dangerous cooling and heating mechanisms. Therefore, environmental sustainability is the need of the hour. Thus, now a days, biological farming is getting attention as it also enhances ecological standards by reducing the part of bug spray and reduces the amount of high-energy feed (Chien et al., 2022; Zhou et al., 2022) Therefore, agricultural activity need to be based on green sustainable methods in order to reduce CO2 emissions. In this research, the main focus is on CO2 emissions due to agricultural activities. The main motivation of this research is based on the campaigns about green agricultural practices, climate change awareness efforts, and efforts for reducing CO2 emissions due to agricultural processes. Although past studies have investigated the link between CO2 emissions and agriculture but they fail to consider the moderating effect of transportation. The contributions of this study are manifold, first, this study aims to examine do agriculture activities impact on CO2 emissions under the moderating effect of transportation which will help stakeholders and policy makers in improving the agriculture sector by designing appropriate policies. Second, this study will provide in-depth insights to researchers and practitioners about how livestock and crop production can be enhanced. Third, the findings of this research will provide crucial strategies which other countries can follow to achieve agricultural sustainability along with a decrease in CO2 emissions.

The necessity to reduce global warming and CO2 emissions has received much attention from all countries across the globe. Therefore, the government and policy makers has called for empirical studies and practical measures to achieve sustainable environment. This issue of sustainability is the main priority for environmentalists, researchers, policy makers and government. However, it seems nearly impossible to achieve the targeted goals because of the increase in economic growth that degrades the environment due to various activities like agriculture, forestry and manufacturing products. In view of past studies, the existing research on environmental quality has considered a number of key variables that can influence the quality of the environment, most notably urbanization, globalization, tourism, industrialization, direct expenditures, literacy, public expenses, and inclusive finance (Usman et al., 2022). However, there is a dearth of literature about the moderating role of transportation. Therefore, this research mainly focuses on providing new perspective on the existing environment literature. This research seeks to provide answers to following key research questions: 1) Is there any effect of agricultural activities on environmental degradation in China? 2) What sort of moderating effect do transportation has on the relationship between agriculture processes and CO2 emissions ? 3) What is the role of transportation sector in increasing CO2 emissions in China ? In this way this research aims to recommend policymakers about pragmatic initiatives needed in the agricultural sector of China.

1.2 Significance of the study

This study will pursue three precise objectives to fill the existing research gaps in the literature. The first goal is to evaluate the role of transportation in figuring out the carbon dioxide emissions of the transport sector. The second objective is to empirically examine the effect of agricultural productivity on carbon dioxide emissions. The study's third and last goal is to calculate the transportation sector's emissions of CO2. In this paper, we explicitly include transportation in imagining the relationship with carbon emissions.

2 Literature review

In the past, several experimental studies have documented the relationship between agricultural productivity and emissions of carbon dioxide, and these studies have been discussed below. However, literature has shown a dearth of studies taking transportation as the moderator. It is generally accepted i.e. there is a relationship between agricultural productivity, CO_2 discharge with the subsequent temperature change.

As per literature, the agriculture accounts for a quarter to a third of worldwide CO2 emissions (World Bank, 2013; Pickson et al., 2020). Agricultural activities account for about one-tenth to 12th percentage of total global emissions. Meanwhile, land use and land cover converted to agriculture account for about twelve-twenty % of worldwide carbon discharges (Villoria & Nelson, 2019). Agriculture's share of worldwide carbon dioxide emissions is relatively smaller than that of the thermodynamic industry. To decrease carbon dioxide emissions due to agricultural activity, there is a high demand to introduce low-carbon farming methods that encourage economic development and safeguard the environment, (Dufour et al., 2009; Zhou et al., 2022; Jiang et al., 2020; Koondhar et al., 2020).

In another study, Reynolds et al. (2015) determined the link between agronomical product yield and CO2 emissions for South Asia and sub-Saharan Africa. The model estimates confirm a link between agricultural yield and CO2 emissions. Likewise Wang H. et al. (2020) studied the effect of crops, crop byproducts, and harvesting procedures on CO2 discharges. This research hypothesizes that harvest residues either raise CO2 discharges or degrade environmental quality. Similarly a study found that the effects of imitated CO2 emissions effects agriculture production and household well-being (Edoja et al., 2016). The simulation results of this study admitted the negative correlation between CO2 emissions and agricultural productivity. The relationship between climate change and the production of agriculture, and the difference in agricultural production to global warming was found smaller than the response of production to CO2 fertilization are determinant by (Nwaka et al., 2020).

Since a few decades, China has been gradually improving as a country. Several agricultural machinery subsidies tend to promote agricultural progression in the Chinese Government. As global warming becomes more serious, actual CO2 emissions have become a key research field in recent years (Shin et al., 2014, Zeng et al., 2019; Zhu et al., 2021). Through photosynthesis (plants) agriculture contributes to reduce CO2 emissions on one hand, while on the one hand, it adds to its metabolism and endurance from the energy-related CO2 discharges that are unavoidable in the production process because input elements lead to increased CO2 emissions. A study by Yang et al. (2020a) discussed the energy linked CO2 emissions due to using coal and electricity. Another study highlighted that CO2 emissions are linked to the utilization of energy per unit (Chi et al., 2021) and it is also found that CO2 emissions has a strong relationship with the gross domestic product (Wang R. et al., 2020; Yan et al., 2020; Aslam et al., 2021). Considering these facts, based on total factor output and factor replacement, the data envelopment analysis (DEA) method is broadly applied to measure environmental and energy performance, especially carbon emission performance.

Agricultural production extensively uses machinery and transportation that preoccupies bio-fuels and releases carbon emissions (Sardar, 2022). Transport and transport exercise in the sector of agriculture, such as elevating crops, animal husbandry, forest ranging, fishing, sources of pollution of the environment leads to the emission of CO2 (Gomez et al., 2020). Machines used in agriculture, for instance land tilling, yielding crops, and groundwater pumping, emit CO2 (Rahman et al., 2021). Transport of agricultural products, livestock and fishing, forest timber, etc. Are primarily done using bio-fuel-based modes of transport, causing pollution through carbon emissions (Zhan et al., 2018). Two types of emissions are seen in agricultural production processes (Yang et al., 2018). This includes direct and indirect discharges of CO2 gases. Direct carbon emissions arise from the use of fossil fuels in various agricultural and transportation activities (Bhatti et al., 2021). While the indirect carbon emissions are due to the various processes used in agricultural activities. The carbon emissions that are embodied are larger than those produced in course of production of agriculture (Niu et al., 2020; Khursheed et al., 2021). In addition, emissions of CO2 released during international and domestic transport of agricultural activities are an important part of CO2 emissions (Wang et al., 2019).

In this research, transport competitiveness adjustment is used as a moderator to determine changes in agricultural trends. This suggests that the high competitiveness of the transport sector plays a value-adding role for the agricultural sector in reducing CO2 emissions in the transport sector. This research has the theoretical underpinning of the environmental Kuznets curve (EKC). This theory is selected because it is used in several past empirical studies. This theory is also validated by several past researchers (Hanif, 2018; Sharma et al., 2021). This research using the theoretical foundation of EKC proposes that agricultural productivity effects on CO2 emissions and the transportation positively moderates this relationship. Based on the literature reviewed, we propose the following hypothesis;

H1: A positive relationship exists between agricultural productivity and CO2 emissions.

H2: Transportation moderates the relationship between agricultural productivity and CO2 emissions.

TABLE 1 Variables and definitions.

Variables	Symbol	Definitions	Sources
Co2	Co2	CO2 emissions (kt)	World Bank
Livestock Production	LP	Livestock production index (2014–2016 = 100)	World Bank
Crop Production	CP	Crop production index (2014–2016 = 100)	World Bank
Transportation	TP	Transport services (% of commercial service imports)	World Bank

TABLE 2 Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
ID	30	1	0	1	1
YEAR	30	2004.5	8.803	1990	2019
CO2	29	303448.28	305289.98	-100000	1000000
LP	30	75.61	21.91	31.22	100.89
CP	30	74.322	20.711	42.3	107.9
TP	30	33.996	13.193	18.382	78.896
I.LP	30	2339.989	432.955	1603.142	3081.996
I.CP	30	2323.566	421.832	1486.414	3337.309

FIGURE 1
Graphical representation of LP over time.

FIGURE 2
Graphical representation of Co2 over time.

3 Methodology and data

3.1 Data source

The purpose of the study described above is to identify whether transportation has a moderating effect on agricultural productivity and carbon emissions. In order to test the relationship between study variables, the ARDL method was applied to time series data spanning 1991 to 2019. World Development Indicators (http://data.worldbank.org) provided the data sets of the selected variable for this study in order to accomplish the study objectives. Here, CO2 emissions represent a dependent variable, and livestock production represents an independent variable. Table 1 provides a comprehensive overview of the variables, their definitions, and symbols, as well as the source of the data and the descriptive analysis. Kilotons are used to measure CO2 emissions. Based on 2014–2016 = 100, the livestock and crop production indices are calculated. From Figure 1 to Figure 3, it is illustrated that there has been a trend in the variables, LP, CO2, CP, and TP in China during the period 1990 to 2019.

Figure 2 shows the trend in variables (i.e., CO2, LP, CP, and TP) as a function of time. As shown in Figure 4 and Table 1 contain all the details regarding the variables and sources of the data in regard to the description of the variables.

3.2 Empirical model

Most observed and hypothetical studies consider the agricultural and transport sectors the most important factors

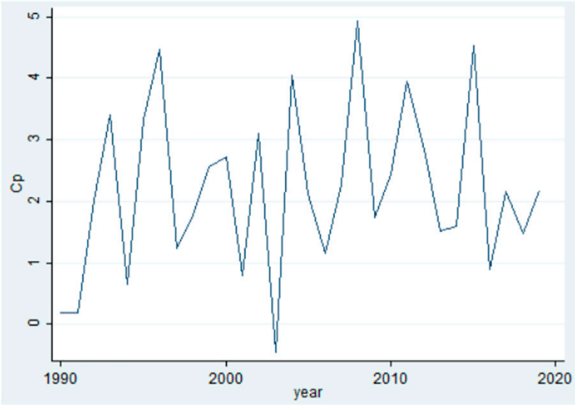

FIGURE 3
Graphical representation of CP over time.

FIGURE 4
Graphical representation of TP over time.

affecting CO2 emissions (Ullah et al., 2020). An important source of income, agriculture, has contributed to increased environmental pollution. As the agricultural sector subsidizes to economic development, it is also responsible for the emission of CO2 and environmental deprivation from land use, deforestation and livestock use of machinery, fertilizers, stump burning and fossil fuels. An analysis of the impact of AP on the environment is conducted using Borlaug's hypothesis (Angalsen et al., 2001). This hypothesis suggests that the early stages of AP reduce eco-friendly value. As a result of agricultural productivity, environmental value is enhanced through increased demand for goods and services produced per environmental regulations. In general, the econometric model of our study can be characterized as follows:

$$Co2, t = \beta0 + \beta1AP + \beta2\,TP + \varepsilon \tag{1}$$

Where CO2t represents CO2 emissions, APt represents agricultural productivity, t denotes time series and ε is the error term. The estimate of β1 is likely to lead to the conclusion that agriculture productivity reduces environmental pollution by reducing the number of dirty activities in the economy (Ullah et al., 2022).

Based on the findings of this study, it is suggested that Transportation (TP) might act as a moderating factor in the case of China since it directly affects CO2. Consequently, this study seeks to discover the role of TP in moderating the effect of LP on CP and CO2 emissions. An interaction variable was presented by (Cohen et al., 2014) to check the moderating effects of the interaction variables in this setting. According to (Chen and Myagmarsuren, 2013), as a second step, we construct two models to verify moderating factors' effects. First, we added a proxy for transportation (lnTP) to Equation 2 in order to estimate the main effect as presented below:

$$\ln Co2\,(t) = \beta0 + \beta1\,(\ln LP) + \beta2\,(\ln CP) + \beta3\,(\ln TP) + \varepsilon \tag{2}$$

Added interaction variables to Eq. 2 as an independent variable in the second model after which we get new Eq. 3 to evaluate transportation's moderating effect.

$$\ln Co2\,(t) = \beta0 + \beta1\,(\ln LPt) + \beta2\,(\ln CPt) + \beta3\,(\ln LPt*\ln TPt) + \beta4\,(\ln CPt*\ln TPt) + \varepsilon \tag{3}$$

An interaction variable will be considered moderating if it shows statistically significant relationships with the other variables, according to Cohen et al. (2014). The coefficients should also be statistically significant, thus confirming that transportation plays a moderating role in our study. Thus, TP is an important moderating variable in statistical methodology since it affects the direct relationship between CO2 emissions and the regressors (LP and CP).

3.3 Methods

Whenever a long-term relationship is to be estimated, it is necessary to determine the order of integration by testing the unit root of each variable. Appropriate methods for the study are determined by factors such as integration order or stationarity characteristics. In the results and discussion section, we present the results of the analyses of Dickey and Fuller (1979), Dickey and Fuller (1981) and Phillips and Perron (1988) using the ADF and PP tests, respectively. In order to answer research questions empirically, we consider the order in which our study variables are integrated. For the examination of asymmetry relationships among fundamental variables, we used recently advanced econometric methodology, namely, the autoregressive

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distributed lag (ARDL) bounds-testing approach to co-integration, presented by (Pesaran et al., 2001) for symmetric co-integration, and the ARDL bounds-testing approach. A variety of techniques have been used to investigate long-run associations between variables in literature in the related field (Engle and Granger, 1987; Johansen, 1991), but as indicated in a recent study (Liu et al., 2020) and based on the following superior characteristics, this technique has been selected: The use of ARDL models is recommended only when the underlying variables have mixed integration orders of I (0), and I (1), and none of the series have been integrated at the second level. Alternatively, other conventional co-integration methods are limited to series in the I (0) and I (1) states (Pesaran et al., 2001; Satti et al., 2014). The second benefit of the ARDL framework is its ability to provide efficient results, as it is free of serial correlations and endogeneity issues, as well as when endogenous explanations are present (Liu et al., 2020). Lastly, both techniques produce solid results, even when the sample size is small (Hsueh et al., 2013).

3.3.1 The linear ARDL bounds test to the Co-integration framework

Agriculturalization leads to a shift from green to blue economic growth. We can estimate CO2 emissions in the long run using Eq. 4. We will then assemble our model into an error-correction format, which will enable us to assess agricultural productivity over the short and long term using the same equation. According to (Pesaran et al., 2001), the authors describe the ARDL bounds testing approach for exploring long-run and short-run linear relationships in Eq. 4.

$$\Delta CO2, t = a_0 + \sum_{n=1}^{p} \pi \Delta \mathrm{CO2, t-1} + \sum_{i=0}^{p} \psi \Delta AP, t-1 + \sum_{n=1}^{p} \mu \mathrm{i} \Delta \mathrm{TPt} - 1 + \dot{\omega}1 CO2, t-1 + \dot{\omega}2 AP,\ t-1 + \dot{\omega}3 \mathrm{TP}, t-1 CO2 + \varepsilon t \tag{4}$$

Calculating lags in the short and long run requires consideration of several factors: 1) the first difference operator, 2) the intercept or continuous parameter, 3) the optimal number of lags, 4) and 5) the short and long-run coefficients. An alternative hypothesis of linear co-integration among variables (H0: γ1 = γ2 = γ3 = γ4 = 0) is compared with the null hypothesis of no co-integration among the underlying variables (H0: γ1 = γ2 = γ3 = γ4 ≠ 0). Testing for the null hypothesis of no co-integration among the underlying variables is conducted by applying the ARDL bounds approach. These hypotheses are tested based on the nonstandard F-test proposed by (Pesaran et al., 2001), famously known as FPSS. The authors provide critical bound values at different levels of significance. A null hypothesis that no co-integration exists is rejected if the calculated value of the test statistics is higher than the upper bound's critical value. The null hypothesis is accepted if the test statistics decrease below the inferior bound critical value. We could conduct another co-integration test if the test statistics fall between the upper and lower bound critical values. Additionally, ARDL assumes that all variables explain the dependent variable in an asymmetric manner.

TABLE 3 Pairwise correlations.

Variables	CO2	LP	CP	TP	I.LP	I.CP
CO2	1.000					
LP	0.921	1.000				
	(0.000)					
CP	0.975	0.963	1.000			
	(0.000)	(0.000)				
TP	−0.650	−0.825	−0.769	1.000		
	(0.000)	(0.000)	(0.000)			
I.TP	0.290	0.309	0.202	0.154	1.000	
	(0.120)	(0.096)	(0.285)	(0.415)		
I.CP	0.169	−0.003	0.023	0.544	0.827	1.000
	(0.373)	(0.989)	(0.906)	(0.002)	(0.000)	

4 Empirical results and discussion

All variables in the study are described in Table 2, including mean and standard deviation, maximum and minimum values, and *p*-values for Cramer von Mises, Shapiro-Wilk, and anderson Darling tests. As a result, Co2 and both interaction variables of AP have significantly higher means. In both the interaction terms of AP and the standard deviation of Co2 there is a high level of volatility compared to the rest of the variables.

The results in Table 3 indicate that TP correlates negatively with CO2, LP, and CP. On the other hand, it has a positive correlation with the other variables. The moderating term (I. LP, CP) correlates positively with the other variables, except for the correlation of I. LP with LP.

We must ensure that our variables are stationary when using time series data. This is because estimations based on non-stationary data can be misleading. Therefore, before we perform long-run estimations (through ARDL), we apply the unit root test to ensure that variables involved are stationary. Table 4 presents the unit root test results as described by (Ng and Perron, 2001).

In Table 5, it is stated that the ARDL bounds test could only be applied to variables with mixed integration orders I (0) or I (1). We used the ADF test, developed by (Dickey and Fuller, 1978; Dickey and Fuller, 1981), as well as the PP test, developed by (PHILLIPS and PERRON, 1988) to determine the stationary properties of the variables; the results are presented in Table 5. Based on this, both LP, I. LP, the

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TABLE 4 Unit root testing.

Variables	Augmented dickey-fuller		Phillips-perron	
	I (0)	I (1)	I (0)	I (1)
CO2	−2.303	−4.151***	−3.314	−6.854***
LP	−5.515***	-	−2.765*	-
CP	−0.092	−6.000***	0.309	−7.846 ***
TP	−3.181**	-	−4.639***	-
I.LP	−1.953	−3.986***	−1.736	−4.274***
I.CP	−2.551	−4.783***	−3.081***	-

Note: ***$p < 0.01$; **$p < 0.05$; and *$p < 0.1$.

interactive term (i.e. the interaction variable that results from multiplying the TP and I. LP in order to examine the moderating effect of TP), CO2, and CP are non-stationary at the level, however, as per ADF, they are stationary when the first difference is taken. ADF results are also confirmed by the PP test. At both the level and the first difference, the TP and LP are found to be stationary. The results obtained from unit roots are supported by both tests, demonstrating their robustness.

Based on the results of the linear ARDL bound test on the stationarity of the variables, first, we applied the co-integration test using the linear ARDL bound test, which is shown in Table 5. In all models from Equations (1)–(3), ARDL F-statistics are greater than the upper bond critical values given by (Pesaran et al., 2001) at all significance levels 1%, 5%, and 10%. In the case of China, the co-integration between the AP, the Co2, the TP, and the interactive term was established over the period of study. A diagnostic and stability test was performed to ensure the robustness of the results; as a result, ARDL bounds test of (Pesaran et al., 2001) proved to be robust, reliable, and useful for the formulation of policy recommendations. This study also demonstrates a strong long-term co-integration among variables (significant F-statistics) found in the linear ARDL model (Table 5).

Also, we apply some robust analysis to the diagnostic test, and the results are also provided at the bottom of Table 5. It is demonstrated that the residuals are normally distributed in the BJarque-Bera test, BD-Watson test, and BAmsey's RESET test that the data is homoscedastic under the given model, whereas BD-Watson test reveals no autocorrelation. Finally, the BAreush Pagan Godfrey test demonstrates that data is homoscedastic within the given model.

ARDL model is implemented in a suitable manner using the cumulative sum of the square of recursive residuals (CUSUMsq) tests, as Brown 1976) suggested. As shown in Figure 5, the CUSUMsq test graphs lie within the red colored critical bounds at a 5% confidence interval. The blue line in the middle of the graph represents the measurements of the cumulative sum of the squares of the residuals. According to the CUSUMsq graphs, our model appears to be well-stable.

Using ARDL approach, Table 6 provides the results of short-run and long-run estimations. Carbon dioxide emissions (CO2) in panel 1) are positively and statistically significantly related to livestock productivity and transportation, while negatively and statistically significantly related to crop productivity. In the short run, the coefficient of LP is 32907.8, while in the long run, the coefficient is 4829.8. This indicates that a 1% increase in LP will result in a 98% increase in carbon emissions per capita.

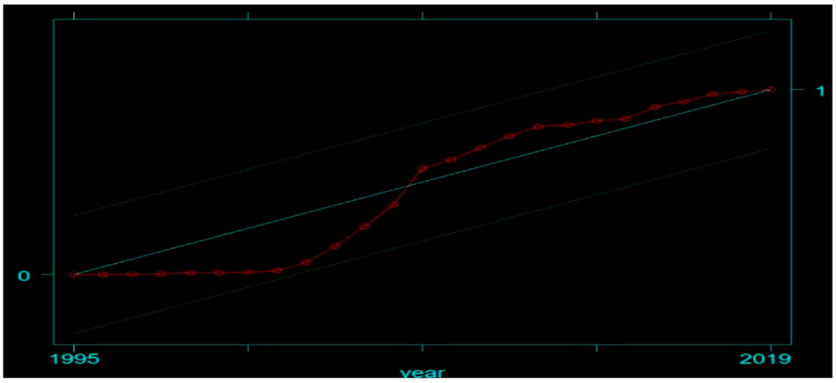
Table 6, also provides the results of the estimation with interaction variables (see panel b). The analysis results are still significant after the inclusion of interaction variables, except livestock productivity (LP). The coefficient of crop productivity is significant but its sign is negative (β = -13890.14, $p < 0.05$). Further, when interaction terms (variables) are included in the analysis, LP and CP have a greater impact on carbon emissions than before. The main difference between model 1) and model 2) is that the inverted U-shaped relationship has disappeared and the interaction variables (lnLP x TP and CP x TP) have become statistically significant. It is evident that Transportation acts as a moderator in the relationship between Agriculture Productivity (AP) and Carbon Dioxide (CO2). Nasir and Rehman found similar results as described in Table 6. Overall, the long-run results suggest that transportation contributes significantly to CO2 emissions as a moderator.

In the second portion of Table 6, the short-run estimates are presented for both cases: the main effect (without an interaction term) and the main effect with an interaction or moderating effect. Crop productivity error correction terms are statistically significant at 1% and have a negative coefficient.

TABLE 5 Linear ARDL bounds test to co-integration.

Estimation method			Diagnostic test			
ARDL Bounds Test	Lag Length	F-Statistics	JB	LM	BPG	RR
CO2t = LP, CP, TP	(1,0,2,0)	0.0174	0.236	0.083	0.072	0.326
CO2t = LP, TP I. LP	(1,0,2,2)	0.0022	1.993	0.003	0.008	0.454
CO2t = CP, TP, I. CP	(1,2,1,0)	0.0087	0.601	0.050	0.038	0.967

Note: (PBG, represents the p-values of the Heteroskedasticity Test, while BPG, and RR, represent the p-values of Breusch-Pagan-Godfrey tests. The Jarque Bera test p-values are depicted in Jarque Bera.



Source. Authors' calculation

FIGURE 5
Stability test based on the cumulative sum of the recursive residuals CUSUM of squares.

TABLE 6 Results of ARDL Short run and long run analysis.

	a) Without interaction effect				b) With interaction effect			
Variables	**Coeff.**	**Std. Error**	**t stat.**	**Prob**	**Coeff.**	**Std. Error**	**t stat.**	**Prob**
	Long-run (Dep. Variable = CO_2)				**Long-run (dep. Variable = CO_2)**			
ln LP	32907.83	9712.71	3.39	0.003	4829.807	3586.442	1.35	0.192
ln CP	−16985.18	9618.306	−1.77	0.092	−13890.14	6211.071	−2.24	0.037
ln TP	−32363.84	9606.89	3.337	0.003	−27851.88	13094.96	−2.13	0.047
ln (LC*TP)	-	-	-	-	514.3898	164.1147	3.13	0.005
ln (CP*TP)	-	-	-	-	994.7256	211.9986	4.69	0.000
Const	0.1850	0.1561	1.1850	0.2476	3.1016	0.8624	3.5961	0.0369
	Short-run (Dep. variable = CO_2)				Short-run (Dep. variable = CO_2)			
Δln LP	−71822.82	40539.45	−1.77	0.091	28160.59	24043.95	1.17	0.255
Δln CP	−0.3391	0.31781	−1.07	0.296	−96055.72	38909.91	−2.47	0.023
Δln TP	-	-	-	-	−40386.38	19275.09	−2.10	0.050
Δln (LC×TP)	-	-	-	-	959.0669	370.319	2.59	0.018
Δln (CP×TP)	-	-	-	-	61383.84	49203.56	1.25	0.228
Const	−6.461	2.769	−2.33	0.004	−1.0689	0.4779	−2.23	0.035
R2	0.7521				0.8177			
Adj. R^2	0.6409				0.7409			
D-Watson stat	1.707				3.0399			

To determine the robustness of the model, the pairwise Granger causality test is estimated between two variables simultaneously, which elaborates the directional linkages between them. In Table 7, we demonstrate the results of the pairwise Granger causality analysis. The estimations of the pairwise Granger causality shows unidirectional causality between LnLP to LnCO2, LnLP to LnCP, ln (LP*TP) to LnCO2, Ln (CP*TP) to LnCO2, lnLP to Ln (CP*TP) and LnTP to Ln (CP*TP).

5 Discussion

China is one of those countries which are progressively improving its agricultural methods for achieving environmental sustainability. Further, China produces energy from coal, a non-renewable source, this research recommends using a renewable source to control CO2 emissions. Further, as per Abdoli et al. (2018) latest biofuels, including biogas and other agricultural

TABLE 7 Granger Causality/Block Exogeneity Wald test.

Variables	Δln CO_2	ΔLP	Δln CP	ΔLn TP	ΔLn (LP*TP)	Δln (CP*TP)
Δln CO_2	–	12.214*** (0.0005)	12.419*** (0.0007)	0.027 (0.868)	12.198*** (0.0007)	11.464*** (0.0005)
Δln LP	2.971* (0.0951)	–	7.878*** (0.0050)	0.821 (0.3647)	6.821*** (0.0095)	7.342*** (0.0067)
Δln CP	1.748 (0.2863)	0.020 (0.8858)	–	0.000 (0.9921)	0.102 (0.8934)	0.017 (0.6944)
Δln TP	1.031 (0.4065]	0.238 (0.6251]	0.002 (0.9617]	–	0.706 (0.4519]	0.446 (0.8197)
Δln (LP*TP)	0.045 (0.9502)	0.088 (0.5666)	0.008 (0.9271)	0.723 (0.3948)	–	0.118 (0.6419)
Δln (CP×FP)	2.380 (0.1810)	7.817*** (0.0065)	6.277*** (0.0060)	1.302 (0.2629)	7.146*** (0.0069)	–

Null hypothesis, no causality; represents to *p*-value; *, ** and *** indicate rejection of the null hypothesis at 10%, 5% and 1% level of significance.

deposits such as hazelnut, wheatgrass etc, are the key source of renewable energy in the agriculture sector. Therefore, the increase in global warming due to CO2 emissions is one of the most investigated research topics. Although several studies have analyzed the factors leading to pollution, in this research a new comprehensive framework is developed and tested on Chinese economy. The findings of this study reveal a significant relationship between agriculture and CO2 emissions under the moderating effects of transportation. Thus, this study recommends that the government of China should organize trainings for farmers regarding the latest harvesting techniques. This study's results give policymakers direction to focus more on research and development activities. This study also has a few limitations, including limited inclusion of variables and sample size. Thus, future researchers can increase the variables with a huge sample to analyze this key relationship. As the effects of agricultural productivity on CO2 may differ among different economies. Further, all categories of green activities can reduce the level of CO2 emissions as the energy generally used in the agriculture sector is highly dependent on fossil fuels. Therefore, the agriculture sector of China should increase the photosynthesis process to increase the oxygen supply for the environmental sustainability. Thus, organic farming will not only positively affect human health but also help environmental sustainability. This study also deserve consideration from policy makers in China for designing policies regarding the significance of transportation in understanding the relationship between agricultural activities and CO2 emissions. Additionally, the policy makers should design policies to create the awareness about the necessity of decreasing CO2 emissions through the understanding the importance agriculture processes. Thus, it is crucial to develop the rural areas focused on modern and green agriculture policies. Therefore, this study will help policy makers in designing more suitable policies for reducing the emissions of CO2 considering the characteristics of that country.

6 Conclusion

In this study, the impact of agricultural activity on CO2 emissions is investigated under the moderating effects of transportation. For the empirical results, we have used very widely applicable econometric methodology, ARDL applied on a data from 1991 to 2019. For the presentation of agricultural productivity, crop and livestock production are used. The findings revealed that the crop production negatively affects carbon dioxide emissions in the long and short run. While livestock production positively affects the carbon dioxide emissions and negatively in the short run, the moderator (transportation) shares a negative relationship with the dependent variable, that is CO2. Therefore, both hypotheses are accepted. As a result, the Granger Causality test confirms that agricultural productivity contributes to CO2 emissions in a bidirectional fashion, as opposed to the one-way causality between transportation and CO2, which does not show a causal relationship with CO2. Hence, the findings of this study reveal a significant relationship between agriculture and CO2 emissions under the moderating effects of transportation.

In case of with moderation effect, the results reveal a significant and positive moderation effect of transportation on the relationship between agricultural productivity and CO2 in the long and short run. This result is consistent with past studies (Adams et al., 2020; Kocak et al., 2020). Thus, the results highlight the significant role of agricultural productivity, and transportation in understanding the environmental degradation due to CO2 and the research objectives are achieved. The study concludes with highlighting significant role of agriculture and transportation in understating the control on CO2 emissions. Further, the study also provides empirical implications, as the moderation of transportation confirms its effect on the relationship between agricultural activity and CO2 emissions. Therefore, this study recommends that government should strengthen the control of transportation and should regulate the use of green agricultural methods. Further, if the grip on transportation is strengthened then CO2 emissions will be reduced leading to achieve environmental sustainable goals. In the presence of strict government regulations, green agricultural practices should be adopted and resultantly, the CO2 emissions will be decreased. This study gives a new perspective to researchers and practitioners for understanding the significance of reducing CO2 emissions by considering the role of agriculture sector along with transportation sector. Thus, this study recommends that China should adopt organic farming techniques and the latest technological and innovative farming techniques and the farmers should be introduced to new farming techniques.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DW wrote the paper draft and collected the data. RH helped in formatting and also managed statistical issues. IA ensured grammar checks and overall structure of the paper.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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State asset management paradigm in the quasi-public sector and environmental sustainability: Insights from the Republic of Kazakhstan

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This study aims to improve state regulation and administration of quasi-state sector of environmental sustainability in the Republic of Kazakhstan within the social sustainability paradigm. This study is due to the need to search the balance of business interests, and efficient use of resources and their conservation on a global scale. The issues of state asset management are identified and ways to resolve them are proposed based on the corporate foresight methodology using the strategic planning mechanism. As a result of the analysis of the tools introduced into the practice of leading transnational corporations, the main directions are identified in which it is advisable to take measures aimed at streamlining and optimizing the quasi-public sector in the Republic of Kazakhstan. This article presents proposals for improving state regulation and administration of quasi-public companies in the Republic of Kazakhstan. The outcomes of this study can assist policymakers, experts, and stakeholders in gaining awareness about these problems while simultaneously improving sustainability practices.

KEYWORDS

clean energy transition, environmental sustainability, strategic planning, state assets, quasi-public sector

1 Introduction

Today, more than ever, the problem of balancing the interests of business, both public and private, and the global problems of scarcity of resources and the related problem of their preservation on a global and regional scale is acute. In international practice, the sustainable development of the state is presented as interconnected with the quasi-state sphere, which needs a balance of economic, social, and environmental spheres (Francis, 2001; Kim, 2003; Collier, 2005). The quasi-public sector in any state is the foundation of the country's economy, on which all modern processes are based, both in terms of institutional affiliation and in terms of sectoral structure. Since the state's assets are a rather complex and multi-level system, their state management is considered a rather multifaceted process.

The main components of sustainable development are political, social, cultural, economic, and environmental sustainability. In a market economy, the achievement of sustainable development is interrelated with environmental sustainability. The reason is the increase in resource efficiency use through the introduction of more advanced and environmentally friendly (non-waste) technologies is becoming the main task of many states, including quasi-state companies and market participants. Currently, the relationship between macroeconomic and environmental parameters is given great importance (Shan et al., 2021; Ojekemi et al., 2022). In this regard, scientifically based environmental management, recycling of production, and consumption of wastes are relevant topics (Adebayo, 2022a; Adebayo, 2022b; Du et al., 2022). The reason is that ecological production, at this stage of development of the economy of states, is becoming an increasingly significant factor in competitiveness. The production of ecological products and waste processing are promising types of entrepreneurial activity (Adebayo et al., 2022; Akadiri et al., 2022; Hossain et al., 2022). The higher the environmental sustainability of market participants, the higher the environmental efficiency of the development and functioning of the economy, and the social and environmental stability of society.

However, quasi-public companies have a greater impact on the economy than small private companies. Therefore, quasi-public companies can increase the level of environmental awareness and activity in society by resorting to formal and informal education methods from childhood, as well as regular posting of information on official Internet resources and social media accounts, and other measures. Populations living in environmentally sensitive areas should have greater opportunities to participate in the decision-making process that will affect society. Environmental sustainability issues should be reflected in educational programs and in all strategic decisions, the consequences of which are subject to regular evaluation (Shutaleva et al., 2020a; García-Morís and Martínez-MedinaTrainee, 2022; Ma and Jin, 2022). The proposed measures will make it possible to form an "ecological culture of the population" in society, and the promotion of environmental knowledge—the development of environmental education and enlightenment to ensure sustainable development. Thus, environmental sustainability is the effective management of natural resources in production activities, allowing them to be preserved for future needs. And quasi-state companies and state companies cannot dispose of it as an inexhaustible source of resources, even if their goal is to satisfy human needs through consumption.

This article is devoted to studying ways to improve state regulation and administration of quasi-state companies within the sustainability paradigm in the Republic of Kazakhstan. Currently, the Government of the Republic of Kazakhstan is asking a difficult task to reform the quasi-public sector. Economic and social problems in the Republic of Kazakhstan demonstrate the need to search for effective strategies for the development of a quasi-public sector. This circumstance determines the relevance of the presented study of the existing situation, considering the social, economic, and environmental aspects of the serial development of society.

One of the main problems of the modern development of the Republic of Kazakhstan is the need to determine a clear role and place of the subjects of the quasi-public sector in the system of state planning. This situation distinguishes the state of the Republic of Kazakhstan from developed countries and creates the need to comprehend international experience and apply its methodology, considering the specifics of the socio-economic development of the country.

In the Budget Code of the Republic of Kazakhstan, the concept of "state assets" is set out in the following wording: "state assets are property, and non-property benefits and rights that have a valuation received into state ownership because of past operations or events" (Budget code of the Republic of Kazakhstan, 2022). Quasi-state companies have more liquid assets than the state companies. However, quasi-state companies play an important role in the markets (Makushkin and Lapshin, 2021). The issue is aggravated by the accelerating processes of digitalization of the process of interaction between subjects of various forms of ownership. The Internet determines the life of modern society, including the main business processes (Afonasova et al., 2019; Khachaturyan, 2021; Nicolaou, 2021). It is necessary to consider the specifics of the digital economy and the need for state regulation of electronic interaction. In the Republic of Kazakhstan, this trend also applies to public sector procurement and information resources (Subjects of the quasi-public sector, 2022). Currently, the relevance of improving asset management efficiency is only increasing.

The Republic of Kazakhstan strives to be consistent with the goals and principles of sustainable development. However, several important aspects should be considered when analyzing the specifics of the implementation of the concept of sustainability in the Republic of Kazakhstan. Such aspects include structural, eco-nomic-geographical, and traditional priorities of the Kazakh society.

The interaction between the public and private sectors has historical roots in the Republic of Kazakhstan. The modern trend of this interaction is to shift the focus on the problem of sustainable development of cities and the growth of the quality of life. These processes require a rethinking of the goals, institutions, and mechanisms of policy in the field of public asset management. We proceed from the fact that the policy of managing state assets should achieve systemic and transparent management of state property and ensure social and economic stability in the country and its regions.

The economy of the Republic of Kazakhstan is characterized by low dynamics in the development of the private sector and dependence on primary industries (Aubakirova, 2020; Nurpeisova et al., 2021). This circumstance predetermines the fixation of the quasi-public sector as an essential factor in the development of the economy. Currently, the Government of the Republic of Kazakhstan is taking certain actions to strengthen the management of the quasi-public sector (Kazakh Government Adopts Plan to Reform Quasi-Public Sector, 2022). These measures include the separation of the role of the state as owner and manager, the creation of national holdings for the management of state assets, and development institutions. However, today there are challenges in the economy and social problems in the population of the regions. This circumstance allows a state that the quasi-public sector's current model has several systemic shortcomings.

A legitimate mechanism for the effective management of state assets in the quasi-public sector of the economy of Kazakhstan is impossible without a comprehensive analysis of the state of management of state assets. We believe that the key problem is in the inefficient use and management of state assets, even if they can be sold commercially. This trend leads to the lack of proper influence of state assets on economic growth in the region and improvement of the quality of life of the population of the Republic of Kazakhstan. In this regard, the authors of this article intend to propose the results of a study aimed at creating an effective system for managing state assets in the quasi-public sector.

This article is aimed to find ways to improve state regulation and administration of quasi-state companies in the Republic of Kazakhstan within the framework of the sustainability paradigm. The relevance of this study is in the need to introduce balanced strategic planning, rethinking the goals and mechanisms of socio-economic state policy in the Republic of Kazakhstan. We proceed from the international theory and practice of applying the methodology of corporate foresight using the strategic planning mechanism. We undertook a study to develop recommendations that will allow reformatting the management system of the quasi-public sector in the Republic of Kazakhstan. The implementation of this goal determined the following logic of this study. Section 2 shows the results of the study of existing approaches and issues of quasi-public sector development in the context of the sustainability paradigm. Section 3 presents the foresight methodology as the main one for the proposed study. Section 4 presents an analysis of the process of regulating the activities of quasi-state companies with the participation of government departments. The quality of regulation of quasi-state companies needs to be addressed the most problematic issues, among which we have considered the following: lack of a clear institutional framework; low financial efficiency of quasi-state companies; high share of the state in the economy; lack of a comprehensive system for monitoring and evaluating the activities of quasi-state companies; the imperfection of a single information resource about quasi-state companies; weak corporate governance. Section 5 presents proposals for improving state regulation and administration of quasi-public companies in the Republic of Kazakhstan. Section 6 presents conclusions drawn about the ways to streamline and optimize the quasi-public sector in the Republic of Kazakhstan.

2 Literature review

Sustainability is a paradigm that affects the environmental, economic, technological, industrial, social, and other areas of society in its current and future development perspective. In 1987, the United Nations General Assembly published the report Our Common Future, which presented the concept of sustainability as a concept for the development of society, involving the responsible use of natural resources, considering the preservation of nature for the life of future generations [(WCED, 1987), p. 43]. One of the main conclusions of the World Conference in Rio de Janeiro (1992) is the recognition that the existing production and consumption systems will inevitably lead to a global catastrophe (Rio Declaration on Environment and Development, 1992). This concern and the formation of a paradigm of sustainability are based on the fact of environmental destruction and the catastrophe that threatens all of humanity. In this regard, innovations in the sphere of macroeconomic and environmental parameters (Shan et al., 2021; Ojekemi et al., 2022), production and economy (Schaltegger et al., 2012; Baimuratov et al., 2020; Yizhe et al., 2020), environmental management, recycling of production (Adebayo, 2022a; Adebayo, 2022b; Du et al., 2022), environmental ecology (Frazier et al., 2019; Valko, 2021a; Leigh and Li, 2015; Piscitelli and D'Uggento, 2022), production of ecological products and waste processing (Adebayo et al., 2022; Akadiri et al., 2022; Hossain et al., 2022), urban development (Trencher and Karvonen, 2017; Krupkin and Gorodnova, 2018; Dixon and Brears, 2021), education for sustainable development (Berchin et al., 2012; Shutaleva et al., 2020b; Valko, 2021b), improvement of the welfare of the population (Pissourios, 2013; Mendoza-Cavazos and Leal Filho, 2019; Shutaleva et al., 2022), preservation of cultural traditions, and mutual respect of members of society (Alaimo, 2018; Loginov, 2019; Bakeeva and Biricheva, 2021).

For the study of state regulation and administration of quasi-state companies, the concept of economic sustainability as the main element of sustainability is of particular interest. Economic sustainability is fundamental to social sustainability, which requires a basic level of financial resources to meet the needs of society's members (Dernbach, 1998; Zeijl-Rozema et al., 2008; Rai et al., 2021). The economic perspective of sustainable development emphasizes the maintenance of various types of capital (Kevin, 2010; Costanza, 2020; Porreca, 2020). Sustainability is a synergistic phenomenon; that is, it is formed in the interaction of economic, environmental, and social spheres and types of capital (Illankoon et al., 2017; Eklova, 2020; Simangan et al., 2021). However, the social, environmental, and economic aspects of sustainability tend to be mutually exclusive in practice, which creates threats for Morelli (2011) paid attention to such an aspect of economic sustainability as the inclusion in it of an analysis to minimize social costs and compliance with environmental asset protection standards.

One of the significant aspects of economic sustainability is the development of a unified measure of economic and environmental aspects of sustainability. Scott (2013) defined economic sustainability as long-term competitiveness, profitability, and shareholder satisfaction. Competitiveness and profitability must be associated with innovativeness, resource optimization, elimination of short-term thinking, and environmental hazards of production.

Economic sustainability needs a balance of efficiency and sustainability, it is determined by the nature and measurable structures of economic systems (Lietaer et al., 2009). Economic efficiency assumes that the requirement to satisfy more needs at the expense of fewer resources is met. The sustainable functioning of firms implies financial viability and the protection of the firm from external and internal threats in the present and future perspective (Naciti, 2019; Rustam et al., 2020; Hermundsdottir and Aspelund, 2021). Sustainability and security are the most important components of the enterprise economy, ensuring its integrity and unity as a system. An organization's security involves protecting its human and intellectual potential, information, technology, capital, and profits. The company's economic security is realized through the effective use of corporate resources to ensure the stable functioning of the organization. In this regard, the strategic development of economic, organizational, legal, engineering, and social measures is particularly important. Strategic planning allows the company to remain in a state of life support in the face of economic crisis and risk (Hastings, 2000; Lagâri et al., 2021; Waiganjo et al., 2021).

In the macroeconomic aspect, the following criteria of economic sustainability are significant: competitiveness (Buhalis, 2000; Armenski et al., 2018; Arunachalam and Fountis, 2021), innovativeness (Hemmelskamp et al., 2000; Jänicke et al., 2000; Akbar, 2021), and public debt (Albu and Albu, 2021; Grosu et al., 2021; Adeve and Karabou, 2022). In 2005, Spangenberg (2005) noted that in the context of sustainable development, such criteria of economic sustainability as inflation and trade imbalance are practically not discussed. However, in studies of recent years (Barthélemy and Cléaud, 2018; Elimam, 2021; Skvortsova et al., 2022), trade balance, imbalance, and inflation are the subjects of research. Spangenberg (2005) also notes that traditional economic sustainability measures, such as aggregate demand and consumption levels are secondary in the current debate. However, these issues are significant for the modern discussion of economic sustainability (Sağlam and Egeli, 2018; Aydın and Tirkolaee, 2022; Chan et al., 2022).

One of the significant topics of the sustainable development of society is the liberal intellectual tradition and its criticism in modern studies (Hart-Landsberg and Burkett, 2005; Petrucciani, 2020; Sørensen, 2022). The reason for the criticism is that the transition to the market has led to the widespread dissemination of quasi-public and quasi-private phenomena based on the interpenetration between the state and society. Francis (2001) points to an alternative concept implemented in China's emerging market economy.

Developing the quasi-public sector of the economy is important for the sustainable development of society and the state (Francis, 2001; Qian et al., 2019; Kamenev, 2021). At the same time, studies of the functioning of the quasi-public sector in the Republic of Kazakhstan relate to certain problems, for example, the mechanism for monitoring procurement in the quasi-public sector (Khamitov, 2020), institutional and investment mechanisms to support the agro-industrial complex (Taubayev et al., 2017). Issues of the quasi-public sector in the Republic of Kazakhstan need further research for further development and improvement.

The state has a large mass of assets and corporate governance tools. In connection with this circumstance, there are opinions about the need to establish control over the activities of state corporations (Avdasheva and Simachev, 2009). One of the significant problems is the problem of inefficient management of state property and the contradiction in the performance of enterprises in public and private sectors (Fominykh, 2004; Luzan, 2004; Zhavoronkov, 2004).

The development of an effective state policy for the prudent use of regional assets is necessary to reduce the degree of the negative impact of international sanctions on the state. At the same time, the main role of state policy should not be in the distribution of income between regions but in creating conditions for the involvement of these assets in economic activity, which should improve the population's quality of life (Emelyanov et al., 2016). At the same time, tools for assessing the effectiveness of state property management are not properly involved in different regions of the country (Kamaev, 2012). Solovyov (2008) believes that when managing state assets of the economy, it is important to observe the principle of ensuring a balance of interests between economic efficiency and social responsibility.

The key indicator of the effectiveness of public administration is its impact on the population's quality of life (Baimuratov et al., 2020; Vasiliev and Sushko, 2021; Zhanbayev et al., 2021). The ability to apply country experience and, in general, international trends in public asset management in "transition" countries depends on many factors that influence the development of these countries and specific national and international forces (So, 2005; Roje and Redmayne, 2021). Nazif Çatık et al. (2020) analyzed asset pricing models considering changes in oil prices and exchange rates. They refine the methodology for assessing asset management's effectiveness in terms of market prices' influence on them and conclude that this factor affects industry profitability less than the exchange rate return.

Yan et al. (2020) investigate the incentive effect of reputation and the deterrent effect of oversight on the allocation of public assets in budget management. The researchers conclude that the incentive effect of reputation is effective for a high cost of the budget unit, and the constraining effect of supervision is effective for a budget unit with a low cost.

It should be noted that a significant part of the research in the field of state property management states inefficiency due to bureaucracy and lack of accountability of state organizations. At the same time, research on the activities of private structures is devoted, on the contrary, to the accumulation of profits from the investments of private investors, and the lack of analysis of the effectiveness of public investments (Noring, 2019).

3 Materials and methods

Methodological database of research in the field of public asset management. When studying the state of private asset management, empirical general scientific methods of cognition were also used. A method of observing and collecting facts of regularities in the processes of reproduction in their nature. This method of identifying the neonatal state of state assets in a quasi-state republic was determined in Kazakhstan and revealed a problem.

A systematic approach is used as a methodological approach, within which methods of logic, statistical analysis, and synthesis are provided. This methodological approach served by our procedure for the corporate foresight mechanism to use the right of transnational corporations (Kovářiková et al., 2017; Semke and Tiberius, 2020; Wenzel, 2022).

Foresight is based on the method of self-expression of expert assessments and includes the active formation of an image of the future and the determination of development priorities. This method makes it possible to develop a forward-looking program of action to respond to the main requirements and achieve the goal. The obvious advantages of corporate foresight have served to form improved expectations from its practical application, which is associated with the choice of research methodology. There was an opinion that now there is a transition from management to strategic foresight (Gatignon and Xuereb, 1997; Danielson, 2014). However, it is believed that the possibilities of foresight are still limited. Foresight cannot fully replace the selection system, but it can significantly increase its effectiveness as its complement.

We find with those authors who believe that foresight's strength is not in tools and methods but in influencing the minds and views of people. Carries out foresight competencies that can transform their organizational culture (Ansoff et al., 1976; Ruff, 2015). Thus, using the foresight mechanism attracts more responsibility for improving the efficiency of quasi-state litigation. When addressing issues of research methodology, emphasis is placed on the approach to private asset management from an objective orientation towards dynamically changing emerging markets in the context of special transformations of the competitive landscape. The implementation of this goal is possible when using the foresight methodology. The effectiveness of such a methodology is its benchmark for achieving sustainable economic development. Of course, the foresight mechanism is crucial for transnational businesses (Bereznoy, 2017). For us, foresight is of interest in sequential analysis in the next protocol for the economy of Kazakhstan, namely, in the quasi-statistical protocol.

We proceed from the fact that using foresight tools makes it possible to increase the efficiency of managing third-party assets. The application of this methodology is carried out in the main directions aimed at streamlining and optimizing the quasi-energy sectors in Kazakhstan: *Firstly,* the need to distinguish between three levels of the quasi-public sector, depending on the degree of influence on operational activities and the loss of income for the development of the country's economy. *Secondly,* creating a new national holding showed that the attitude toward the state is strategic and a priority for the country's economy. *Thirdly,* the creation of a share of the quasi-public sector increases the risk of reducing the functions of the state structure and body to use the synergistic effect of public-private consumption. *Finally,* the quasi-public sector should not restrict competition but oppose the stimulation of business development in all its forms and the diversification of the economy.

4 Results

We justified the application of the triple helix model in forming a conceptual mechanism aimed at the interaction of the prominent participants: business, government, education, and science, which correlates with (Baimuratov et al., 2020). In this study, we believe it is correct to use and test the methodology of the above-mentioned conceptual approach for

TABLE 1 Elements of the corporate foresight mechanism for quasi-public companies.

No.	Tools of the mechanism	Content	Main participants
	Assessment of the current state of affairs	Formation of an information basis for the analysis of the past, present, and future situations of interaction between business, society, quasi-state companies, and the state	Quasi-state companies
	Mission	Definition of a comprehensive goal that includes both internal and external guidelines for cooperation	Quasi-state companies
	The general goal	Establishment of specific end states of the interaction model or the desired result	Quasi-state companies
	SWOT analysis	Analysis of the strengths and weaknesses of the socio-economic development of the region, as well as potential opportunities and threats	Quasi-state companies
	Priorities		
	Business development	A set of actions aimed at implementing favorable conditions for effective development that meet the needs of society and business	Business community and quasi-state companies, government
	Cooperation	Development of joint projects of stakeholders and businesses on the so-called "information mediation."	Business community and quasi-state companies, government
	Clustering	Development of joint development programs within the framework of the creation of industry groups	Business community and quasi-state companies, government
	Partnership in moving forward	Ensuring cooperation with stakeholders to create a favorable market environment	Business community and quasi-state companies, government
	Practice and Discourses (Planning)	Practice and discourses in which the forecasting and design of the "Future in the present" is carried out	Business community and quasi-state companies, government
	Shaping the Future (Implementation of Strategic Directions)	Development of a strategy for the implementation of the concept Formation of scenarios, drawing up roadmaps that increase competitiveness and quickly respond to market changes in the internal and external environment when making managerial business decisions	Business community and quasi-state companies, government

public-private interaction based on the corporate foresight toolkit. Table 1 presents elements of corporate foresight for the sector on which the sustainable development of the economy depends, which is the quasi-public sector.

Here are the main elements of the corporate foresight mechanism for quasi-state companies that most strongly affect the achievement of sustainable economic development goals. The expansion of the activities of quasi-state companies requires the development of a single vector of development, considering the specifics of the market segment, the application of a systematic approach to monitoring compliance with the norms of optimal conditions for assessing their economic and social results, and considering the development priorities of the Republic of Kazakhstan. At the same time, special attention should be paid to effective infrastructural support for business and the identification of stakeholders, raising the level of awareness of business and society, and identifying the country's resource and market opportunities. In this regard, the application element can be used to increase the use of digital technologies.

The lack of a clear institutional framework for quasi-state companies is noteworthy, which negatively affects the ability to determine priority goals and objectives and to measure their achievements qualitatively and quantitatively. Clustering allows tracking changes in the current architecture of the system of state and quasi-state companies. On this basis, it is possible to activate the system of monitoring and evaluating their effectiveness while influencing the goal of development stability.

Action planning involves solving the problem of financial returns from the activities of quasi-public companies and, consequently, state participation. To this end, an action plan is being drawn up, and ongoing measures are aimed at modernizing the activities of state and quasi-state companies, including increasing investment attractiveness.

From our point of view, the results of the search for the results of activities of quasi-state companies are especially relevant for the economy of the Kazakhstani regions. Today, the issues of public-private ownership in the regions are in a state of lack of demand. This tendency is due to the low growth of the innovative dynamics of the socio-economic development of the regions and the subsequent weak competitive environment. In this plane, the role of the public sector represented by the quasi-public sector, which, as you know, manages the distribution of most of the resources, is more important than ever. Thus, planning their activities is a necessary factor in the economy's stability.

Sustainable development is possible with the balance of three main components: the growth of economic and social responsibility and environmental balance. In this article, the emphasis was on economic growth and social things, and environmental things were considered in our observations.

TABLE 2 Information on the number of state institutions in the Republic of Kazakhstan (for 2021).

No.	Name	Quantity, units
	State bodies (thousand)	8.3
	State institutions in the field of education (schools, out-of-school organizations), (thousand)	7.8
	Objects of culture and sports (houses of culture, sports schools, archives, libraries), (thousand)	1
	Objects in the field of healthcare and social protection (hospitals, clinics, centers for adaptation, employment)	500
	Institutions are represented in the structure of the ministries of defense, internal affairs (military units, detention centers, penitentiary institutions)	400
	Youth centers	180
	Other institutions (service centers, veterinary stations, transport organizations)	150
	Total, (thousand)	18.3

TABLE 3 State and quasi-state companies in the non-social sphere of the Republic of Kazakhstan.

No.	Name	Quantity (units)
	Organizations of the Samruk-Kazyna Fund	204
	Veterinary stations	194
	Water supply	79
	Development Institute	63
	Organizations supporting the activities of state bodies	37
	Mass media organizations (media)	33
	Organizations in the field of housing and communal services (heat, energy, gas supply, water supply, landscaping)	25
	Investment funds	29
	Single operators	20
	Organizations in the field of energy and electricity supply	23
	Plants	22
	Transport organizations	13
	State monopolies	11
	Service companies	29
	APK	7
	National companies	10
	FEZ operator	2
	Other	17
	Total	818

From this point of view, we examined the analysis of the process of regulating the activities of quasi-state companies with the participation of government departments. This study made it possible to identify the most problematic issues that can sufficiently improve the quality of their management, and this should be focused on the sustainable development of the economy.

4.1 The first problem is the lack of a clear institutional framework

In 2021, the state will be the owner of about 25 thousand state institutions, state enterprises, JSCs, and LLPs. 18.3 thousand (Table 2).

6.4 thousand subjects of the quasi-public sector, including five thousand organizations (or 78%) are social (education (3.5 thousand), culture and sports (more than 800), healthcare and social protection (more than 700); related to the non-social sphere, 818 organizations, excluding organizations included in the Comprehensive Privatization Plan (736 organizations) (Table 3).

So, out of 25 thousand state institutions, state enterprises, joint-stock companies, and limited liability partnerships, 23.4 thousand organizations belong to the social sphere, these are state bodies, organizations in the field of education, healthcare, social protection, culture, and sports.

These subjects strategically influence the economic system at the state level. However, objectively, such a mass of subjects needs to create a balanced mechanism for managing quasi-state structures. The reason is the lack of consistency based on their classification and accounting makes it difficult to develop a single vector for the development of the industry. It is necessary to identify the main groups of quasi-state companies, in respect of which it is necessary to apply various management mechanisms. To complete this task, the following factors must be considered:

1. First, the system does not divide quasi-state companies into commercial and non-commercial activities. As a result, the same approach is applied to all enterprises; common requirements are imposed, even though organizations are all different in terms of goals and objectives of creation. For example, national companies face different challenges than schools and hospitals. There are also non-commercial enterprises among the national companies—Kazakhinvest JSC, by its nature, cannot generate income; therefore, it cannot be put on a par with other commercial joint-stock companies of the quasi-public sector.
2. Lack of systematic approaches to defining organizational and legal forms. As a result, when creating quasi-state companies, the issue of applying one or another type of organizational and legal forms is determined by the initiating state body itself. For example, in the field of education, organizations operate in various organizational and legal forms, which is associated with the lack of a unified approach to their financing. Thus, schools are registered as state institutions or state enterprises

on the right of economic management. This is because, for state-owned enterprises, the per capita funding standard is higher than for state institutions. As a result, this leads to a different amount of funding, the level of remuneration of teachers, as well as accounting for the property.

At the same time, it is not entirely clear what institutional differences exist between one or another status of quasi-state companies: national management holdings, national holdings and companies, and national and regional development institutions.

3. Accounting for state property is carried out at four levels. Each of these levels is vested with the right to independently determine the procedure for managing state property, which creates conditions for a fragmented policy in this area. Accounting in the authorized body (State Property and Privatization Committee) is not subject to the property of organizations, the founder, participant, or shareholder. In this regard, completeness and reliability of accounting are not ensured, as there are cases of lack of information about individual objects.
4. The lack of a clear institutional framework for quasi-state companies negatively affects the system for monitoring and evaluating the effectiveness of quasi-state companies, the ability to determine the necessary goals and objectives based on the specifics of the activities of quasi-state companies, measuring their achievements and implementation.

4.2 The second problem is the low financial efficiency of quasi-state companies

Net income at the end of 2020 amounted to 67,98,510 thousand tenges. That is, it remained at the level of 2019 for 67,91,000 thousand tenges. At the same time, 95% of the net income of quasi-state companies falls on the share of NWF Samruk-Kazyna JSC and only 5% on the share of other legal entities. In 2020, the total income of quasi-state companies for the reporting period amounted to 23.1 billion tenges, which is 15% lower compared to 2019 and amounted to 27.08 billion tenges. The total expenses in 2020 of quasi-state companies for the reporting period amounted to 14.2 billion tenges, which is 26% lower than the same period in 2019, which amounted to 19.2 billion tenges.

The practice of state financing of quasi-state companies continues. So, in 2019, 817.4 billion tenges was allocated from the republican budget, in 2018—659.2 billion, and 2017—838.8 billion tenge. In addition, funds allocated from the budget to support businesses in various sectors of the economy have become a source of income for many quasi-state companies. For example, receiving 0.5%–1% from the budget or the National Fund, some quasi-state companies finance businesses and citizens at inflated rates of 9%.

The level of external debt of the quasi-public sector remains quite high and continues to grow. In 2020, its size amounted to 20.1 billion US dollars. There are systemic shortcomings in the dividend policy. At the end of 2020, the growth of debt obligations compared to the level of 2019 amounted to 15%. The amount of dividends paid to the state does not exceed 7% of the net income received. This fact is associated with an increase in the unprofitability of quasi-state companies and other distributions in favor of the shareholder to finance non-core facilities. Thus, strengthening control over the debt load and clear regulation of corporate and dividend policy should be one of the stages of the implemented strategic planning.

4.3 The third problem is that the state's share in the economy remains high

The share of state participation in the economy remains high compared with the Organization for Economic Cooperation and Development indicators. Thus, the actual share of the consolidated assets of the national managing holdings of Kazakhstan to the country's GDP amounted to more than 50%. The main tools to reduce the state's share in the economy are privatization and a reduction in the list of activities carried out by quasi-state companies. However, the potential for using these mechanisms is insufficient. For example, the selection of quasi-state companies for privatization is carried out without an appropriate level of transparency and in-depth analysis of the consequences of privatization. In addition, despite the reduction in the list of permitted activities for quasi-state companies in 2020 by 107 types, 306 activities currently remain, some of which can be performed in the private sector. The reduction did not lead to the actual optimization of quasi-state companies since the reduced activities were not related to their main activities.

According to the list of activities approved by Government Decree No. 1095 of 28 December 2015, quasi-public sector entities can still carry out activities in the areas of interpretation and translation, buying and selling real estate, cleaning activities, web portals, bus transportation, advertising in the media, the activities of security organizations and other areas. The imposition of a moratorium on the creation of new quasi-state companies did not help increase efficiency.

4.4 The fourth problem is the lack of a comprehensive system for monitoring and evaluating the performance of quasi-state companies

The applied system for monitoring and evaluating the effectiveness of state property management does not allow for improving the quality of the activities of quasi-state companies.

We note the following shortcomings:

1. Only certain categories of quasi-state companies are subject to assessment. Mainly these are state institutions and enterprises. Large quasi-state companies (for example, NWF Samruk-Kazyna JSC and its portfolio companies) are not subject to the requirements for assessing the effectiveness of their activities. A significant share of quasi-state companies in terms of assets and budgetary investments remains without regular objective assessment.
2. For the assessment, the Rules for monitoring the effectiveness of state property management, approved by the Government Decree of 4 December 2012, No. 1546, as well as the Rules for assessing the effectiveness of state property management, approved by order of the Ministry of National Economy of 11 March 2015 No. 193, are used. However, they do not allow to fully carry out monitoring of the activities of quasi-state companies. Thus, the Rules for the implementation of monitoring (1,546) do not regulate the mechanism for implementing recommendations based on monitoring results, which reduces the effectiveness of the analytical process. The rules for evaluating the effectiveness of state property management (193) also do not reflect the real situation of the activities of quasi-state companies. They do not contribute to improving the efficiency of state property management. The reason is that the assessment uses common parameters. For example, criteria are used for "Reducing the number of organizations with a negative financial result," "The presence or absence of state-owned enterprises and state-controlled joint-stock companies (LLPs) that do not have key indicators that can be quantified in the approved development plan."

4.5 The fifth problem is the imperfection of a single information resource on quasi-state companies

Currently, the informational secrecy of quasi-state companies is maintained. In the public domain, there is no data on the structure of many companies, financial activities, staffing, dividends paid to the shareholder, and other aspects. This trend is especially true for state-owned enterprises that do not publish the necessary information about their activities.

By transferring part of the functions of information technologies of portfolio companies to a competitive environment, several tasks can be solved: 1) development of the information technology management function, 2) ensuring business continuity, taking into account the balance between obtaining benefits and optimizing risks and resources, 3) developing the domestic market information technologies.

In addition, it is also important to ensure the information security of quasi-state companies. To build a system for managing and ensuring information security at a group level according to the principle of a service model, the following actions are required: 1) increase the level of maturity of management and information security processes, 2) reduce their risks, 3) reduce response time, 4) reduce the costs of eliminating the consequences of information security incidents. Thus, the key factor for the success of quasi-state companies should be the effective completion of the digital transformation processes of quasi-state companies.

4.6 The sixth problem is weak corporate governance

Corporate governance in Kazakhstan, not only in quasi-state companies, is used quite formally and is not in demand by business owners, shareholders, and stakeholders. At the same time, in joint-stock companies, the issue of corporate governance is regulated by the Law of the Republic of Kazakhstan "On Joint Stock Companies" and other regulations. However, only separate corporate governance elements have been implemented for state-owned enterprises and limited liability partnerships. The current legal framework does not provide for the responsibility of members of the supervisory and executive bodies of quasi-state companies, which, in turn, affects their effectiveness. Issues of transparency and accountability of quasi-state companies have not been settled. In terms of decision-making, there is a risk of the excessive influence of the central and local executive bodies in charge of the relevant industry, their excessive interference in the activities of quasi-state companies, including the centralization of tasks, often at odds with the strategy of quasi-state companies.

The sustainable state's economic basis is provided to a large extent by the quasi-public sector. Therefore, there is no doubt about the need to determine priorities in the management of quasi-state companies that would give a vector for the sustainable development of the economy. In this regard, we assume the following recommendations for reforming the quasi-public sector management system in the Republic of Kazakhstan.

1. It is necessary to form a new institutional structure for the activities of quasi-state companies, reflecting a clear delineation of functions, processes, tasks, and criteria for assessing their effectiveness.
2. Considering the classification and type of activity, for each group of quasi-state companies, establish separate financial criteria and indicators for the implementation of strategic and tactical tasks.
3. Improve the financial discipline of quasi-state companies.
4. Reduce the share of state participation in the economy.
5. Ensure transparency of activities and openness of quasi-state companies of the Republic of Kazakhstan.

6. Increase the information content of monitoring and evaluation of quasi-state companies.
7. Ensure the quality of corporate governance in accordance with global ethical standards.

5 Discussion

This study is based on the analysis of problems and the search for their solutions in the regulation of the activities of quasi-state companies. In this regard, in this section we discuss proposals for improving state regulation and administration of quasi-state companies. In this section, we discuss such aspects as economic growth, the social dimension, and environmental issues of the proposed recommendations. The legitimacy of this approach lies in the fact that the quasi-public sector, like no other, is most represented in the social sphere and the environment.

5.1 It is necessary to form a new institutional structure for the activities of quasi-state companies, reflecting a clear delineation of functions, processes, tasks, and criteria for assessing their effectiveness

It is important to revise the current classification of quasi-state companies based on the goals and objectives of these organizations. First, it is important to provide for the separation of legal entities with the participation of the state, depending on the commercial and non-commercial orientation. Further, commercial, and non-commercial quasi-state companies are proposed to be divided into two types presented in Table 4:

5.2 Considering the classification and type of activity for each group of quasi-state companies, establish separate financial criteria and indicators for implementing strategic and tactical tasks

If the organizations are non-profit social and implement national policy, then the following conditions should apply to them:

- they should not be subject to requirements in terms of profitability, while their activities should be break-even;
- indicators of their effectiveness should be the quality provision of social services and the achievement of strategic (key) indicators;
- financing of these groups should be carried out by the estimated principle and through the state order.

To commercial infrastructure, strategic quasi-state companies, as well as development institutions:

- there must be requirements for profitability;
- indicators of their effectiveness to consolidate the achievement of strategic indicators;
- implementation of financing at the expense of own funds and through budget financing and borrowing in the capital market.

5.3 Improve the financial discipline of quasi-state companies

We consider the experience of some developed countries (for example, Australia), where methodological instructions (Commonwealth Government Business Enterprises – Governance and Oversight Guidelines) have been developed for government business companies that help manage their activities. The instructions contain companies' main financial, strategic, and reporting requirements to comply with. By analogy with these instructions, it is necessary to develop a document that fixes the basic requirements for the activities of quasi-state companies.

The risk of insolvency of quasi-state companies can become a threat to the stability of the country's economy. In this regard, it is necessary to strengthen monitoring of the level of external debt of quasi-state companies. For example, constant monitoring and control over external and internal loans of the CSC have been carried out since 2018 in pursuance of the order of the Head of the Presidential Administration "On approval of the Action Plan for the implementation of the instructions of the President of the Republic of Kazakhstan given at the opening of the third session of the Parliament of the Republic of Kazakhstan of the sixth convocation on 4 September 2017." The issue of maximizing the payment of dividends is being worked out as part of the instructions of the Head of State following the expanded meeting of the Government of 10 July 2020. Transparency and accountability of the activities of the quasi-public sector are being worked out within the framework of the National Action Plan for the implementation of the Address of the Head of State.

5.4 Reduce the share of state participation in the economy

It is advisable to carry out separate work to identify and liquidate or restructure or privatize inefficient (unprofitable) organizations. The list and goals of the activity of quasi-state companies should be reviewed, considering new strategic tasks and national priorities of the Republic of Kazakhstan.

TABLE 4 Commercial and non-commercial quasi-public companies.

No.	Commercial quasi-public companies	
	Infrastructural, strategic	Development institutions
	JSC "National Company "Kazakhstantemirzholy"; JSC National Atomic Company Kazatomprom; JSC "National Company "KazMunayGas"; National Welfare Fund Samruk-Kazyna	JSC Baiterek National Managing Holding JSC; JSC "Development Bank of Kazakhstan", Social-entrepreneurial corporations
	Non-profit quasi-state companies	
	Social non-profit quasi-state companies	Companies implementing national policy on specific issues

In addition, conducting a critical assessment of their activities and the return on budgetary investments is necessary. For example, it is advisable to consider the consolidation of development institutions in the development and export promotion field. The same work can be done with organizations in the field of technological development. For example, following the Government Decree dated 30 July 2016 No. 450, Export Insurance Company KazakhExport JSC, National Company KAZAKH INVEST JSC, Kazakhstan Industry and Export Center QazIndustry JSC are designated as institutions in the field of development and promotion of exports. QazTrade Trade Policy Development Center JSC. Also, the issues of supporting exporters are dealt with by the Development Bank of Kazakhstan JSC, Damu JSC, the Foreign Trade Chamber of NCE Atameken, and animats.

Technological development issues are assigned to the Center for Engineering and Technology Transfer JSC, QazTechVentures JSC, and Astana Innovations JSC. Considering the low efficiency of social entrepreneurial corporations and diversion to non-core activities, it is necessary to take measures to reduce the portfolio of social entrepreneurial corporations, their subsidiaries, and affiliates by transferring them to a competitive environment, as well as to get rid of non-core assets, including them in the list of privatized objects. For example, an analysis of the activities of this institution conducted by the Ministry of National Economy shows that among 17 social and entrepreneurial corporations, there is no unified approach to the implementation of state programs and territorial development programs. Often their activities do not correspond to the main goal, namely, to support business initiatives, stimulate economic activity in the growth points of the regions, and are unprofitable. The return on assets of social entrepreneurial corporations in most regions has negative values. More than a third of the subsidiaries of social and entrepreneurial corporations are inactive. There is a lack of activity in these enterprises in the search for investment opportunities.

5.5 Ensure the transparency of activities and openness of quasi-state companies of the Republic of Kazakhstan

We propose the following measures to ensure the disclosure of information about quasi-state companies:

- use of modern information technologies to improve the efficiency of collection, processing, analysis, and public disclosure of information by issuers and other financial market participants, as well as to provide access to databases for all interested parties;
- it is necessary to introduce the standard of openness of quasi-state companies.

For the most effective satisfaction of users' information requests regarding the activities of quasi-state companies, it is necessary to create a data access infrastructure that provides for the organization of feedback. Creating effective feedback will allow the organization's management to quickly respond to changing information user requests, which will increase the organization's value in the eyes of its stakeholders and create a competitive advantage.

5.6 Increase the information content of monitoring and evaluation of quasi-state companies

It is important to revise the approach to accounting for state property. At the same time, the Register of State Enterprises and Institutions, Legal Entities with State Participation in the Authorized Capital should be updated. In addition, it is necessary to ensure at the legislative level that the requirements for monitoring and evaluating the effectiveness of state property management and financial and economic activities are extended to all quasi-state companies. It is also important to strengthen the Rules for monitoring the effectiveness of state property management (1,546) by regulating the mechanism of execution based on the results of monitoring recommendations. Include the Accounts Committee in the system for monitoring the effectiveness of state property management. During the revision of the Rules for assessing the effectiveness of state property management (193), the emphasis will be shifted to the socio-economic efficiency of quasi-state companies.

5.7 Ensure the quality of corporate governance following global ethical standards

To improve corporate governance, ensure the inclusion of more qualified independent directors on the boards of directors and the exclusion of formal members of the board of directors. Strengthen the board of directors and its members' responsibility for implementing strategic objectives. To increase human resources, provide for the phased introduction of minimum qualification requirements for senior positions and the Board of Directors of quasi-state companies (for example, professional certification in corporate governance, FRM, CFA, ACCA). Maintaining a register of highly qualified independent directors and strengthening their role in making management decisions is necessary.

Review the relationship of the quasi-public sector with government bodies, considering OECD standards. As one of the measures in this direction, we propose the exclusion of civil servants from among the members of the Board of Directors. Implementing a set of proposals will create conditions for forming a highly efficient, compact, and transparent quasi-public sector.

6 Conclusion and policy propositions

We investigated the tools, methods, and algorithms for the administrative management of state assets, and qualitative analysis of the advantages and disadvantages of the Republic of Kazakhstan quasi-state companies. The new role and functions of the state in a globalizing world require a rethinking of the goals, institutions, and mechanisms of socio-economic state policy based on the introduction of balanced strategic planning, in which the main indicator is the achievement of sustainable development. The basic factor is the sphere of administrative and strategic management of quasi-state companies.

The quasi-public sector of the Republic of Kazakhstan has several shortcomings the lack of a clear institutional framework for activities, the low financial efficiency of entities, and a high level of the state in the economy. In this regard, the main measures are proposed to reformat the management system of the quasi-public sector to focus it on the sustainable development of the economy as a whole:

- the transformation of the institutional structure and target orientation of quasi-state companies;
- development and approval of requirements taking into account the type of activity of quasi-state companies with a classification by profitability, objectives, strategic indicators, and funding procedures;
- control and financial discipline of quasi-state companies with a decrease in state participation;
- transparency to internal and external stakeholders;
- modernization of indicators for monitoring and evaluating quasi-state companies;
- an updated model of corporate governance in those organizations where it is applied.

As a result of the analysis of the tools introduced into the practice of leading transnational corporations, the main directions were identified in which it is advisable to take measures aimed at streamlining and optimizing the quasi-public sector in the Republic of Kazakhstan:

- clearly distinguish between three levels of quasi-state companies, depending on the degree of intervention in the operating activities of subsidiaries and affiliates, as well as on the significance of assets for the development of the country's economy;
- quasi-state companies should ensure the symbiosis of protecting the national interests of the public sector of the Republic of Kazakhstan and the corporate efficiency of the commercial sector;
- the creation of quasi-state companies is justified if their activities are not aimed at duplicating the functions of a state body but at increasing the synergistic effect of public-private partnerships;
- quasi-state companies should not narrow the competitive environment but provide a multiplier effect for the development of small and medium-sized businesses and related sectors of the economy.

This article examined the effectiveness of managing state assets of the quasi-public sector of the economy in the Republic of Kazakhstan. We proceed from the international theory and practice of applying the corporate foresight methodology using the strategic planning mechanism. However, the study is focused on the current situation in the Republic of Kazakhstan. Today, the economy of the Republic of Kazakhstan is faced with the task of getting out of the low dynamics of the development of the private sector and overcoming dependence on the primary industries. In connection with this circumstance, the development of the quasi-public sector is considered by the government of the republic as the most important factor in the development of the economy. However, the challenges in the economy and the social problems of the population of the regions of the Republic of Kazakhstan show that the current model of the quasi-public sector has several systemic shortcomings. Therefore, we have made recommendations for the development of the quasi-public sector refer to the Republic of Kazakhstan. The new institutional structure of quasi-state companies' activities should reflect a clear delineation of functions, processes, tasks, and criteria for evaluating their effectiveness. Improving the efficiency of quasi-state companies is directly related to their discipline in the financial system. Therefore, it is necessary to develop financial criteria and classification of indicators for the implementation of strategic and tactical tasks. It is impossible to reduce the share of state participation in the economy without mechanisms to ensure transparency of activities and openness of quasi-state companies of the Republic of Kazakhstan. Therefore, the main principles should be information openness and ethical standards of public administration and the activities of the quasi-public sector.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

Conceptualization, RZ, MI, and AS; Methodology, RZ; Validation, AY, KG, MI, and GT; Formal analysis, IC; Investigation, RZ; Resources, RZ; Data curation, RZ and AS; Writing—original draft preparation, RZ; Writing—review and editing, RZ and AS; Visualization, AY; Supervision, RZ and AS; Project administration, RZ. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Optimization of the environmental protection tax system design based on artificial intelligence

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Introduction: China achieved significant economic growth in the past two decades, and the sustained economic growth also brings negative implications for the environment. The Chinese government has introduced various fiscal reforms to mitigate the negative implication of the environment in the economy. Modernization of China's governance system and improvement of social development were the main goals of the 14th Five-Year Plan.

Methods: Literature combing method and Chart analysis method.

Result: Artificial intelligence promotes the efficiency of bonded governance environment and boosts national management modernization.

Discussion: This paper suggests that the artificial intelligence construction of the environmental protection tax system improves tax collection and management, tax payment service, and tax management. In addition, the government should adopt other strategies to promote a clean environment, such as tax exemption for green and cleaner production. Easy loans should be provided to the exports, especially those contributing to clean energy production.

KEYWORDS

ecological, environmental protection tax, artificial intelligence, profit tax amount, tax administration

1 Introduction

The fourth Plenary Session of the 19th CPC Central Committee emphasized on modernizing China's governance system, and social development and tax reforms were the main goals of the 14th Five-year Plan. Implementing a modern governance system ensures tax reforms that could increase government revenue and mitigate the burden on people. Economic development increases the income of the people, helps achieve economic goals, and brings environmental challenges such as environmental pollution and environmental degradation (Ullah et al., 2022; Zeeshan et al., 2022). The Chinese government implemented various reforms to achieve sustainable environmental goals, such as pollution tax and green energy production (Wingender, 2018; Tan et al., 2022). In order to improve eco-environmental governance and accelerate the process of modernizing national governance, Big Data and information technology are integral parts of the national governance system. China introduced an environmental protection tax system in 2018 for ecological protection and environmental pollution control. Improvements and developments based on artificial intelligence can help modernize ecological environment governance by making it an influential policy tool (Faúndez-Ugalde et al., 2020). China began to investigate and implement tax information as early as the 1980s. After 30 years, the information system represented by the "Golden Tax Project" has progressed to its fourth phase (Xing and Whalley, 2014). The goal of the fourth phase of the Golden Tax Project is to promote the modernization of tax administration-based intelligent taxation. The environmental protection tax can rely on the experience and conditions of the development of the existing "Golden Tax Project," which significantly improves the information and intelligence of tax categories and solves the problem of difficult measurement and monitoring of pollutant emissions. Therefore, this paper aims to illustrate the application of artificial intelligence in the environmental protection tax system.

Description of the research process: From the perspective of artificial intelligence optimization tax system construction, this paper discusses how to improve the environmental protection tax with the help of artificial intelligence technology. First of all, the paper analyzes the specific changes in pollutant discharge fee after it was changed into environmental protection tax, and the main research results after the current fee was changed into tax to provide a theoretical basis for sorting out the shortcomings of environmental protection tax. Second, the shortcomings of the environmental protection tax are analyzed from the perspective of tax principle, tax neutrality, tax substantive law, and tax procedural law. Then, based on the analysis of the existing problems of the environmental protection tax, the construction and improvement path of the environmental protection tax is discussed from the perspective of artificial intelligence. Finally, we focus on the future challenges of environmental protection tax.

This paper contributes to the literature in the following aspects: First, the paper summarizes and evaluates the changes and research emphases after the change in environmental "fee to tax." As an important environmental regulation measure, environmental protection tax is an important tool to improve the ability of ecological environmental protection and governance. The study of its change and development is of great significance to the study of environmental protection tax reform and the improvement of the tax system. Second, the research perspectives of the environmental protection tax from the perspective of taxation principle should be expanded. Environmental protection tax comes from the reform of "fees" and has many characteristics of fees, so the purpose of environmental protection tax is significantly different from that of other taxes. The improvement and development of environmental protection tax and other taxes have a great difference, and from the perspective of taxation principle analysis, it can theoretically promote the construction of the environmental protection tax. Third, from the perspective of artificial intelligence to explore the environmental protection tax improvement path. The development of artificial intelligence technologies such as Big Data, Internet, blockchain, and cloud computing can solve the difficulties in environmental protection tax accounting, measurement, detection, and monitoring; make up for the deficiencies of existing measurement technologies and methods; provide quality of tax data; and improve the efficiency and effect of tax collection and management.

2 Review of literature

2.1 Specific changes of environmental "Fee to Tax"

The current environmental protection tax is based on the reform of pollutant discharge fees, and it is basically the same in terms of the objects to be collected, the scope to be collected, and the basis for calculating taxes (fees). In order to not increase the tax burden of enterprises and smoothly promote the reform of fees and taxes, local governments basically adopt the principle of "Tax Burden Translation" to design tax rates (Lianchao et al., 2021). Therefore, there is no substantial difference between the current environmental protection tax and "Sewage Charge." The main reasons for the change are endogenous law enforcement, low charging standards, and insufficient incentive effect on enterprises (Guo Junjie et al., 2019). It is anticipated that the system of the Environmental Protection Tax Law can be constructed and gradually improved through legislation to achieve the purpose of emission reduction and pollution control and improvement of ecological environment quality.

2.1.1 The main changes after the change of environmental charges are reflected in the following aspects

The first one is to increase the rigidity of law enforcement (Table 1). The collection procedure has been changed from "Environmental Protection Billing and Enterprise Payment" to "Tax Collection and Management, Enterprise Declaration, Environmental Protection Monitoring, Information Sharing, and Collaborative Governance." The form of the collection was changed from "Fee" to "Tax," which strengthened the enforcement of the environmental protection tax and confirmed its legal status. Tax collection and management, environmental monitoring, multi-department participation, law enforcement, and supervision occurred at the same time. It reduces the degree of local government intervention in tax collection, reduces the possibility of enterprise rent-seeking, reduces the risk of lax law enforcement, and can show the incentive of the environmental protection tax on enterprise economic behavior (Table 1).

Second, the upper limit of the collection standard has been increased. The upper and lower limits of environmental protection tax collection standards have been set, and the upper limit has been increased. The specific standards for collecting the environmental protection tax by regions are set by local governments and submitted to the National People's Congress for approval and filing. Statistics show that 42 percent of the 31 provinces where the environmental protection tax has been implemented have raised the tax collection standard (Li Yue, 2021). In the Beijing–Tianjin–Hebei region, Jiangsu, and Shanghai and Henan provinces, the tax rate is five to 10 times higher than the minimum rate (TIAN Cui-Xiang,et al., 2021). It reflects the standard of adjusting measures to local conditions, gives room for tax collection adjustment, and gives full consideration to the level of regional ecological and economic development, while increasing the intensity of collection and incentive.

Third, the environmental protection tax has increased the number of tax exemptions and exemptions and preferential tax policies. The motto that says "one size fits all" should be avoided, the environmental protection tax should be made more specific to enterprises, and more incentive should be provided. As stipulated in the Environmental Protection Tax Law, if the concentration of taxable pollutants or water pollutants discharged by taxpayers is less than 30% of the national and local pollutant discharge standards, the environmental protection tax shall be reduced by 75%; and if the concentration is less than 50%, then the environmental protection tax shall be reduced by 50% to encourage enterprises to lower their pollutant discharge standards.

TABLE 1 Changes before and after the introduction of environmental tax.

Change of environmental "charge to tax"	
Similarities	Object of collection; scope of the collection; tax basis is the same
Differentiation	01) Changes in taxation procedures have increased enforcement rigidity
	02) Variation of tax attribution; revenue power belongs to local governments
	03) The upper limit of the collection standard has been increased
	04) Increase in tax incentives; increase in the flexibility of the environmental protection tax

2.2 Literature review of environmental effects after tariff change

2.2.1 Domestic scholars focused on the following aspects after the introduction of environmental protection tax

One example is the impact of environmental protection tax on enterprises (as Figure 1). First, the impact of environmental protection tax reform on enterprise environmental technology or green technology innovation: scholars took A-share listed companies in Shanghai and Shenzhen stock markets, A-share industrial listed companies in Shanghai and Shenzhen stock markets, enterprises in specific regions (such as the Yangtze River Delta, the Yangtze River Economic Belt, and the Beijing–Tianjin–Hebei region), clean production enterprises, and non-clean production enterprises as samples to analyze the impact of environmental protection tax reform on technological innovation. The basic conclusion is that the environmental protection tax reform has a positive incentive effect on green technology, which can promote the green transformation of heavily polluting enterprises and the production transformation of non-clean production enterprises, and the green innovation effect of large enterprises is significantly better than that of small and medium-sized enterprises. Second, the impact of environmental protection tax reform on enterprise performance capacity: the research on analyzing the effect of enterprise performance is mainly performed to compare the changes in enterprise performance before and after the implementation of the environmental tax, such as LONG Feng et al. (2021) and Xiao-Guang Liu et al. (2021). They concluded that there are differences: the former think green taxes on business performance are influenced by the institutional environment, favorable in the institutional environment in the eastern area, and green taxes have an inhibitory effect on corporate performance in the short term or think that green taxes impact on corporate performance, affected by technological innovation. In addition, technological innovation has a mediating effect, and environmental tax has little fluctuation on enterprise performance in the short term. Third, the impact of environmental protection tax reform on enterprises' investment in environmental protection: Tian Lihui et al. (2022) believed that the environmental tax reform effectively improves the environmental protection investment of heavily polluting enterprises. The preventive environmental protection investment is more effective than the political environmental protection investment. The promotion effect of environmental protection investment of non-state-owned enterprises and small-scale enterprises is more significant. Niu Xiaoye et al. (2021) believed that the collection standard and enforcement intensity of the environmental protection tax affect enterprises' environmental protection investment. Other scholars analyzed the impact of environmental protection tax reform on enterprises' FDI, earning management and information disclosure (Figure 1).

The second is the impact of the environmental protection tax on regional environmental protection and pollution control. In this part of the research, most scholars take provinces or economic zones as the main samples, select some taxable pollutant data, empirically analyze the data of several years before and after the introduction of the environmental protection tax, and test and analyze the effect of the environmental protection tax on emission reduction and pollution control. Xue Gang et al. (2020) selected the emissions of air pollutants and water pollutants to analyze the effect of environmental tax. They concluded that China's environmental tax and pollutant emissions show an "inverted U" model, and the current tax collection standards find it difficult to achieve the goals of emission reduction and pollution control. Zhu Xinling et al. (2020) made an empirical analysis of environmental tax data in the Yangtze River Economic Belt considering tax effectiveness and tax timeliness and suggested that environmental tax had a positive promoting effect on regional economic development, which could reduce resource consumption and pollutant emissions, but its influence had a time lag. Lu Hongyou et al. (2019) used quasi-environmental tax data to study the double dividend of environmental tax in prefect-level cities. They believed that the collection of sulfur dioxide had an emission reduction effect on their pollution. According to the literature review, there are relatively few analyses on the effects of environmental protection tax reform on regional emission reduction and pollution control, which will be one of the focuses of future environmental tax reform research.

Third, the improvement and promotion of environmental protection tax revenue elements: the environmental protection tax is shifted from the sewage charge, which has deficiencies in many aspects. The concern of tax authorities and researchers is to improve the environmental protection tax system and enhance its collection effect. At present, most scholars believe that the current environmental protection tax has some problems, such as too low collection standards, too narrow a scope of taxation, and inappropriate tax preferential and reduction policies. The Research Group of "New- Era Public Finance and Tax Policy Reform Promoting Green Development" (2020) considers that volatile organic compounds and solid waste disposal should be included in the scope of collection. Xue Gang et al. (2020) believed that carbon dioxide, persistent organic matter, and household waste treatment should be included in the scope of collection. Huwei et al. (2020) showed that the adjustment of the environmental protection tax levy standard has a positive significance on enterprises' green technology innovation engine oil and has a more prominent effect on high-pollution industries and cities with strong policy implementation. The Research Group of "New- Era Public Finance and Tax Policy Reform Promoting Green Development" (2020) suggested that the identification of tax preference and tax deduction should be set differently according to the local reality.

Fourth, environmental protection tax collection and administration: pollutant discharge fees are mainly collected and used by environmental departments. The environmental protection department is responsible for the substantive identification of the

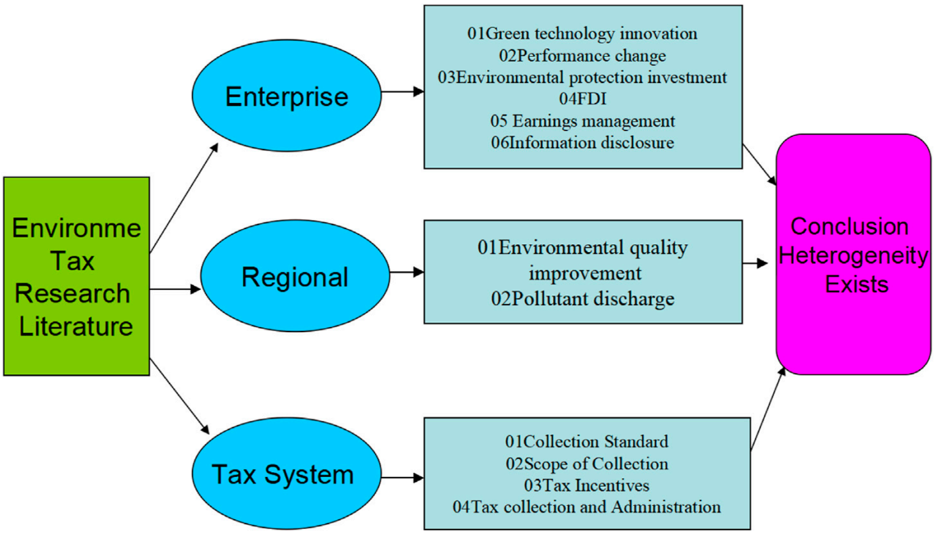

FIGURE 1
Literature analysis of research results of environmental protection tax.

nature and quantity of pollutants, and its work efficiency is directly related to the amount of the environmental protection tax collected by the tax department. At present, most scholars believe that the factors affecting the efficiency of environmental protection tax collection are lack of synergy between the environmental protection department and the tax department, lack of cooperation mechanism, and insufficient tax collection and management. In order to ensure coordination and efficiency of collection and management cooperation, the problems such as unclear cooperation orientation, unreasonable allocation of responsibilities, and unknown incentive measures should be solved in cross-department cooperation (LIN Wei, 2021). Due to the limitations of technology, capacity, and equipment, tax authorities are unable to substantially review the data provided by environmental protection departments, which is inconsistent with the original intention of setting tax authorities as the main and environmental protection departments as the auxiliary in environmental tax legislation. If environmental protection departments do not cooperate or taxpayers seek rent, the efficiency of collection and management will be affected.

From the literature review, the main methods used by scholars to study the environmental protection tax are the dual difference and triple difference formula. Xue Gang et al. (2020), Zhu Xinling et al. (2020), and Lu Hongyou et al. (2019) investigated the environmental tax on air pollution. However, tax efficiency and mechanism of the environmental tax implementation are not discovered in the previous literature. Therefore, this study uses artificial intelligence in the environmental protection tax system. Furthermore, it provides more robust estimations and policy recommendations such as efficiency of taxation, especially from the perspective of taxation principle. The application of artificial intelligence provides robust results and policy implications. Improvements in the quality of tax data, as well as in the efficiency and effectiveness of tax collection and management, are all partly attributable to implement the artificial intelligence technologies like Big Data, the Internet, blockchain, and cloud computing, which have been developed to address problems with environmental protection tax accounting, measurement, detection, and monitoring by adjusting for the shortfalls of existing measurement technologies and methods.

3 Environmental protection tax and the angle of taxation principle

3.1 Quantitative interest taxation principle

Western tax theory believes that taxpayers benefit from public services at different levels of welfare, the level of tax payment should match their benefit level, and the benefit should be the basis to judge the fairness of tax payment Verboon et al. (2009 and Edmund (1986). The quantitative interest taxation principle and quantitative energy taxation principle are the secondary principles of the principle of tax fairness (SU Ri-sha,2020). The quantifiable taxation principle focuses on whether the tax paid by taxpayers can meet the financial needs, while the quantifiable taxation principle focuses on the extent to which taxpayers benefit and pays the state fees or consideration. The main purpose of the environmental protection tax is environmental protection, supplemented by increasing fiscal revenue. From this point of view, the environmental protection tax is more suitable for the quantitative interest taxation principle. Ye Jinyu (2019) analyzed the significance of the existence of Environmental Protection Tax Law from the perspective of the imputation mechanism and accrual mechanism to make up for the absence of tort law and environmental law. The imputation mechanism determines the tax object and tax subject of the environmental protection tax, and the accrual mechanism determines the measurement performance of the environmental protection tax. Due to the particularity of the environmental protection tax, the traditional tax basis based on accounting standards cannot effectively measure pollution emissions. The professionalism and complexity of the measurement based on the amount of emissions or decibels increases, and the measurement of the benefit degree of environmental protection tax is subject to advanced technology and a perfect system.

3.2 Neutral taxation principle

Tax neutrality is the basis for determining tax efficiency. Western taxation defines tax neutrality as taxation that should not affect the original resource allocation of the private sector. As tax is a means of government intervention in the economy, tax neutrality has become an ideal theory. In reality, tax neutrality is emphasized to reduce the interference degree of tax on the economy as much as possible and reduce the excess burden of tax payment on the subject of negative tax. From the perspective of sewage discharge fee, it belongs to the category of "usage fee," that is, the public authority collects fees from beneficiaries of public facilities according to law, which has the characteristics of special funds and special use, which is opposite to those of the principle of tax neutrality. The nature of the environmental protection tax has not changed significantly after the "fee to tax." It can also be said that the idea of special funds for the environmental protection tax is not in line with the principle of tax neutrality, which will affect the efficiency of environmental protection tax collection. In addition, the environmental protection tax is regressive, that is, the taxpayer's environmental protection tax burden has a diminishing marginal propensity to consume. The low-income group bears more tax burden due to the elasticity of commodity demand than the high-income group, and the poor group bears environmental protection tax burden due to the income difference than the rich group (LIN Xingyang, 2021). The regressive character of the environmental protection tax directly leads to the loss of tax fairness, which seriously deviates from tax neutrality principle.

3.3 Substantive tax law

The tax entity factors will affect the scope, object, burden transfer, destination, and efficiency of the environmental protection tax and then affect the accumulation of human capital and economic growth. As the current environmental protection tax is a shift from the sewage charge tax, its tax scope and tax standard have not changed much. Taking the Taxation Standard as an example, the environmental protection tax rate should not be too low, which cannot give full play to the efficiency of the environmental protection tax and deviates from the purpose of environmental protection tax. However, if the environmental protection tax rate is too high, it will reduce the enthusiasm of enterprises to participate in economic activities and inhibit economic growth. Wei Sichao et al. (2020) proposed that the rate of the environmental protection tax should achieve the goal of maximizing social welfare, to promote the transformation from the maximization of economic output to the maximization of social welfare (the specific formula is designed as follows, 5–7). B represents the level of production technology; K represents physical capital; L represents labor, capital, and labor elasticity coefficient related to total output; R represents the interest rate; and W represents wages. Then, we consider the maximization of steady-state social welfare to take the derivative, while proving that the goal of economic maximization is not equal to the goal of social welfare maximization, and deduce the optimal tax rate formula. However, there is no uniform standard for tax rates, Wang Youxing et al. (2016), and the design formula is as follows (8). The denominator is pollution equivalent, and the numerator represents the cost of environmental governance. The author believes that the upper and lower limits of the tax rate can be designed, and the upper limit takes tax burden, economy, and employment factors into account. The lower limit considers the direct cost and opportunity cost (formula 9). However, in general, the reasonable environmental tax rate is helpful to promote the coordinated governance of pollution reduction and carbon reduction.

In 2019, China's environmental protection tax accounted for .14% of the total tax revenue. The average proportion of the environmental protection tax in European and American countries was more than 2% of the total tax revenue. The empirical data show that there is still room for increasing the current environmental tax rate in China. The establishment of tax rate should be combined with regional environmental carrying capacity, ecological pollution and treatment, economic and social development level, etc., to establish the corresponding tax rate for different industries and achieve sustainable development of the regional ecological economy. In addition, due to the complexity of taxable items, the environmental protection tax has higher professional requirements on the identification of tax objects, detection of taxable pollutants, and calculation of tax burden. Artificial intelligence is needed to improve the accuracy of identification, detection, and calculation to improve the effect of environmental protection tax collection.

3.4 Tax procedure law

Tax legislation not only needs to consider its ability to increase fiscal revenue and its impact on economic activities but also needs to pay attention to the tax costs generated in the process of tax collection. The government's ideal tax design should be to obtain sufficient revenue with a small tax cost, that is, to achieve the efficiency of the tax system. Western taxation includes administrative cost, compliance cost, and political cost in tax expenses. The purpose of tax collection and administration is to realize the efficiency of tax collection at a lower cost. As a new tax, the environmental protection tax has no practical experience in tax collection. There are differences between environmental protection and tax departments in terms of work content, working methods, and professional background and the inconsistency of rights and obligations in the current environmental protection tax collection process. It results in serious information asymmetry of environmental protection tax collection, ultimately resulting in the omission, under-collection, and wrong collection of the environmental protection tax. The environmental protection tax has a strong professional accounting of taxable pollutants. Tax collection and management informatization can improve the standardization of data processing, solve the professional requirements of tax-related indicators and calculation methods, improve the professional judgment ability of tax-related information of tax departments, and enhance the strength and effectiveness of tax collection and management. At present, the basic level of tax collection, management, and payment services is not high. Tax authorities can build an information sharing platform with the help of artificial intelligence to increase environmental protection tax collection and payment services and monitor public opinion on environmental protection tax.

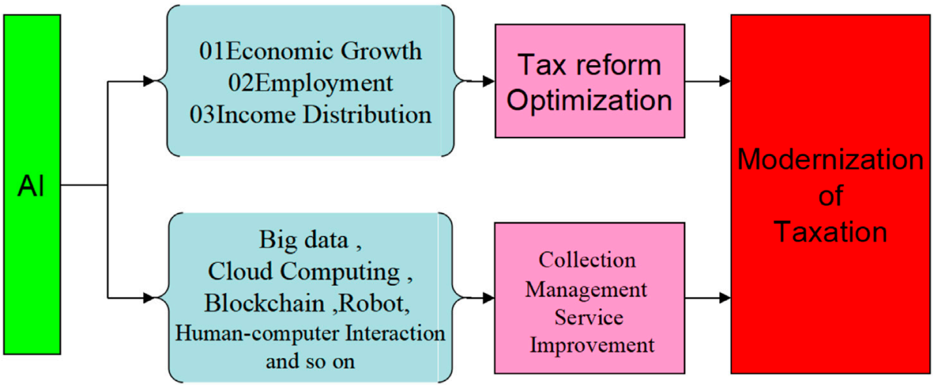

FIGURE 2
Effects of artificial intelligence on tax modernization.

4 Improve the design of environmental protection tax from the perspective of artificial intelligence

4.1 Artificial intelligence and tax modernization

Artificial intelligence in economic growth (Kromann et al., 2011; D Autor et al., 2018), labor force employment (Sarah Bankins1CA1,2021; Amisha Bhargava et al., 2021), and income distribution, Ullah et al. (2020) (T Gries et al., 2020; A Goyal et al., 2020) has a direct effect on social economy. Driven by artificial intelligence, tax modernization has entered a stage of rapid development. In 2021, China launched the fourth phase of the Golden Tax Project. The logical relationship of artificial intelligence to tax modernization is shown in Figure 2. The specialization and complexity of environmental protection tax put forward new requirements for artificial intelligence. The collection, identification, sorting, and analysis of tax-related data can standardize the workflow of tax personnel with the help of machine learning, pattern recognition, and human–computer interaction technologies and significantly improve their efficiency.

Based on the aforementioned analysis, this paper attempts to form the perspective of artificial intelligence, improve the environmental protection tax design and environmental protection tax information construction goals in the safety standard system and data management system, and implement environment tax efficiency between stakeholders, tax services, tax administration, and intelligent tax management, as shown in Figure 3.

4.2 Artificial intelligence and environmental protection tax system improved

First of all, the problems reflected by the principle of volume benefit taxation and the principle of tax neutrality of environmental protection tax must be solved. We can draw lessons from the advanced experience of foreign countries and adopt the way of coordinated taxation with other taxes. From the perspective of the development of the environmental protection tax system in developed countries, in the beginning, most countries only levied taxes on certain specific pollutants. With economic development and social demand, many countries began to impose taxes on two or more types of pollutants. For example, the Eco-tax in the United States covers taxes related to individual consumption, such as automobile fuel charges and corporate resource extraction taxes. These taxes are reflected in China's consumption tax and resource tax. Therefore, in order to reduce double taxation, environmental protection tax can be levied in coordination with other related taxes.

Second, for tax object recognition: using Big Data, accurate recognition of artificial intelligence in government, business, services, and other taxable objects, based on dynamic input information through various channels, such as centralized data processing, the identification is taxable natural area distribution of the pollutants, taxable enterprise mode of production, taxable personal way of life, etc, we extract the main cause set of taxable pollutant discharge. Data processing of these external information and internal tax information can increase the recognition of taxpayers. On this basis, we established environmental protection tax files and card data for enterprises and gradually built the environmental protection tax information resource database.

Then, there is the problem of low levy standards. Because the current environmental protection tax collection standard is shifted to the sewage charge, the time span of the establishment of the sewage charge standard is too long, and the guiding significance for the current social and economic development is insufficient. Local governments can use Big Data analysis of artificial intelligence, cloud computing, and blockchain to obtain data related to the tax area, for example, natural resource endowment, ecological environment quality, economic and social development level, taxable enterprises, and taxable pollutants. To realize the differentiation of environmental tax rate standards, we gradually increased the lower limit of environmental tax rate and set multiple targeted preferential tax rates to increase the tax incentive effect.

Finally, we considered the tax burden transfer, destination, efficiency, and other issues. We can learn from foreign environmental tax collection methods to optimize. For example, the United States follows emission trading, supplemented by environmental taxes; Russia uses the form of ecological fund to

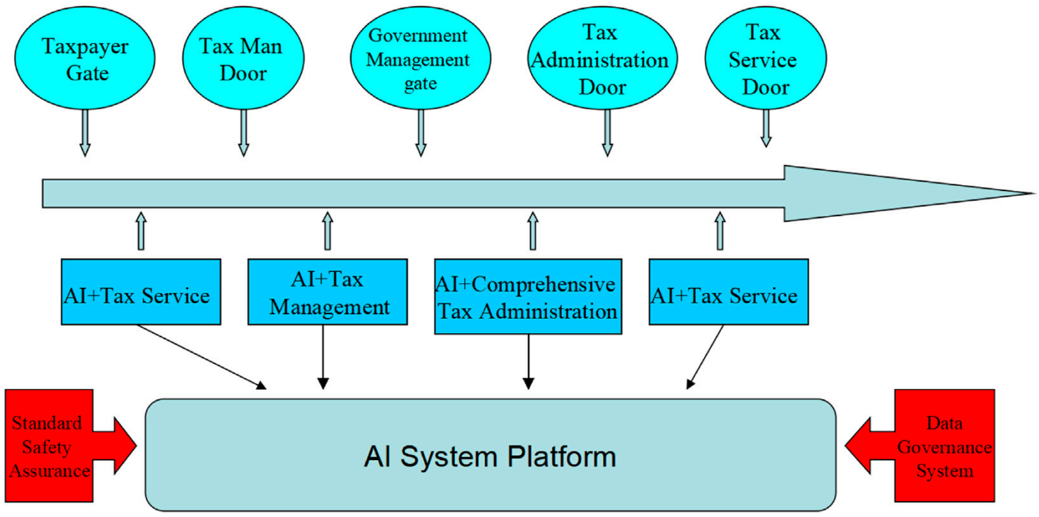

FIGURE 3
Environmental protection tax information construction objectives.

collect pollutant tax; Germany has a relatively perfect eco-tax system; and British tax department and environmental protection department division of labor and cooperation.

4.3 Artificial intelligence and tax collection and administration of environmental protection tax

This study suggests artificial intelligence (IA) for the analysis, the IA is a significant tool that evaluates the complex problem and provide optimal solution. Following are the main reasons for using IA essential for this study; first, artificial intelligence will refine environmental tax data. Information is the starting point of tax source management. Artificial intelligence can help tax collection departments collect, screen, analyze, and transfer data related to taxable pollutants from massive tax-related information. The “Golden Tax Phase iii” intelligent information system project has replaced experiential management decision by Big Data analysis decision. On this basis, the environmental protection tax can promote the tax department and the environmental department to integrate the information resources and technological advantages of the province and build the exchange and sharing system of pollutant discharge and treatment data. The basic contents of the system shall include the data index specification, data exchange system, and data sharing system for the discharge of taxable pollutants and environmental treatment. Part of the index specification is mainly compiled in accordance with the work requirements of environmental quality of the national ecological environment force and the work management requirements of environmental protection tax collection by the State Administration of Taxation. The content should cover the specific accounting indicators and monitoring methods of taxable pollutants and provide reference value as data samples. The data exchange system is mainly used to realize data sharing, especially the particularity of environmental protection tax requires environmental departments and tax departments to cooperate in collecting, to ensure the accuracy and timeliness of data.

The data sharing system can improve the efficiency of environmental protection tax collection.

Second, artificial intelligence reduces the asymmetry of tax-related information. The environmental protection tax involves complex tax objects and requires strong professional requirements for the detection, measurement, and accounting of taxable pollutants, which requires the cooperation of ecological environment authorities. The cooperation efficiency of departments is affected by the allocation of rights and responsibilities and information communication. The data exchange and sharing system of pollutant discharge and treatment can realize timely communication of data flow among departments. Specifically, cloud video and voice can be used to accurately deploy taxable pollutant discharge and treatment work, and artificial intelligence can be used in the form of application software. In addition, it is necessary to clarify the rights and obligations of tax authorities and ecological and environmental authorities. Environmental monitoring, data collection, data review, and other work also need a lot of resource consumption. The corresponding tax can be allocated based on the role and effect of the ecological environment department in the tax collection process.

Third, artificial intelligence can improve the efficiency of environmental protection tax collection and management. At present, tax administration adopts the online and offline mode mixed management, but in practice, the efficiency of tax collection and management is low due to the impact of tax collection cost and tax efficiency of tax authorities. In particular, due to the limitation of various factors, the accuracy of detection and calculation of taxable pollutant data of environmental protection tax is low, and the efficiency of tax collection and management is not ideal. The artificial intelligence information platform by using intelligent perception, intelligent processing, and intelligent feedback based on three key links integrates and feedbacks fragmented tax-related information to improve the accuracy of taxable pollutant data

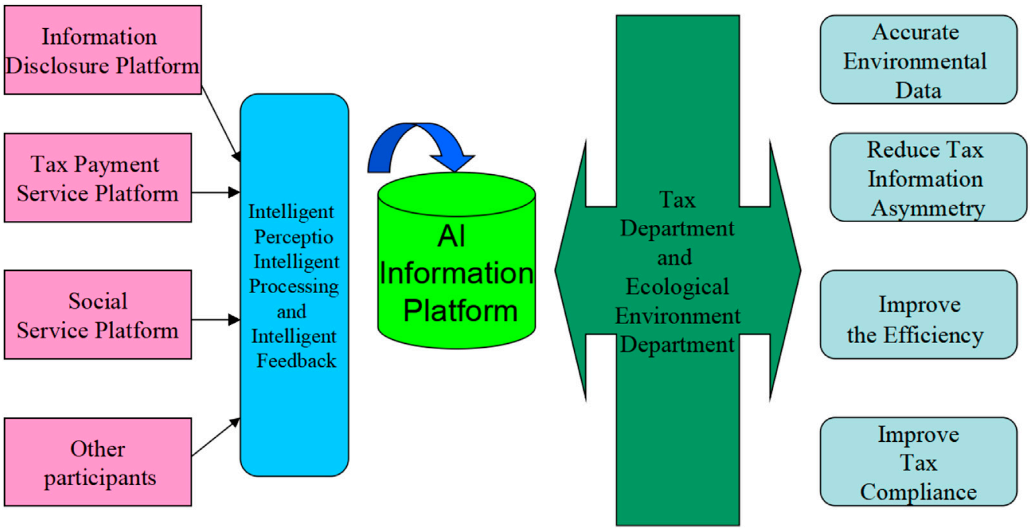

FIGURE 4
AI and environmental protection tax governance.

monitoring. Using the database of multiple data types, we identified the false information of taxable objects, obtained the new trends of the discharge and treatment of taxable pollutants in a timely manner, and comprehensively supervised the collection efficiency and tax effect of the environmental protection tax. Also, artificial intelligence could improve tax compliance. The construction of the tax-related information sharing platform of the environmental protection tax can accurately manage the risk of tax-related behaviors and reduce tax evasion and tax avoidance behaviors of taxpayers when the risk cost of tax evasion increases. Artificial intelligence simplifies the tax declaration process of environmental protection tax, reduces the cost of tax declaration, and enhances the willingness of taxpayers to pay. Artificial intelligence can actively publicize and popularize the knowledge of taxation and ecological environment, improve citizens' awareness of taxation and environmental protection, and improve their willingness to comply with tax payment. In addition, various forms of the government transfer payment can be adopted. For example, the tax rebate and other special expenses will be used to encourage taxable enterprises to install automatic online monitoring equipment to provide accurate environmental protection tax data.

The concrete framework structure is shown in Figure 4.

4.4 Artificial intelligence and tax payment service of environmental protection tax

Tax payment services should be designed according to the characteristics of the environmental protection tax. Figure 5 shows the design process.

First, artificial intelligence can improve the efficiency of tax services. In the tax payment service, some cadres could not meet the demand of tax payment due to lack of patience and objective data integration ability. Blockchain technology can connect the collection platform of the Department of Affairs with the financial management platform of taxpayers and the service platform of social service organizations into a comprehensive service platform integrating information collection, analysis, feedback, and decision-making. Taxpayers can access round-the-clock all-inclusive environmental protection tax services powered by artificial intelligence technology. It can not only avoid the emotional tax service providers but also obtain reliable information services, reduce the difficulty of tax declaration, and improve the efficiency of tax management.

Second, artificial intelligence can reduce the negative impact of asymmetric tax information. The speed of data flow is critical in the information age. The cloud video platform can be built with the help of artificial intelligence technology to realize the link between government agencies at all levels in the province and combine pollutant discharge and ecological governance system with the video system. It can connect with the national ecological and environmental departments upward and can connect with the provincial municipal, county, and township ecological and environmental management departments or institutions downward to realize the visual communication of ecological and environmental governance instructions and tax policy information, as shown in Figure 6. Users of environmental protection tax information can use mobile phone clients, PC clients, and multimedia terminals to connect to the cloud video platform to achieve smooth information communication. In addition, the robot, small assistant, personal butler, and other roles are set to help users answer questions, understand customer information needs, early warning of tax risks, and grasp the real-time dynamic information of environmental protection tax. It can not only meet the tax payment needs of users but also improve the government's supervision of users and ultimately reduce the information asymmetry between taxpayers and tax authorities.

Finally, artificial intelligence can improve the accuracy of tax services. The powerful information processing capacity and machine algorithm analysis of artificial intelligence can quickly analyze and integrate massive tax-related information, match the requirements of tax-related information users more accurately, and provide intelligent tax consultation and tax-related services. Users can

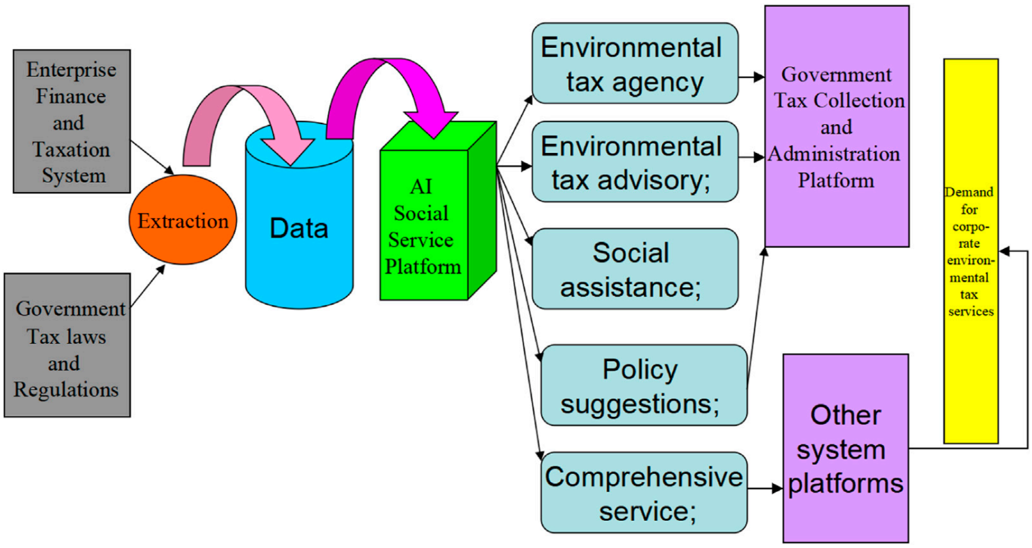

FIGURE 5
AI and environmental protection tax payment services.

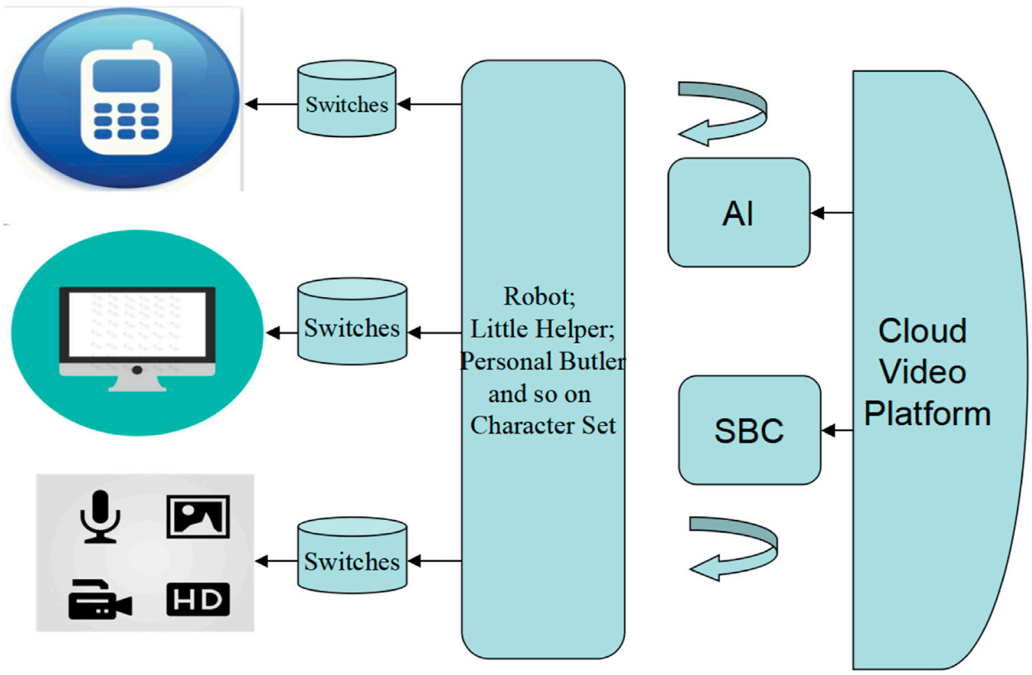

FIGURE 6
Cloud video platform.

obtain information by means of multiple terminals, realize information service acquisition anytime and anywhere by means of a portable mobile service platform, and track the whole process of service process, which can improve service efficiency and supervision efficiency. Blockchain technology can help solve the problem of the invisibility and uncertainty of environmental tax data. The various service ends connected by the Internet provide various communication channels for pollutant discharge and environmental governance information, which not only improves tax payment services but also better publicizes and popularizes tax information, contributing to the improvement of tax awareness of the whole people.

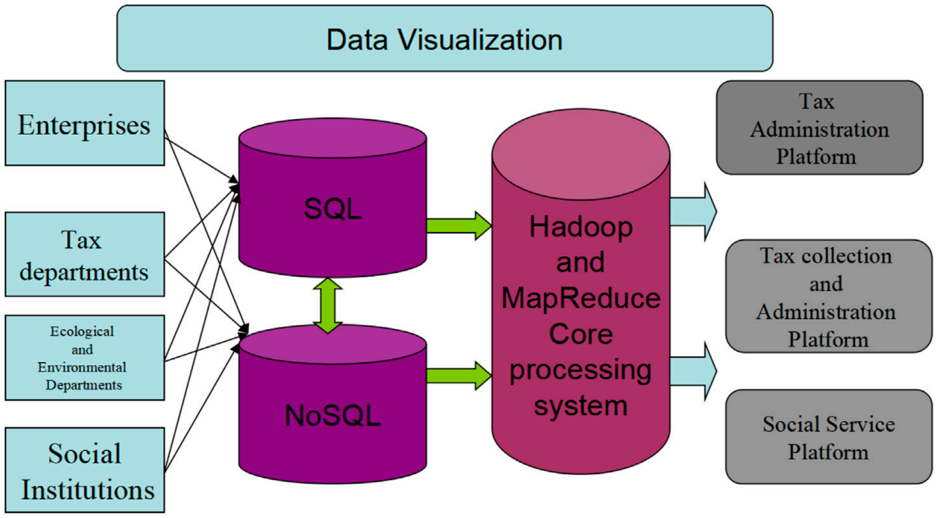

FIGURE 7
Environmental protection tax governance data system.

5 Artificial intelligence and tax governance of environmental protection tax

First, artificial intelligence can improve the level of tax governance. Information is the basis of the tax administration process, and the application logic of information determines the efficiency of tax administration. The application of artificial intelligence technology in tax collection and management is an inevitable requirement to improve the level of tax administration. The purpose of environmental protection tax is to reduce the discharge of taxable pollutants and improve the ability of ecological environmental governance. The main reasons why the current environmental protection tax has no obvious effect on environmental governance are unreasonable collection standards, narrow collection scope, and ineffective tax collection and management. According to the aforementioned analysis, artificial intelligence can solve these problems. In addition, artificial intelligence uses computer processing technology to evaluate and monitor the efficiency of regional environmental protection taxes and the progress of the treatment of taxable pollutants.

Second, artificial intelligence can strengthen tax risk control. Artificial intelligence can use Hadoop and MapReduce to construct a computing and processing ecosystem for Big Data ecological pollution control. With HDFS and Hbase as the data core systems, artificial intelligence uses SQL and NoSQL to store data, meeting the requirements for structured data processing and processing diversified data formats such as files, images, and logs (as shown in Figure 7). Information security has become a problem that artificial intelligence must pay attention. Tax departments can develop a special information security management platform and risk management platform by relying on their own technical forces. The former monitors and prevents security threats brought by AI applications, while the latter tracks hotspots and trends in the field of tax risks in time. They can perceive significant risks in tax risk management and implement tax risk response. Third, artificial intelligence can improve the supervision efficiency of environmental protection tax. We used Big Data information technology, GIS technology, and new media information technology for construction of the tax-related information dynamic tracking system. The accuracy of taxable pollutant data monitoring should be improved by screening massive amounts of taxable pollutant information, environmental governance information, and tax-related information of industries and enterprises. At the same time, dynamic monitoring of tax-related activities, tax-related activities, tax-related industries, and enterprises will be implemented. Multi-directional and multi-level monitoring can identify the new trends in the discharge and treatment of taxable pollutants and comprehensively improve the efficiency and treatment effect of environmental protection tax.

Considering the professional requirements of environmental protection tax testing, measurement, accounting, and monitoring and the level of economic and social development, we can vigorously promote the neutral testing business of third-party professional institutions. It can not only reduce the cost of small- and medium-sized enterprises to purchase testing equipment but also guarantee the fairness, justice, and openness of tax information with the independence of the third party and improve the quality and efficiency of tax collection and administration. Tax authorities may strengthen supervision over third-party testing institutions in terms of technical guidance, qualification assessment, archives management, and industry self-discipline. Third-party professional monitoring organizations can use artificial intelligence to realize policy guidance, information exchange, dynamic monitoring, etc., to ensure the authenticity and reliability of tax-related information.

6 Conclusion and prospects

This paper analyzes the application of artificial intelligence in environmental protection tax from four perspectives: tax system improvement, tax collection and management, tax payment service, and tax administration. The conclusion is that artificial intelligence can improve the improvement and construction of the environmental protection tax system, improve the efficiency and effect of environmental bonded tax collection, and promote the realization of the fundamental purpose of environmental protection tax. It can promote the realization of the fundamental purpose of the environmental protection tax, which is an important component of the construction of the environmental protection tax and the construction of the future tax system. The application of artificial intelligence technology in environmental protection tax collection, service, and governance needs to pay attention to its challenge to the current tax system. First, artificial intelligence has higher requirements for the intelligent tax system, including information architecture design, information management, hardware and software resource allocation, and professional and technical personnel. Second, relevant tax legal system norms have not been established, so relevant applicable norms should be added to the Tax Collection and Administration Law. Third, the tax authorities should strengthen the cooperation with tax-related service organizations, construct the information sharing center of the tax industry, and better realize the service and collection of the environmental protection tax. Fourth, to promote a green environment, government should also give corporate tax reductions to those industries which adopt renewable energy in the production process. Fifth, the government may provide easy access to the credit to the firms who have good tax record, which motivates the producers to participate in the tax collection activity. Sixth, from the tax revenue, the government may compensate those industries which are affected from the environmental degradation, such as agriculture and fisheries. In addition, government should raise the public's awareness of environmental protection, actively promote policy publicity through Internet platforms, set up special lines for environmental tax business, and answer questions related to the environmental tax in a timely manner. This paper has some limitations; first, this study covers only environmental tax using artificial intelligence, which can be further expanded by adding other methods. Second, this paper is only related to one country, which can be applied to many countries' cases. Third, the study did not add the institutional aspects to the tax system; and institutional aspects can be added in future research in the tax system Deborah Knirsch (2007), Liu and Shao, 2021, Zijie, 2020.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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What influences the climate entrepreneurship? Chinese-based evidence

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Climate change is the biggest threat to the public as it threatens water scarcity, heat waves, economic losses, and food insecurity. Consequently, the control of climate entrepreneurship is very significant to ensure business sustainability. However, the identification of controlling measures for climate entrepreneurship remained unexplored. Therefore, the purpose of this study was to examine the influence of organizational performance, carbon management practices, and attitudes toward emission trading schemes on climate entrepreneurship. The study is based on 180 respondents from large Chinese firms. Using structural equation modeling, the results report a significantly negative influence of organizational performance, carbon management practices, and attitudes toward emission trading schemes on climate entrepreneurship. This suggests to the management and policymakers that an increase in organizational performance, carbon management practices, and attitude toward emission trading schemes brings a significant decline in climate entrepreneurship and, thus, ensures a sustained business environment. One of the few studies examines variations in company responses to climate change from an entrepreneurial viewpoint. In order to advance the body of knowledge on the strategic management of climate change challenges, the study offers a theoretical foundation. Chinese policymakers are very keen to adopt an emission trading scheme and by the implication of articulate results can help them to attain their climatic goals.

KEYWORDS

Chinese firms, organizational performance, carbon management practices, attitude toward emission trading schemes, climate entrepreneurship

Introduction

Universal contribution to extinction begins when natural resources are being used abusively; this creates an imbalance in nature. Throughout the world's main integrated energy management, climate change alleviation and adaptation processes manage and reduce energy consumption. There is a need to manage climate change risks and develop carbon strategies and renewable energy projects. Innovative solutions are developed to support long-term stability, local sustainability, and sustainable economic growth.

In previous studies, focus on carbon management practice and climate change is based on opportunities and challenges (Arakawa et al., 2001). Many of the researchers address governance, policies, and accountability issues with carbon management practices and climate change effects (Marland et al., 2003; Bache et al., 2015). Concerning the research gap, this study will make important contributions. First, this study contributes to exploring how carbon management practices (CMPs) make differences in business activities, which play an important and equal role in sensing and interpreting climate change issues and integrating these issues into the managerial decision-making process. Second, this paper will examine the firm's attitude and CMP toward CE right after China launched its ETS. Third, this study will analyze the relation of performance, that is, operational and market performances, with CE in the context of the People's Republic of China. This study features the significance of climate change, and it additionally states to the organizations that their exhibition can influence the climatic issues.

The business environment is getting tougher and competitive through this climate changing issue. Climate change is one of the most emerging issues business community faces around the globe (Lash and Wellington, 2007; Howard-Grenville et al., 2014; Howard-Grenville et al., 2014). The Paris Agreement, adopted on 13 December 2015, after 14 days of rigorous negotiations at the Paris Climate Change Conference, created a global approach for tackling climate change by 2020 and beyond. On 22 April 2016, a high-level signing ceremony was held at the United Nations Headquarters in New York. On that occasion, the leaders of 175 countries signed an agreement to control climate change and sustainable development (NATION, 2016; Kong et al., 2021). China is the world's largest contributing country with 10.06 billion metric tons of greenhouse gas emissions, with a trend that has progressively risen over the years. Notably, the biggest culprit of greenhouse gas emissions for China is electricity and burning coal (Farooq et al., 2019).

The People's Republic of China has actively participated in the global carbon market since 2005 through the clean development mechanism (CDM) under the United Nations Framework Convention on Climate Change (UNFCCC) (Shin, 2010). The CDM was the world's first global carbon market, allowing developing countries who had ratified the Kyoto Protocol[1] to develop and transfer emission reductions from low-carbon projects to industrialized countries for compliance with their targets under the Kyoto Protocol. Consequently, China now has 10 years of emission trading experience through the CDM and through piloting seven carbon markets. China has slowly transitioned from being a seller of emission reduction units into the UN carbon market to establishing seven pilot carbon markets in 2011 and is now preparing for a nationwide emission trading scheme (ETS) (Zhang et al., 2014). Its experience with the CDM and subnational pilot carbon markets has given China confidence in setting a pledge of reducing carbon intensity by 60–65 percent by 2030 as its contribution to the new climate agreement (Zhang, 2021). China is committed to accelerating emissions by 2030 and net-zero emissions by 2060. By 2030, China aims to reduce its carbon emissions per unit of GDP by less than 65% from 2005 levels and increase the share of non-fossil energy in basic energy use by around 25%, like wind and solar energies to create total energy potential, more than 1200 GW of power (Fang et al., 2021). The main objectives for this study are to explore opportunities for businesses from climate sensing and to explore the difference from integrating climate change issues into the strategic decision-making process. Next is to build an understanding of the firms to adopt climatic managerial practices and ensure them to implement on different levels. The third one is to inquire the effects of organizational performance including the factors of operation, market, and environment on corporate social responsibility (CSR).

The Chinese Ministry of Ecology and Environment (MEE), after so many years of homework, announced the first round of compliance for the national ETS scheme on 5 January 2021. The Chinese energy sector now requires 2,225 companies to measure their emissions and issue emission permits for every ton of greenhouse gas they emit (Gu et al., 2022). The Chinese ETS is about 3.5 gigatonnes of greenhouse gas (GHG) per year, which places China as larger than European the ETS. In the beginning, the Chinese government will give licenses on a standard basis and will not charge any cost (Gao and Song, 2021). Some of the organizations need to purchase licenses, especially those having insufficient licenses, and these kinds of dealings or relations will work together in producing carbon emissions in China. This scheme will work for China, and this scheme is also very active in the Chinese climate policy; it puts great efforts in overcoming climate changes across the world.

As one of the key steps toward achieving the national goal, China is going to launch ETS in 2021, the first nationwide "cap and trade" scheme to operate in Asia and Europe. Experts from the China Council for International Cooperation on Environment and Development (CCICED) have confirmed that China's ETS will gradually cover eight sectors: petrochemical, chemical, building materials, steel, non-ferrous metals, paper, and domestic aviation sectors (Cui et al., 2020). Transportation, housing, agriculture, forestry and agriculture, construction, and other public sectors were excluded from the Chinese ETS as the number of entities in these sectors was so high that they were not effectively monitored and since they are a small part of the emission (Zhang and Zhang, 2020).

1 The Kyoto Protocol operationalizes the United Nations Framework Convention on Climate Change by committing industrialized countries and economies in transition to limit and reduce greenhouse gas (GHG) emissions in accordance with the agreed individual targets.

Firms have reacted differently in tackling climate change (Bibi et al., 2020). Although some companies, such as ExxonMobil, one of the largest emitters in the United States, vehemently opposed unfavorable climate regulations, others, such as Passive Gas and Electric, Ford Motors, and DuPont, adopted an active position by lobbying for tougher climate change policies in the United States (Jones and Levy, 2007; Asensio et al., 2016). Previous research has sought to better understand how firms differ in describing different responses to climate change (Reid and Toffel, 2009; Slawinski and Bansal, 2012; Lynch-Wood et al., 2014; Lee and Kim, 2015). Therefore, the literature is limited in the form of organizational responses to climate change from the managerial point of view. Environmental strategies could be different for corporates even though companies are in the same context of competitiveness (Bansal and Roth, 2000; Sharma and Vredenburg, 1998). Environmental risks and opportunities, organizational capabilities, and management's perceptions of the slow availability of resources within an organization can influence environmental management decision-making, which determines the extent and level of corporate response to climate change (López-Gamero et al., 2011; Wang et al., 2019; Yuan et al., 2022).

Few studies are conducted on the basis of managerial perspective on climate change, but when the corporate environmental strategies came, it perceived differently although in the same context (Delmas et al., 2016). Both these managerial and corporate environmental strategies are inter-connected but the management perception about environmental strategies may affect the decision-making of organizations that actually determines the range and the level of response for corporates about climate change (Bobby Banerjee, 2001; Lee and Ahn, 2019). However, the research questions, which are going to be addressed in this study, are about realizing the potential effects of climate change on their business, finding business opportunities from climate change, and integrating climate change issues into the strategic decision-making process, and how the difference is not explored. Second, there is a limited understanding of the firms' active stance on climate change, which is considered in this study as CE activity, such as whole industrial climate change management practices are adopted and implemented on different levels. Third, very limited studies have observed the effects of a firm's actual performance, including operational, market, and environmental performances, on CE as a corporate response to climate change.

Literature review

China is making great strides in tackling climate change. In this section, Chinese policies and practicalities have been discussed. In 2017, China started working on the launch of the ETS and made some regulations for the polluters who were charged to pay for harming the climate. On the other hand, some opportunities and incentives were created for those who try to reduce their carbon emissions. In 2019, China started the transition from coal to renewable energy and installed more solar panels and wind power generators, which takes China to a leading manufacturer of these technologies (Zhu et al., 2019). China decided in 2020 and started to reduce and stick to CO_2 emissions properly by implementing the ETS (Swartz, 2016). Policymakers decided to reduce this in a cost-effective manner. They decided that initially gas and coal-based power plants were included. It will allocate a plant-based production allowance (also known as a permit), with a different standard for each fuel and technology. China's ETS is poised to expand to seven other sectors, covering one-seventh of global CO_2 emissions from fossil fuel combustion, the world's largest CO_2 emissions (Zhongming and Wei, 2020). The early years of operation will be crucial for testing the ETS design and building trust. Given the dominance of coal power in China's power sector and its overall CO_2 emissions and how the country's fleet of coal-fired power plants is handled, China's climate targets for sustainable energy goals must be met (Agency, 2020).

A natural resource-based view (NRBV) builds the logic that relates to natural resources of the firms that they used for their own viability. Environmental sustainability will become a crucial component of strategic management as firms become more aware of the limitations imposed by the natural environment. This will help them in maintaining their resource-based competitive advantage.

The impact of the ETS on coal-fired power operations is worth assessing as the ETS will work closely with other policies, such as energy conservation standards, air pollution standards, electricity market reforms, and capacity appointment plans. The report weighs on the implications of the benchmark options proposed under the ETS for China's coal-fired power sector. It assesses how different options will affect the allocation of allowances to different types of plants and will consider the key factors that will determine which breeding units are in deficit or more than allowances. The report also looks at how these effects will be distributed to provinces and companies. The report explains how the ETS design can play a more central role in advancing China's energy transition (Agency, 2020).

Developments in China's energy system make great changes, and 2020 is proving a pivotal year as far as developments are concerned in the energy sectors. The important task of setting goals and priorities for the 14th Five-Year Plan (2021–25) was difficult, without thousands of implications of COVID-19 (Heggelund and Economics, 2021; Province, 2021). However, the acceptance of the widespread use of market mechanisms has become another important moment for Chinese policymakers. The introduction of a regulating and effective nationwide emission trading scheme (ETS) could be a key factor in China's recovery from the economic effects of the coronavirus while at the same time accelerating a clean energy revolution. Climate change is the whole world's concern, and the world is mutually reliant and interrelated. If the Chinese ETS gets the success, it would create a positive impact on the rest of the world.

Coal-fired power plants emit about half the CO_2 emissions from fossil fuels in China. Reducing emissions from coal-fired power plants will be necessary to achieve China's low-carbon goals, and these plants will be key sources of ETS coverage (Xu et al., 2021). About 50% of Chinese CO_2 emissions come from the industrial sector, 40% from the power sector, and 8% from the transportation sector (Zhou et al., 2013; Suberu et al., 2014; Hao et al., 2015). Emission related to this division is much different from other countries, especially in most developed countries, like the United States have 22% of heat-trapping gas emitted from the industrial sector, 28% from the electricity sector, and 29% from the transportation sector (Harris, 1999; Zhou et al., 2013; Suberu et al., 2014; Bourne et al., 2018; Godil et al., 2021).

A previous study explored with the sample of four oil companies in Europe and the United States explored the strategic response, that is, avoidant, resistant, complaint, and proactive to climate change (Levy and Kolk, 2002). The significant relationship between the corporate carbon strategy and firm performance shows in cluster analysis with the sample of 241 Korean firms. This study focuses on six types of corporate carbon strategies: "wait-and-see observer," "cautious reducer," "product enhancer," "all-round enhancer," "emergent explorer," and "all-round explorer" (Lee, 2012). In the other study, the carbon strategy of the firms is being defined through all-rounder, compensator, substituting compensator, reducer, substituting reducer, and preserver with the cluster analysis of 91 worldwide firms from the electricity industry (Weinhofer and Hoffmann, 2010).

In collaboration with the IEA[2], the clean energy transition program examines the potential implications of the proposed ETS design for China's coal-fired power fleet. It is part of an ongoing project examining how the national ETS can contribute to China's clean energy transition. In the IEA clean energy transition program, the ETS will then be analyzed in-depth, including the impact on gas-fired power plants and the entire power sector by 2035. The ETS with other directly affected existing policies all together work for coal-fired power plants in China. The reports begin with an explanation of the institutions and policies governing coal-fired power plants and an analysis of the development trends for coal-fired power plants. It then evaluates the impact of the ETS design on coal-fired plants using subtechnology at the national, provincial, and company levels and identifies key findings and recommendations.

2 The International Energy Agency works with countries around the world to shape energy policies for a secure and sustainable future.

Climate entrepreneurship

Firms, subjected to the same set of external environmental pressures, may adopt different practices and policies (Delmas et al., 2016). The management insights of external stakeholders and their demands on environmental issues have served as a key element of the subsequent action (Sharma, 2000). Taking a proactive approach to climate change is a starting point for examining how the external competitive environment is translated into the corporate action (Lee and Ahn, 2019).

This research identifies "entrepreneurship" to visualize management's views on environmental risks, opportunities, and organizational capabilities related to climate change, which are believed to play a role in management decision-making and also determine the extent and degree of consequences related to carbon strategies of corporates. Entrepreneurship generally combines limited resources to secure value and return in new and innovative ways to solve problems under business resource constraints and the decision-making ability. By researcher's consent with the combination of entrepreneurship, organizational capabilities, and proactive environment, the "Climate Entrepreneurship" concept is characterized with the consistency of three elements, sensing, seeking, and integrating climate change issues (Lee and Ahn, 2019).

First, climate change "Sensing" is an aspect of recognizing the potential effects of climate change in a business. Sensing provides the basis for a deeper understanding of climate change issues and then responding to them. There is no need to plan carefully, considering different alternatives (Lehtonen et al., 2019).

Managers or respondents have now put some effort and tried to involve in relative processing to get information, and they try to learn the procedure to gather the climate change information. Sensing means relying on intuition, which is specifically important in the context of increasing climate change issues as it enables the firm to coordinate a wide range of stimuli in the category of usable information (Yang et al., 2013). Second, "seeking" climate change is a trend of looking for business opportunities potentially facing the challenges of climate change (Gössling et al., 2018; Lee and Ahn, 2019). The executives have their eyes on opportunities and sensing strong business values related to climate change, and they get updated with proper information and summarized results of climate change to decide in favor of the organization. They develop new products, services, and businesses using a creative approach to address climate change challenges (Koelbl et al., 2015). When it comes to business performance, the focus should be on management considerations rather than the costs or risks of actively responding to climate change. Firms may differ in implementing CMP because of how managers evaluate the consequences of their reactions to climate change.

Managers who focus on the bright side of the response to climate change (i.e., better than positive expectations) take a proactive approach to climate change issues. Third, "integration" is an aspect of organizational capacity that incorporates climate change into the strategic planning process (Cobb et al., 2012; Lee and Ahn, 2019). It is a way of giving high priority to climate change, which supports organizational measures for climate change. "Integration" can provide an opportunity to develop valuable, exceptional, and easily replicable capabilities, resulting in new competitive advantages (Barney, 1991).

Research framework

Organizational performance and climate entrepreneurship

Academia provides generous evidence to expand the relationship between the performance of the organization and CE. First, a proactive and careful environmental management can reduce manufacturing costs, reduce environmental responsibilities, and increase productivity. Second, firms can increase the revenue by accessing new markets created by climate change and enhance the environmental reputation of existing markets with the help of green products (Pinkse and Kolk, 2010; Lee, 2012). Third, organizational operational performance can lead organizations to industrial competitiveness regarding CE (Bayarçelik and Özşahin, 2014). The delivery of the targets by the manufacturers and working efficiently make the organization more competitive in the market, and all these proactive tasks and operations make the organization more vigilant for climate change and enable it to make a significant impact on the CE. In the electric vehicle e-market, Tesla, Honda, and Toyota are perfect examples of their hybrid vehicles with huge market share and advantage, experimental economies, status, and profit maximization. CE can facilitate professional technical organizational learning and innovation (Lee and Klassen, 2016), which is called "innovation equalizers" (Porter, 1995).

It emphasizes using creative approaches, regardless of whether they have sufficient resources in search of opportunities for environmental and social challenges. It also tells how to improve an organization's environmental performance by observing environmental issues locally, nationally, and internationally, also by raising environmental awareness within an organization, supporting good environmental practices and promoting environmental initiatives. Enthusiasm can be thought of as effort and activity. It can persuade and enable an organization to transform environmental concerns into effective innovative programs to make an organization successful (Silvestre and Ţîrcă, 2019), providing this model with a theoretical background for dimension thrilling and integration. From this perspective, the corporate carbon strategy differs regarding its dynamic perceptions of climate change and its ability to integrate climate change issues into the managerial and strategic decision-making process. This framework differentiates between moderately shallow and more reflective approaches for each of the CE dimensions. As a result, a combination of different levels of a firm's climate of entrepreneurship indicates its particular strategy. To manage uncertain environmental issues, such as climate change, managers can seek protective measures rather than simply responding to previous events (Aragón-Correa and Sharma, 2003; Barnett, 2001). Evolution may also help shape the nature of imminent conversations with stakeholders and competitors. Management's entrepreneurial risk-taking on the climate change issues that see climate change at the center of competition would favor a "proactive" approach (Wallace, 2009).

Technical knowledge, technical methods, capabilities, and high-level expertise are required to produce low or carbon-free products. Even the processes also require these capabilities. These practices make the organizations result-oriented with high-tech innovations since these practices can promote a learning culture in the organizations. The main purpose of this article is to test hypotheses about the relationship between organizational performance (OP) and climate entrepreneurship. This study will also observe the differences in operational, market, and emission reduction environmental performances between the different dimensions of CE. This reasoning presents the following hypothesis.

H1: Climate entrepreneurship productivity related to operational, market, and emission reduction performance.

Carbon management practices and climate entrepreneurship

Proceedings have mentioned the consistent evidence of the relationship between management's pending views on environmental issues and the adoption of new methods. An active response to an emerging environmental problem may require the investment of substantive firm-level resources, which has only been performed with the consent of top management (Child and Tsai, 2005). Environmental support behaviors of individuals in environmental support positions influence others at the top level for environmental advocacy initiatives (Chen et al., 2013).

Entrepreneurship has an exclusive element to take the risk, although a long-running argument that the risk susceptibility of entrepreneurship is greater than that of organizational managers is widely supported (Vereshchagina and Hopenhayn, 2009). In production operations, CMPs emphasize waste reductions, efficient and effective input use, and control of internal processes. Progress is seen in quality, on-time delivery, cost efficiency, and quick response to customer's demand (Lee and Kim, 2015).

In many countries, regulations have been adopted unexpectedly, amid the tight public policy in favor of low-carbon emissions and limited or no regulation. For example, many firms have lobbied vigorously to delay or avoid legislation on climate change, stressing their ability to predict the costs and competitive effects of such measures (Delmas et al., 2016; Zhang et al., 2019). Therefore, the authors presume that several managers may resist or hesitate to take precautionary measures in response to climate change and that they may implement small token adjustments if they have to take such steps. However, others who threaten CE may have a different stance and may actively encourage their organizations and policymakers to respond creatively and proactively to the challenges of climate change. This reasoning leads to the following hypothesis.

H2: Adoption and implementation of carbon management practices are significantly related to climate entrepreneurship.

Attitude toward climate change regulation and climate entrepreneurship

The stimulus argument literature suggests that psychologically defensive reactions, such as denial of risk, vary according to previous attitudes. The socio-psychological research shows that predictors affect the information on ETS regulation processes and observe polarized responses. Traditional beliefs/global ideologues (Republicans/hierarchical individualists) are more likely to accept the reality of CE after reading about the technical response, and if there would be a discussion on ETS regulatory sanctions on these solutions, it will be rejected straightly. Therefore, lower level attitudes toward climate change regulations, that is, conservative and liberal thoughts, might be risk-takers toward CE, and they are keeners to adopt regulations to protect climate rather than mitigation (Tang and Tang, 2012). Both thoughts embrace new regulations, and they are involved in minimizing emissions reduction.

Researchers need to study how firms' attitudes toward ETS regulations toward climate change are affected by adoption and mitigation while exploring the actions of responsibilities that may affect climate change productivity and CE. To date, no studies have been explored yet with this aspect in China, that is, the attitude of ETS regulations toward CE. This study will examine whether exposure to ETS regulations of China adaptation may affect the relation of attitude toward CE.

H3: Attitude toward climate change is substantively related to climate entrepreneurship.

Materials and methods

Research framework

Based on the literature and hypothesis development, the framework for this study is given as follows Figure 1:

Sample and data collection

Previously, it has been generally considered that firms are not responsible regarding their operations related to climate change. For the collection of data, a random data sampling technique is used and targeted the chemical sector, building material sector, and energy sector of China, and focused on Jiangsu province, Suzhou, Wuxi,

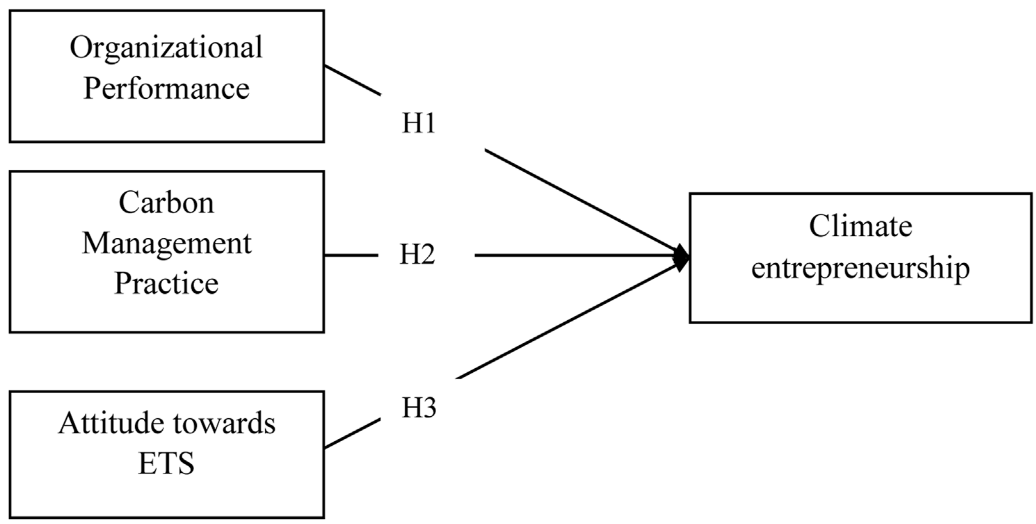

FIGURE 1
Theoretical research framework.

and Nanjing, having their industrial zones. Several reasons why this study is based on these Chinese sectors are as follows: China is an emerging economy, so this study addressed these high-tech industries because they are facing some pressure to produce eco-friendly products and satisfy the explosive needs of the market (Begum et al., 2021). Based on Hussey and Eagan (2007), Stefanelli et al. (2014), and Cheng et al. (2019), the sample size was selected. The questionnaire was adapted from Lee and Ahn (2019) and distributed physically and through emails. This study followed the way of Awan et al. (2020) for the mailed questionnaire. Researchers made follow-up calls to the organizations that had not responded in the first month mail. After 1 month of calls and follow-up, practice gets more responses. To reduce the bias, scholars clearly state that their information will not be disclosed and all the given information would be used for research purposes. The sample for analysis was conducted among 650 key informants, although their convenience and confidentiality were assured. The questionnaires which were unfilled and unanswered were removed, and in total, the authors received 180 considerable questionnaires. From this original dataset, the authors limited the samples to companies that would be exposed to a benchmark emission policy for a specific reason. This study examines the productivity of CE, which depends on the performance and management of emission reduction. The acquired data are only from those companies which followed the benchmark policy on carbon emissions, and benchmarks are settled values of carbon emissions in tons. The authors obtained data from public sources on the actual emissions of GHG and carbon emissions, which are estimated as each output or input per unit of emission.

Measurements

Three dimensions of climate entrepreneurship

Sensing, seeking, and integrating are three dimensions used to identify CE. This concept is new, which was just introduced in Lee and Ahn (2019). CE "sensing" is defined as "a firm's ability to understand the impact of climate change on the current business and future business." In "seeking," CE focuses on opportunities and is fully aware of the challenges posed by climate change. Administrative decision-making is seen as focused, and strategic planning is concerned with the challenges of climate change, which relates to the third element of CE "integration."

Operational, market, and environmental performance

This study measures the organizational performance in three dimensions, that is, operational, market, and environmental performance.

This study considers three dimensions of performance based on operations, market, and environmental performances, and nine of the total items are used to measure these performances. Four items are based on operational performance, considering industrial competitive priorities that could serve as core performance targets for manufacturing, delivery, performance, efficiency, and flexibility (Ward et al., 1998). This study is used as a proxy for market performance enhancement, and sales and market share. In general, environmental performance is measured with greenhouse gas emission reduction and the efficiency of energy.

Carbon management practices

The study explores a variety of CMPs, including low-carbon product development (LPD), low-carbon process improvement (LPI), employee engagement (EE), external initiative participation (EIP), and supply chain cooperation (SCC). The study examined these methods using a seven-point Likert scale, in which the level of adoption and implementation of these methods can be redetermined. The authors used measuring instruments adapted from prior studies (Jeswani et al., 2008; Lee, 2012; Lee and Klassen, 2016).

Attitude toward the Chinese emissions trading scheme

This study also surveyed how Chinese companies view ETS regulations regarding the company's ability to implement the Chinese ETS in the items, deferring the Chinese ETS to the extent of the mesh, and preparing for this regulation of the Chinese ETS (Lee and Ahn, 2019). This construct has been measured with items based on a seven-point Likert scale.

Methodology

Smart PLS version 3.2.7 is a statistical tool used to analyze the structural model statistically. The structural equation modeling approach is used to examine the relationships between all the constructs (Awan et al., 2020). With the help of Smart PLS, this study is used to conduct structure equation modeling, and it allows the testing of theoretically supported linear and additive causal models; structural equation modeling (SEM), a second-generation multivariate data analysis technique, is frequently utilized in management research. PLS-SEM can handle both types of measurement models, that is, reflective and formative. The proposed model for the study includes these types as well. This study is cause-and-effect; therefore, PLS-SEM effectively estimates interactions between all constructs in the structural model. First, the measurement model is analyzed separately, and several tests are performed to analyze the reliability and validity of the data. The PLS measurement model results showed that the factor loadings of scale items were more than 0.60, and the average variance extracted (López-Gamero et al., 2011) was more than the recommended cut-off value, which supports convergent validity. The construct and discriminant validity of these data were assessed using the criteria described by Ringle et al. (2018). Scholars assessed the construction reliability using composite reliability (CR) and Cronbach's alpha (CA).

Results and discussion

Measurement model

Structural equation modeling (SEM) examines the relations among CE, attitudes toward the Chinese ETS, CMP, and OP. SEM models are effective when tests of reliability and validity of the data are consistent with the structure and up to the mark since all these tests are included in the measurement model. For evaluating the measurement model, some of the items are deleted based on the term factor, loading less than 0.40 Figure 2. The following measurements had adequate model fit data: chi-square (3,363.709), CFI (0.841), and RMSEA (0.071) (Durdyev et al., 2018). Reliability and construct validity have also been measured through Cronbach's alpha, which exposes the consistency of the whole scale and reliability of the questionnaire. This study shows that all the constructs had achieved thresholds and had values more than 0.70, which shows consistency and reliability of the questionnaire (see Table 1) (Bagozzi and Yi, 1988; Hair et al., 2014). Convergent validity has been measured by the extracted average variance (López-Gamero et al., 2011). The threshold for the convergent validity set by the academia is 0.50 (Chin, 1998), and this study showed that all the constructs had AVE values more than 0.50, and these values are mentioned in Table 1.

Discriminant validities of variables

The discriminant validity has been defined by Fornell and Larker. The standard is defined by using AVE, which should be higher than .50, and then, taking the square root of the AVE of all constructs shows a higher correlation among all constructs, as shown in Table 2 (Fornell and Larcker, 1981).

Structural measures

This study used the standard bootstrapping procedure with 500 bootstrap samples and 180 samples to determine the significance of the path coefficients (Henseler et al., 2009; Hair et al., 2014). The full results of the structural measures of this model are demonstrated in Table 3, where OP has a significant ($\beta = -.314$,

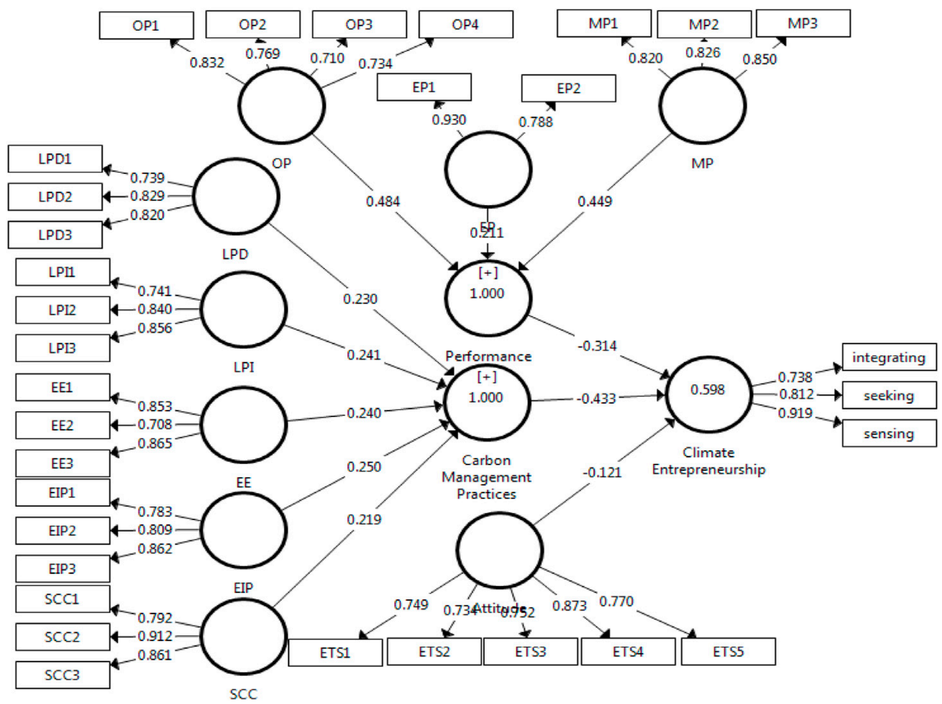

FIGURE 2
Factor loadings and structural factor influence.

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TABLE 1 Reliabilities and validities.

Construct	Outer loading	AVE	CR	CA
Climate entrepreneurship		0.682	0.865	0.762
Sensing	0.738			
Seeking	0.812			
Integrating	0.919			
Organizational performance		0.545	0.878	0.841
Operational performance				
OP01	0.832			
OP02	0.769			
OP03	0.710			
OP04	0.734			
Market performance				
MP01	0.743			
MP02	0.820			
MP03	0.768			
Environmental performance				
EP01	0.788			
EP02	0.930			
Carbon management practices		0.507	0.932	0.921
Low-carbon product development (LPD)				
LPD01	0.739			
LPD02	0.829			
LPD03	0.820			
Low-carbon process improvement (LPI)				
LPI01	0.739			
LPI02	0.829			
LPI03	0.820			
Employee engagement (EE)				
EE01	0.853			
EE02	0.708			
EE03	0.865			
External initiative participation (EIP)				
EIP01	0.783			
EIP02	0.809			
EIP03	0.862			
Supply chain co-operation (SCC)				
SCC01	0.792			
SCC02	0.912			
SCC03	0.861			
Attitude toward the Chinese ETS		0.604	0.884	0.835
ETS01	0.749			
ETS02	0.734			
ETS03	0.752			
ETS04	0.873			
ETS05	0.770			

t-value = 7.777, and *p*-value < .000) relationship with CE, as expected. This result shows that OP is negatively associated with CE, which indicates that when the firms performs well, they can manage the climatic changes more adequately, so it supports H1.

The CMP has a significant impact ($\beta = -.433$, t-value = 9.970, and *p*-value <.000) on CE, as expected. This also indicates that the CMP needs to be more effective to control the climate change effects, so this supports H2. The interaction between attitudes toward the

TABLE 2 Discriminant validities of variables.

	Climate entrepreneurship	Organizational performance	Carbon management practice	Attitude
Climate entrepreneurship	***.826***			
Organizational performance	−.684	***.674***		
Carbon management practices	−.727	.699	***.692***	
Attitude	−.567	.564	.623	***.777***

These are the validities which are highlighted for the constructs, normally highlighted just formatting

TABLE 3 Path coefficients.

Hypothesis relationship	Beta (*β*)	Standard deviation	T-statistics	*p*-values	2.5%	97.5%	Decision
Performance - > climate entrepreneurship	−.314	.009	7.777***	.000	−.386	−.228	Supported
Carbon management practices - > climate entrepreneurship	−.433	.043	9.970***	.000	−.530	−.356	Supported
Attitude - > climate entrepreneurship	−.121	.030	3.904***	.000	−.177	−.061	Supported

This is the level of significance.

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Chinese ETS and CE is negative and significant ($\beta = -.121$, t-value = 3.904, and p-value = .000). This result shows that attitude of organizations toward the ETS also controls the climatic changes as the more the attitude goes higher, the climatic effect will get more controlled, so this supports H3.

The structural equation model shows that R^2, which is known as the coefficient of determination, explains the overall explanatory power of the constructs in PLS-SEM. R2 is categorized in three forms, that is, significant, moderate, and weak, with the values of .60, .33, and .19, respectively. As shown in Figure 3, related to the t-values, R^2 is .597 for the latent constructs, that is, CE, OP, CMP, and attitude of Chinese firms. Therefore, it is explained that exogenous variables have a significant impact on the endogenous construct. This study explains that the OP, CMP, and attitude of Chinese firms toward the ETS together have 60% of the variance in CE.

Discussion

Climate entrepreneurship and performances

There are three OPs, that is, operational, market, and environmental performances are related to the CE in this study. The study reveals the linkages between OP and CE. By maintaining and considering the performances of the organization, it makes an impact on climate change issues. The organizational main stake is to satisfy their customers, and customer satisfaction and flexibility relate to climate considerations. Organizations that worked for social responsibility received more attention than the underperformers. Market performance is related to market share, profit, or revenue policies mostly related to increasing these dimensions. The selected groups of organizations reveal that statistical significance is much stronger. There is a significant relationship between the OP and CE. The positive or negative effects have been shown by firm performances on CE, which supports the assumed H1. This result is based on some previous studies that indicate the relationship between OP and CE (Barnett and Salomon, 2012; Trumpp and Guenther, 2017).

Climate entrepreneurship and carbon management practice implementation

The implementation of the CMP depends on CE, and Table 3 shows the results of H2, which describes the significant relation between these two constructs. In general, this organizational group adopts the carbon management practice with the inclusion of low-carbon product development, low-carbon process improvement, employee engagement, external initiative participation, and supply chain co-operation. The results show a negative but significant relationship between these constructs so that H2 is not properly adopted or implemented. It could be costly for the organizations to change technology and initiate innovative synergy between production and carbon emission (Nejati et al., 2017). These selected groups of organizations are well aware of the perceived impact of climate change on their businesses. They find and grab the opportunities from the scenario of climate change. Their financial investment plans are inclined toward improving the process and working efficiently for the production of low-carbon products. Explorer organizations keenly contribute to global initiatives like the carbon disclosure project. Organizations try to engage customers, suppliers, and societal factors to get involved in the reduction of carbon emissions (Ageron et al., 2012).

Companies consider the impact of climate change in their decision-making process and engage their employees to integrate carbon management issues daily that will help the workforce to increase awareness. It helps employees to be educated and trained. This will tend to lead to an improvement in carbon management practice. Some barriers exist previously, and firms faced structural, cultural, and regulatory barriers in the past, but for now, the government of China takes initiative to adopt CMPs to contribute to GHG emission reduction. China has recently managed carbon practice and established some strong measures to focus on some specific fields like the chemical industry, construction industry, and energy sector. According to the results of this study, the selected groups of organizations contribute a lot in achieving CE through carbon management practicing. The results support the declaration of the proposed hypothesis, indicating that CE is related to the exploration, adoption, and implementation of CMPs.

Climate entrepreneurship and attitude toward the emissions trade scheme regulation

SEM provides very reliable results with the responses to the attitude of ETS policies and their relation with CE. These newly implemented regulations on the ETS in China have a great impact on CE. Table 3 shows the relation between forward-looking attitudes to adopt policies and CE. It shows that laggard between these two will affect the climate, and if these regulations of the ETS in China are enforced strictly and make the organizations bound to adopt and implement newly launched ETS policies, this will be beneficial for China and the whole world (Jiang and Ye, 2020). These selected organizations oppose setting up ETS policies. They argue that ETS policies are not implemented properly across the world. If they go with these policies, it would undermine competition with the global market (Swartz, 2016). These selected groups of firms have some challenges in conforming

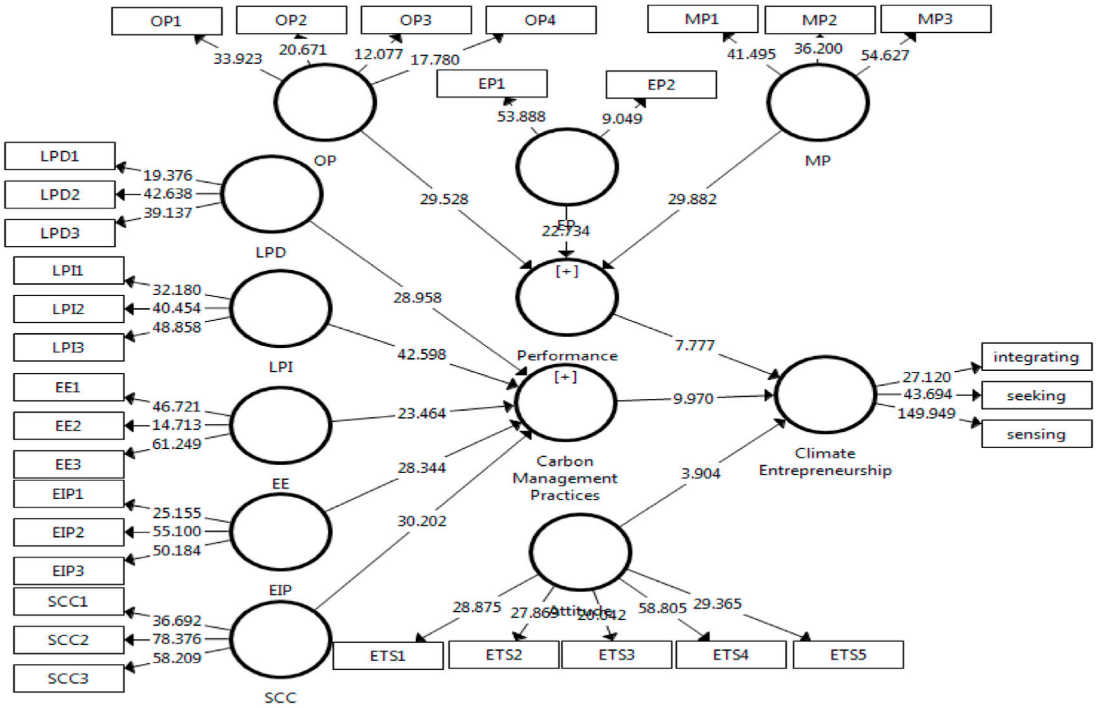

FIGURE 3
Model loadings with the t-values of variables.

to the new policies of the ETS. These results show partial support for H3, affirming that attitudes toward regulations of the ETS are related to CE.

Conclusion, suggestions, and limitations

By using the questionnaire survey of key informants of Chinese organizations, this study draws some interesting and realistic findings. The relation among OP, CMP, regulations, and CE is very strong and significant. These negative relationships show that organizations are not in favor of adopting modern technology, effective for carbon emissions, which is highly expensive and time-consuming, which will harm their profitability. The government needs to make strict policies for organizations and enforce policies that will effectively work for the society, country, and whole world. There is some delay in the Chinese ETS launch, which took more than 10 years to develop. China considers this policy as a tool to promote carbon emission reduction or decarbonization. This could be effective and helpful for the Chinese nation and the world. The Chinese ETS 2021 policy needs strong political support to achieve success, and this support could be driven from the cross-ministry collaboration it requires to make sure that the ETS will help China attain its climate goals.

Theoretical implications for this study, based on logical contributions, are now revealed. This is the first study that analyzes the climate entrepreneurship, that is, sensing, seeking and integrating of Chinese firms. In addition, the study also deployed the impact of three latent variables, that is, OP, CMP, and attitude on CE, in order to offer in-depth analysis. This study may provide the base for upcoming future studies on CE. The results of this current study support the natural resource-based view by the significant impact of latent variables on CE. This also suggested that working on all three latent variables may enable the Chinese firms to control the impact of climate change that affects the society, natural environment, and other stakeholders.

This study concludes by adopting a wide strategy from past exploration studies that selected organizations acquire technologies that better fit the organizational ability to improve CE. The CMP, OP, and attitude of organizations have different implications for emission extraction organizations. As the results show, investments on carbon management and firm's performances are keys to meeting the long-term needs of the society and the firms. The CMP, OP, and attitude of the firms will increase the managerial capability and utilize the resources to control climatic responses. This study proposed that emission-oriented activities are important for the growth and sustainability, and thus, it is an important thing to acquire these practices to achieve CE.

Limitation and future research

Limitations and some suggestions are stated as this study is based on a very specific area and is based on a newly developed concept. The results of this study point out policies related to carbon emissions and more information about OP and management practices that facilitate public awareness. This could help the public create pressure on organizations to decrease carbon emissions. This study is focused on four main factors of the climate change policy network, and the main focus is on OP, low-carbon management, attitudes toward climate change regulations, and CE. Many other possible factors were not included. The present study is focused on a limited sample size, which is based on only one province in the future. This could increase the sample size, and further longitudinal research will show a better understanding over time that how CE changes. Future research requires a vast circle of samples from small–medium enterprises, services, and other sectors. Meanwhile, focusing on the OP, CMP, and attitudes toward climate change regulations can also improve CE and make a positive contribution to controlling climate change. Other areas for the academia are to focus on green practices, how to control climate change effects, and how other sectors creatively strengthen process innovation and achieve green practices. The statistical results of this study are not enough in extracting significant conclusion in futuristic approach, and data samples should be large enough to apply more complex statistical techniques that will make authors get more relevant results.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Carbon emission and financial development under the "double carbon" goal: Considering the upgrade of industrial structure

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Economic growth is fueled by financial development, which also takes the initiative in attaining green development and a low-carbon economy. The advanced industrial constitution is used as a moderator and mediator variable in this article to investigate whether there is a moderating effect and mediating effect between financial development and carbon emissions. This article chooses panel data from 283 Chinese cities from 2006 to 2019 to empirically analyze the impact of financial development on carbon emissions. The consequences indicate that financial development wields an evident active influence over carbon emissions. Additionally, the upgrading of industrial structures wields an evident positive impact on carbon emissions. There exists a medium impact of industrial structure upgrading. Results show that, first, when estimating carbon emissions demand, China's financial expansion should be taken into consideration as a significant driver of rising carbon emissions. Second, although the extent of financial intermediation has a greater impact on carbon emissions than other financial development indicators, its effectiveness appears to have far less impact, even if it statistically has the potential to affect carbon emissions. Third, although the size of China's stock market has a substantially greater impact on carbon emissions, the impact of its efficiency is quite little.

KEYWORDS
financial development, carbon emissions, industrial structure, carbon peak, carbon neutralization

1 Introduction

In addressing global warming, the first legally binding document was the Kyoto Protocol, adopted by representatives of 149 nations and regions in 1997, together with the Paris Agreement in 2016, which requires all countries to meet certain regulations on emissions of greenhouse gas and commit themselves to the transformation of a green and sustainable growth mode. China, the largest developing nation in the world, has demonstrated its responsibility as a major country. In September 2020, China officially announced at the United Nations that it will reach the goal of a "carbon peak" by 2030 as well as "carbon neutral" by 2036. Achieving "carbon peaking," together with "carbon neutralization" is just one complex system project, mainly because many factors affect emissions of carbon dioxide, such as technological innovation, economic growth, energy consumption, foreign direct investment, industrialization, etc. In the meanwhile, the reduction of carbon dioxide emissions demands the backup of policies, financial capital, technology, and other conditions (AhAtil et al., 2019; Zhou et al., 2019; Chontanawat, 2020; Baydoun and Aga, 2021; Hou et al., 2021; Mo, 2022).

In actuality, financial growth may be another factor influencing a nation's carbon emissions in addition to its GDP level. Financial development tends to have a larger role in the rise in carbon emissions in an economy with progressively expanding financial systems for a variety of reasons. First, financial development may draw FDI from abroad, accelerating economic expansion and raising carbon emissions (Frankel and Romer, 1999). Second, thriving and effective financial intermediation appears to be supportive of consumer loan activities, which makes it simpler for consumers to purchase expensive products like cars, homes, refrigerators, air conditioners, washing machines, etc., leading to increased carbon dioxide emissions (Sadorsky, 2010; Ren and Hussain, 2022). Additionally, the growth of the stock market enables listed companies to cut financing costs, expand their sources of funding, spread operating risk, and optimize their asset/liability structures, resulting in an increase in energy consumption and carbon emissions (Dasgupta et al., 2001).

Authors that disagree with the reasons do exist, though. Claessens and Feijen (2007) found that companies with more sophisticated governance are frequently more inclined to embrace low-carbon development; hence, financial growth may boost companies' performance, which in turn may lead to a decrease in energy use and carbon emissions. In addition, Tamazian et al (2009) note that financial development aids listed companies in fostering technological innovation and implementing new technologies, which in turn helps them progress in low-carbon economic development and boost energy efficiency. As a result, the carbon emissions intensity may be greatly reduced. As a result, it may be concluded that further empirical research is needed to clarify the relationship between financial development and carbon emissions. In reality, China has to do this sort of study in order to rationally assess the difficulties of achieving carbon emissions intensity decrease and scientifically design the road to do so. Three objectives will be covered in this paper: industrial constitution and financial development, industrial constitution and carbon emissions, and carbon emissions and industrial constitution.

As the driving force of economic growth, the correlation between financial development and carbon emissions has caught much attention. There exist dominantly three opinions. To begin with, it is supposed that the financial development will boost enterprise expansion, ascend the demand and consumption of energy, and then bring about a growth in carbon emissions; Next, it is supposed that the financial development could enhance the efficiency of the energy and fulfill the energy storage and emission decrease through boosting economic development, industrial upgrading and technological innovation; Third, we believe that financial development exerts no effect upon carbon emissions (Boutabba, 2014; Abbasi and Riaz, 2016; Dogan and Turkekul, 2016; Jamel and Maktouf, 2017; Tian et al., 2019; Acheampong et al., 2020; Bui, 2020; Guo and Hu, 2020; Hasan et al., 2021).

When discussing the correlations between carbon emissions and financial development, this article focuses on the perspective of industrial constitution promotion and tries to use the upgrading of the industrial constitution for moderator variable and mediator variables to verify the straightforward impact and indirect impact of the financial development upon the carbon emission and divides cities into four types of urban groups by the light of the combination of the level of the financial development and the level of industrial constitution promotion, discussing the difference between the moderating role and the mediating impact of industrial constitution upgrading in different types of urban agglomerations could offer an appropriate reference for the government for the sake of adopting different financial development policies when promoting green development and low-carbon economic transformation. The remaining sections of the article are arranged as follows. Section 2 provides an overview of the empirical evidence on how financial development and carbon emissions are connected. The definitions of research data and the empirical procedures used in this article are presented in Section 3. In Section 4, empirical findings are presented, and the paper is concluded in Section 5.

2 Literature review

Scholars choose different research objects for the purpose of empirically researching the effect of financial development and industrial constitution upon carbon emissions and draw different conclusions. This study will review the literature from three aspects: carbon emissions and financial development, industrial constitution and carbon emissions, and industrial constitution and financial development.

2.1 Financial development and carbon emissions

Researchers have not reached an agreement on the effect of financial development on carbon dioxide. Some scholars believe that financial development will increase carbon emissions, a few researchers suppose that financial development could decrease carbon emissions, and a few scholars believe that financial development and carbon emissions exert no effect.

The main reason why financial development is going to ascend carbon emissions is that financial development can enable enterprises to obtain funds to invest in new production lines, expand production scale, and purchase heavy machinery and equipment, which will cause more pollutant emissions; At the same time, financial development can also provide more consumer credit services, promoting personal consumption, such as the purchase of cars, household appliances, real estate, etc., which will also increase carbon dioxide emissions (Bui, 2020; Hasan et al., 2021). Boutabba (2014) found that the financial development inside India exerts a long-run active effect on carbon emissions. Moreover, financial development will aggravate environmental quality degradation; Hao found that in the period of rapid economic development in 29 provinces of China, financial development will damage the environment (Boutabba, 2014; Hao et al., 2016). Cetin and Ecevit found that financial development, economic growth, and trading openness exert an active influence on carbon emissions through Turkish data research; additionally, financial and economic advancement is at the expense of environmental quality degradation (Cetin and Ecevit, 2017).

The main reason why financial development is able to decrease carbon emissions is just that enterprises could use funds for technological innovation, Introduction of advanced technology, technology transfer and other means to enhance energy efficiency and decrease carbon emissions; It can also encourage governments and enterprises to invest in projects with a friendly environment and low-carbon equipment through low-cost capital to improve environmental quality (Tamazian et al., 2009; Tamazian and

Bhaskara Rao, 2010; Abbasi and Riaz, 2016; Acheampong et al., 2020). Shahbaz found through data research on South Africa that the financial development is going to decrease carbon emissions; Saidi and Mbarek (2017) discovered, through data analysis of 19 innovative economies, including Mexico, Colombia, and Brazil, that financial development both limits the degradation of environmental quality and has a long-term negative impact on carbon dioxide emissions; Shahbaz and colleagues found that French financial development would reduce carbon dioxide emissions; Zaidi et al. (2019), in APEC member nations, financial development helps to decrease carbon emissions. The financial sector allocates financial resources to organizations and production units that protect the environment (Shahbaz et al., 2013) and support the use of green technologies (Saidi and Mbarek, 2017; Shahbaz et al., 2018; Zaidi et al., 2019).

In 12 countries in North Africa and the Middle East, Omri et al. (2015) found no causal relationship between carbon dioxide emissions and economic development; Dogan and Turkekul (2016) found no causal relationship between US financial development and carbon emissions; Jamel and Maktouf (2017) found no causal relationship between European financial development and carbon emissions. Acheampong discovered that in independent finance countries, the overall growth of the financial markets and its sub-indicators had no obvious influence on the intensity of carbon emissions (Acheampong et al., 2020).

2.2 Industrial structure and carbon emissions

Scholars construct different industrial constitution indicators such as industrial constitution upgrading, industrial constitution rationalization and industrial constitution transformation to explore the impact on carbon emissions (Li and Lin, 2017; Tian et al., 2019; Wang et al., 2019; Wu et al., 2021). The effect of industrial development on carbonous emissions counts on the structure for its industrial advancement. Resource-consuming industries are crucial elements impacting carbon emissions (Li et al., 2018; Tian et al., 2019). At present, the fact that China's energy consumption mainly depends on coal resources is still difficult to change. Therefore, we can achieve the important strategy of reducing carbon emissions by optimizing as well as promoting the industrial constitution so as to decrease the depletion of the energy and improve energy utilization (Chuai and Feng, 2019; Zhang et al., 2020). Zhang et al. (2014) discovered that improving the development of the Chinese tertiary industry can significantly decrease carbon emissions, and the advanced industrial constitution conduces to reducing carbon emissions; Li et al. Found that the growth of the ratio of the secondary industry in the Yangtze River Delta will lead to the growth of carbon emissions in prefecture-level cities; Cheng et al. (2018), Feng and Wu (2022) reached the same conclusion that upgrading and optimizing China's industrial constitution conduces to decreasing carbon emissions. Song's (2019) research on 30 cities and provinces in the east, middle and west in China shows that different regions have different impacts on the efficiency of carbon emissions. The industrial promotion (molar index) in the east exert an active effect upon carbon emissions effectiveness, while it wields a negative effect over the carbon emissions effectiveness in the central region.

2.3 Financial development and industrial structure

Financial development serves to effectively allocate funds to various industrial sectors, which is an essential means and tool for industrial restructuring. Scholars have not reached a consensus on the study about the industrial structure and financial development. Zhang et al. (2019) found that financial efficiency is positively associated with the promotion of production structure among 121 Chinese cities; financial agglomeration and financial scale are negatively related to the promotion of manufacturing structure. Jiang et al. (2020) found that the regional financial development in eastern China wields an evident active effect over the promotion of the industrial constitution; The central regions and western regions exert no evident influence upon the promotion of the industrial constitution. Tao and Xu (2016) found that the effect of Chinese financial development level upon the promotion of industrial constitution is a non-linear correlation, showing a trend of promoting first and then inhibiting. Zhu and Ni (2014) pointed out a significant promotion effect between related financial ratios and industrial structure upgrading. In the meanwhile, there exists an inverted U-shaped correlation between the financial scale and the promotion level of tertiary and secondary industries.

From the perspective of current research, there are many studies on the correlation between carbon emissions and financial development, the correlation between financial development and industrial structure, and the correlation between industrial structure and carbon emissions. However, based on whether there are moderating effects and mediator effects of industrial structure concerning carbon emissions during financial development, namely, there are still preliminary studies on how financial development affects the mediating system of carbon emissions, which need to be discussed in depth. Therefore, one of the major benefits of this article is to position the research perspective in urban areas and break through the limitations of traditional provincial-level research; The second is to examine whether the industrial structure upgrading has moderating and mediator effects between carbon emissions and financial development, in addition what kind of mediator effects and possible regional differences.

3 Research methods

3.1 Data source

283 Chinese prefecture-level cities are considered in the article (including 279 prefecture-level cities, along with 4 municipalities straightforward under the Central Government) to be the object of study. By virtue of the incomplete data and inconsistent statistical calibre of a total of 14 cities, such as Suihua City, Qinzhou City, Sansha City, Danzhou City, Tongren City, Bijie City, Haidong City, Turpan City, Hami City, Lhasa City, etc. The yearly data of every city from 2006 to 2019 were collected and collated, including the percentage of energy, population, overseas direct invest, industry in GDP, year-end deposits, loans, total trade, and other data of financial institutions. Please see Table 1 for data source.

TABLE 1 Research variables.

Variable	Variable name	Code	Measurement formula	Data source
Dependent variable	CO_2 emissions	CO_2	Ln (carbon emissions)	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007, China Energy Statistics Yearbook (cnki.net)
Independent variable	Financial development	FD	Loans from financial institutions/GDP	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007
Moderator	Advanced industrial structure	UIL	(Output value of primary industry/GDP) * 1+(Output value of secondary industry/GDP) * 2+(Output value of tertiary industry/GDP) * 3	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007
Mediator variable				
Control variable	Registered population	POP	Ln (population)	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007
	GDP *per capita*	GDP	Ln (GDP/population)	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007
	Expenditure	EP	Ln (financial expenditure)	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007
	Direct investment abroad	FDI	Ln (FDI)	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007
	Trade openness	OPEN	Ln (total import and export)	https://data.cnki.net/trade/Yearbook/Single/N2021050059?zcode=Z007

3.2 Selection and measurement of variables

3.2.1 Dependent variable

Of this article, the dependent variable is the natural logarithm for the total amount of carbon dioxide emissions. Its calculation method is mainly on the basis of the coefficient of carbon emissions offered by IPCC (2006) to figure out the urban carbon emissions indirectly. Its measurement expression is (Peng et al., 2018; Ren et al., 2020):

$$CO_2 = c_1 + c_2 + c_3 + c_4 = K_1E_1 + K_2E_2 + K_3E_3 + K_4E_4 \quad (1)$$

Including carbon dioxide emissions originating in the natural gas (c_1), the liquefied petroleum gas (c_2), the electricity consumption of the whole society (c_3) and raw coal (c_4); K_1 is the carbon emissions coefficient of natural gas, E_1 is natural gas consumption; K_2 is the carbon emissions coefficient of liquefied petroleum gas, E_2 is the consumption of liquefied petroleum gas; K_3 is the carbon emissions coefficient of the whole society's electricity consumption, E_3 for the whole society's electricity consumption; K_4 is the carbon emissions coefficient of raw coal, and E_4 is raw coal consumption.

3.2.2 Independent variable

The measurement of the financial development dominantly starts from the scale and efficiency of the financial development; Among them, the scale of the financial development is dominantly evaluated by the proportion of the loans from the banking institutions to GDP, the proportion of the deposits originating in the banking institutions to GDP, and the proportion of total deposits and the loans from the banking institutions to GDP; The major measure of financial development effectiveness is the proportion of loans to deposits coming from the financial institutions (Cetin and Ecevit, 2017; Peng et al., 2018). Drawing on the research of Odhiambo and Xu, this paper adopts the proportion of the loan balance of banking institutions at the end of the year to GDP as the assessment of financial development (Odhiambo, 2020; Xu et al., 2021).

3.2.3 Moderating variable and mediating variable

Scholars study the measurement methods of the industrial constitution, such as industrial distribution, industrial structure promotion, industrial structure rationalization, industrial agglomeration, etc (Peng et al., 2018; Wu et al., 2021). Concerning Wu and other studies, the advanced industrial structure is taken as the adjusting variable and mediator variable, and (Li et al., 2018) its measurement method is as follows:

$$UIL = \frac{\text{Output value of primary industry}}{GDP} * 1 + \frac{\text{Output value of secondary industry}}{GDP} * 2 + \frac{\text{Output value of tertiary industry}}{GDP} * 3 \quad (2)$$

The UIL is between 1 and 3. When the UIL tends to 1, it indicates a low degree of sophistication. When the UIL tends to 3, it indicates a high-caliber sophistication.

3.2.4 Control variables

We are employing the study by Yu et al. (2018). Moreover, this paper selected the number (Bui, 2020) of registered population, GDP *per capita*, fiscal expenditure, foreign direct investment and trade openness as control variables (Alotaish et al., 2019; Chuai and Feng, 2019).

3.3 Model settings

On the foundation of the STIRPAT model of Dietz and Rosa (1997) and York et al. (2003) this paper explores the affecting elements of carbon emissions. The pattern is:

$$I_{it} = aP_{it}^{b}A_{it}^{C}T_{it}^{d}e_i \quad (3)$$

TABLE 2 Descriptive statistics.

Variables	N	Mean	Sd	Min	Max
CO_2	3,961	6.153	1.210	2.019	9.603
FD	3,960	0.904	0.602	0.075	9.623
UIL	3,960	2.265	0.159	0.073	2.832
POP	3,961	5.864	0.696	2.868	8.136
GDP	3,961	10.41	0.806	7.923	13.13
EP	3,961	14.45	0.951	10.96	18.24
FDI	3,768	9.851	1.895	1.099	14.94
OPEN	3,960	13.662	2.154	2.769	19.65

Take the logarithm on both sides to obtain its t-variant:

$$Ln(I_{it}) = a + bLn(P_{it}) + cLn(A_{it}) + dLn(T_{it}) + e_i \quad (4)$$

Where I is the carbon emissions, P refers to population; A stands for GDP each capita, T means technology, a, b, c, and d are estimation parameters, i denotes the amount of individuals, t signifies time, additionally, e signifies the error term.

This paper extends the STIRPAT model and proposes the following models based on research assumptions:

$$CO_{2(i,t)} = \alpha_0 + \beta_1 FD_{it} + \beta_2 POP_{it} + \beta_3 GDP_{it} + \beta_4 EP_{it} + \beta_5 FDI_{it} + \beta_6 OPEN_{it} + \varepsilon_{it} \quad (5)$$

$$CO_{2(i,t)} = \alpha_0 + \beta_1 UIL_{it} + \beta_2 POP_{it} + \beta_3 GDP_{it} + \beta_4 EP_{it} + \beta_5 FDI_{it} + \beta_6 OPEN_{it} + \varepsilon_{it} \quad (6)$$

$$CO_{2(i,t)} = \alpha_0 + \beta_1 FD_{it} + \beta_2 UIL_{it} + \beta_3 FD_{it}*UIL_{it} + \beta_4 POP_{it} + \beta_5 GDP_{it} + \beta_6 EP_{it} + \beta_7 FDI_{it} + \beta_8 OPEN_{it} + \varepsilon_{it} \quad (7)$$

With a view to testing if the industrial constitution exerts an mediator effect, this paper uses Baron and Kenny's mediator effect model to build this model (Baron and Kenny, 1986):

$$CO_{2(i,t)} = \rho_1 + cFD_{it} + \gamma_1 control_{it} + \varepsilon_{it} \quad (8)$$

$$UIL_{it} = \rho_2 + aFD_{it} + \gamma_2 control_{it} + \varepsilon_{it} \quad (9)$$

$$CO_{2(i,t)} = \rho_2 + c'FD_{it} + bUIL_{it} + \gamma_3 control_{it} + \varepsilon_{it} \quad (10)$$

Among them, coefficient c refers to the total effect of financial development on carbon emissions; coefficient a means the effect of financial development upon the upgrading of mediator variable industrial structure, the coefficient b stands for the effect of the upgrading of mediator variable industrial structure upon carbon emissions after managing the impact of financial development, and the coefficient c ' means the direct effect of financial development upon carbon emissions after managing the effect of the promotion of mediator variable industrial constitution. When c means significant, test whether coefficient a and coefficient b are significant. If both are significant, there is an indirect effect. Test whether c 'refers to significant. When c' means significant, it denotes a partial mediating impact; When c' refers to not significant, it denotes a complete mediating effect.

4 Empirical analysis

4.1 Sample descriptive analysis

This paper uses a descriptive statistics table (Table 2) to understand the characteristics of individual variables. The value of carbon emissions ranges from 9.603 to 2.019, with an average value of 6.153, indicating an evident distinction in carbon emissions between the cities. The value of financial development ranges from 9.623 to 0.075, with an average value of 0.904, indicating that there also exists considerable distinctions in financial development in the cities. The value of the industrial structure ranges from 2.832 to 0.073, with an average of 2.265, indicating that the city's industrial constitution develops the industry from the secondary to the tertiary.

4.2 Correlation analysis

Table 3 exhibits consequences of the correlation dissection. The coefficient of the correlation between variables reaches less than 0.7, showing that there exists no collinearity between the variables.

4.3 Analysis of the impact of financial development and industrial structure upgrading on carbon emissions

Table 4 displays the empirical results of the relationship between financial development and carbon emissions as well as the relationship between industrial structure improvement and carbon emissions using a blended regression pattern and a fixed effect design. The over identification test's results show that the fixed effect pattern is preferable to the random effect pattern at the 1% level, rejecting the original hypotheses. Each unit gain in financial development will result in an increase in carbon emissions of 0.295 units, according to the fixed effect pattern's coefficients for the financial development, which are clearly positive. Evidently positive industrial constitution promotion coefficients suggest that more carbon emissions will result from this strategy.

4.4 Impact of financial development on carbon emissions: Interaction effect of industrial structure

The consequences in Table 5 indicate that based on the model in Table 4, when the interaction term between financial development and industrial constitution promotion is added, coefficients of financial development are significantly positive, coefficients of upgrading of industrial structure are evidently positive, and the coefficient of interaction term is evidently passive, indicating that upgrading of the industrial constitution wields a prohibitive impact over financial development and carbon emissions.

Additionally, Figure 1 shows the marginal impact of industrial constitution upgrading upon carbon emissions, indicating that with the gradual increase of the financial development, the small impact of

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TABLE 3 Correlation analysis table.

Var	FD	UIL	POP	GDP	Ep	FD	OPEN
FD	1						
UIL	0.538***	1					
POP	0.038**	0.100***	1				
GDP	0.315***	0.610***	−0.095***	1			
EP	0.393***	0.538***	0.583***	0.609***	1		
FDI	0.222***	0.442***	0.404***	0.568***	0.575***	1	
OPEN	0.303***	0.503***	0.381***	0.649***	0.593***	0.725***	1

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; t-statistics in parentheses.

TABLE 4 Regression results of the impact of financial development and industrial structure upgrading on carbon emissions.

Variables	(1) OLS	(2) FE	(3) OLS	(4) FE
FD	0.405***	0.295***		
	(9.87)	(2.63)		
UIL			1.804***	1.794***
			(7.13)	(4.05)
POP	0.947***	0.313	0.798***	0.278
	(20.68)	(1.50)	(16.67)	(1.39)
GDP	1.312***	0.494***	1.063***	0.231**
	(29.61)	(3.19)	(20.47)	(2.03)
EP	−0.360***	0.147	−0.242***	0.243***
	(-9.46)	(1.15)	(-6.29)	(2.90)
FDI	−0.032***	−0.055***	−0.043***	−0.051***
	(−3.16)	(−3.81)	(−4.21)	(−3.61)
OPEN	0.025**	0.106***	0.049***	0.110***
	(2.09)	(3.19)	(4.18)	(3.37)
Constant	−8.265***	−4.116***	−10.448***	−6.474***
	(−33.71)	(−3.82)	(−31.29)	(−5.12)
Observations	3,765	3,765	3,765	3,765
R-squared	0.675	0.445	0.679	0.484
Xtoverid (*p*-value)	25.953 [0.0002]		40.838 [0.0000]	
Number of count		281		281

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; t-statistics in parentheses.

TABLE 5 Regression results of the impact of interaction between financial development and industrial structure on carbon emissions.

Variables	(5) OLS	(6) FE
FD	1.999***	0.781***
	(3.30)	(3.16)
UIL	1.965***	1.869***
	(5.28)	(14.84)
FD*UIL	−0.717***	−0.241**
	(−2.97)	(−2.32)
POP	0.975***	0.482***
	(18.53)	(3.27)
GDP	1.227***	0.458***
	(22.47)	(7.71)
EP	−0.397***	0.044
	(−9.37)	(0.98)
FDI	−0.040***	−0.045***
	(-4.08)	(-5.14)
OPEN	0.020*	0.104***
	(1.65)	(6.42)
Constant	−11.239***	−7.502***
	(−17.27)	(-8.59)
Observations	3,765	3,765
R-squared	0.692	0.494
Number of count		281

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; t-statistics in parentheses.

industrial constitution promotion upon carbon emissions decreases. When financial development exceeds 2.353, it is not statistically evidently; Figure 2 shows the marginal impact of the financial development upon carbon emissions, showing that as the industrial constitution promotion grows, the marginal impact of financial development upon carbon emissions gradually decreases; while the degree of industrial constitution upgrading is higher than 2.73, it is not statistically significant.

4.5 The impact of financial development on carbon emissions: The mediating effect of industrial structure

Financial development as well as industrial structure has interaction effects, which will affect each other. This paper further verifies whether this impact is affected through the mediating path

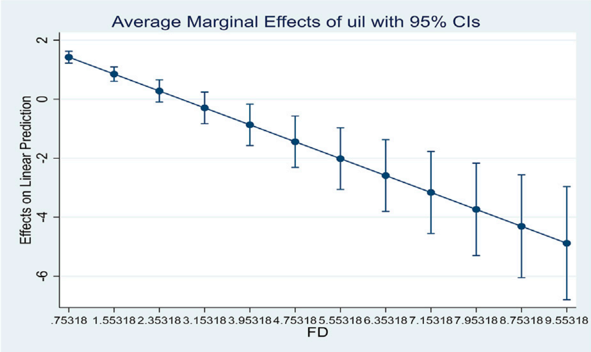

FIGURE 1
Carbon emissions marginal effect of financial development on industrial structure.

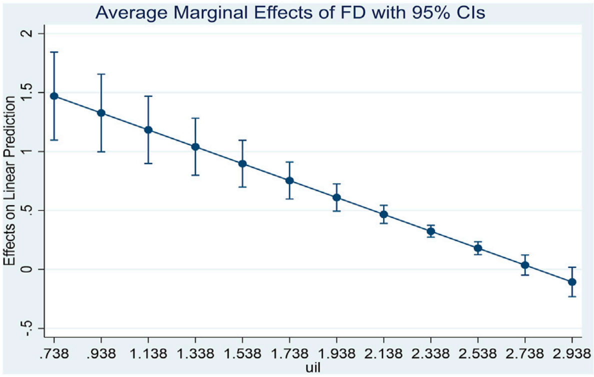

FIGURE 2
Marginal effect of industrial structure on carbon emissions of financial development.

through the mediating effect. Table 6 indicates the consequences of the mediating effect of the promotion of industrial constitution. The upgrading of industrial structure has some mediating effects in the effect of the financial development upon carbon emissions; Among them, the total effect is 0.405, the mediating effect reaches 0.1357; additionally the medium impact occupies 33.5% of the overall effect, which indicates that the financial development could be conducted through the industrial constitution upgrading, thereby affecting carbon emissions.

4.6 Robustness analysis

With a view to increasing the credibility of the empirical results and obtain further explanation, another indicator, FD2, is used to measure (loan amount + deposit amount)/GDP for robustness test. The same results can be obtained from Table 7 Robustness Test Regression Results Table and Table 8 Robustness Test mediating Effect Results Table.

TABLE 6 Mediating effect results.

Variables	(7) CO_2	(8) UIL	(9) CO_2
FD	0.405*** (18.13)	0.103*** (29.40)	0.269*** (11.09)
UIL			1.317*** (12.98)
POP	0.947*** (24.60)	0.017*** (2.67)	0.926*** (24.55)
GDP	1.312** (35.33)	0.092*** (15.68)	1.192** (31.76)
EP	−0.360*** (−11.89)	0.000 (0.04)	−0.360*** (−12.16)
FDI	−0.032*** (−3.43)	0.005*** (3.42)	−0.038*** (−4.22)
OPEN	0.025** (2.51)	0.000 (0.58)	0.024** (2.45)
Constant	−8.265*** (−35.61)	1.060*** (29.03)	−9.661*** (−38.45)
Observations	3,765	3,765	3,765
R-squared	0.675	0.544	0.688
Sobel test	Z = 11.88, p = 0.000		
Mediating effect	Mediating Effect/total Effect = 33.50%		

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; t-statistics in parentheses.

TABLE 7 Regression results of robustness test.

Variables	(10)OLS	(11) FE	(12) OLS	(13) FE
FD2	0.243***	0.218***	1.181***	0.675***
	(15.59)	(5.72)	(5.71)	(4.93)
UIL			1.971***	2.001***
			(5.24)	(13.90)
FD2*UIL			−0.411***	−0.214***
			(−4.78)	(−3.79)
POP	1.038***	0.504**	1.073***	0.679***
	(23.55)	(2.39)	(23.57)	(4.57)
GDP	1.410***	0.727***	1.350***	0.672***
	(32.00)	(5.05)	(26.25)	(10.27)
EP	−0.453***	−0.041	−0.490***	−0.122**
	(−12.16)	(−0.38)	(−13.25)	(−2.44)
FDI	−0.033***	−0.053***	−0.040***	−0.044***
	(−3.29)	(−3.76)	(−4.07)	(−5.03)
OPEN	0.011	0.097***	0.008	0.094***
	(0.97)	(2.92)	(0.69)	(5.84)
Constant	−8.454***	−5.080***	−11.820***	−8.879***
	(-36.04)	(-4.50)	(-17.96)	(-9.80)
Observations	3,765	3,765	3,765	3,765
R-squared	0.685	0.458	0.699	0.502
Number of count		281		281

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; t-statistics in parentheses.

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TABLE 8 Robustness test: mediating effect result table.

Variables	CO_2	UIL	CO_2
FD2	0.243*** (21.43)	0.060*** (34.8)	0.176*** (10.52)
UIL			1.098*** (10.52)
POP	1.038*** (26.77)	0.038*** (6.36)	0.997*** (25.92)
GDP	1.410*** (37.61)	0.115*** (19.97)	1.284*** (33.02)
EP	−0.453*** (−14.63)	−0.022*** (−4.62)	−0.429*** (−14.01)
FDI	−0.032*** (−3.60)	0.005*** (3.35)	−0.038*** (−4.22)
OPEN	0.011 (1.13)	−0.002 (−1.54)	0.014 (1.41)
Constant	−8.454*** (−37.19)	1.010*** (28.84)	−9.563*** (−38.62)
Observations	3,765	3,765	3,765
R-squared	0.684	0.575	0.693
Sobel test	Z = 10.07, p = 0.000		
Mediating effect	Mediating Effect/total Effect = 27.48%		

Note: ***p < 0.01, **p < 0.05, *p < 0.1; t-statistics in parentheses.

TABLE 9 Regression results of impacts of heterogeneous financial development on carbon emissions.

Variables	I	II	III	IV
FD	0.181***	0.481***	0.975***	0.028
	(6.04)	(3.04)	(8.17)	(0.37)
POP	0.837***	0.932***	1.329***	0.396*
	(13.19)	(9.69)	(23.21)	(1.96)
GDP	0.886***	1.134***	1.708***	1.206***
	(14.11)	(12.99)	(30.87)	(6.29)
EP	0.040	−0.375***	−0.871***	−0.090
	(0.81)	(-4.86)	(-18.83)	(-0.65)
FDI	−0.074***	−0.065***	−0.021	0.028
	(-4.72)	(-3.60)	(-1.59)	(0.69)
OPEN	0.006	0.054***	−0.016	−0.009
	(0.32)	(2.82)	(-1.10)	(-0.16)
Constant	−7.776***	−6.031***	−7.328***	−7.596***
	(-18.28)	(-11.53)	(-19.42)	(-5.32)
Suest (p-value)	I and II p = 0.0947 II and III p = 0.021			
	I andIII p = 0.000			
Observations	1,043	767	1,754	201
R-squared	0.678	0.513	0.497	0.408

Note: * * *p < 0.01, * *p < 0.05, *p < 0.1; t-statistics in parentheses.

4.7 Discussion on heterogeneity

Considering the difference between the financial development level and the advanced degree of industrial constitution among different cities, this paper divides all cities into high financial development level, and high industrial structure advanced degree (I), low financial development level and high industrial structure advanced degree (II), low financial development level and low industrial structure advanced degree (III) 4 groups of urban agglomerations, including high financial development level and bad industrial constitution promotion (IV), are analyzed for heterogeneity.

According to Table 9, high-caliber financial development and high-caliber industrial structure (I), poor financial development and high-caliber industrial structure (II), poor financial development and poor industrial constitution (III) financial development of urban agglomeration has an evident active effect upon carbon emissions, whereas the high-caliber financial development and poor industrial constitution (IV) financial development of urban agglomeration exerts an active effect upon the carbon emissions, However, it is not statistically remarkable. Through the test of Suest coefficient, it is found that the financial development of urban agglomeration with poor financial development and poor industrial constitution promotion (III) exerts an energetic active effect upon carbon emissions than that of type I and II urban agglomeration.

According to Table 10, high-caliber financial development and high-caliber industrial constitution upgrading (I) The industrial constitution promotion in urban agglomeration exerts an inhibitory impact of financial development upon carbon emissions, while poor financial development and poor industrial constitution promotion

TABLE 10 Regression results of impacts of heterogeneous financial development on carbon emissions (moderating effect).

Variables	I	II	III	IV
FD	3.471***	5.874	−3.602	0.847
	(5.70)	(1.18)	(−1.35)	(0.45)
UIL	3.424***	3.276**	−0.789	0.471
	(7.20)	(2.19)	(-1.08)	(0.40)
FD*UIL	−1.365***	−2.329	2.103*	−0.370
	(-5.55)	(-1.09)	(1.70)	(-0.44)
POP	0.882***	0.966***	1.308***	0.389*
	(14.06)	(10.16)	(22.71)	(1.85)
GDP	0.856***	1.118***	1.671***	1.194***
	(13.11)	(12.96)	(29.60)	(6.15)
EP	−0.019	−0.416***	−0.854***	−0.085
	(−0.39)	(−5.43)	(−18.35)	(−0.60)
FDI	−0.084***	−0.073***	−0.022	0.030
	(−5.45)	(−4.08)	(−1.61)	(0.72)
OPEN	0.005	0.065***	−0.016	−0.008
	(0.27)	(3.41)	(−1.14)	(−0.15)
Constant	−14.950***	−13.149***	−5.350***	−8.574***
	(−12.94)	(−3.77)	(−3.30)	(−3.04)
Observations	1,043	767	1,754	201
R-squared	0.694	0.528	0.500	0.408

Note: * * *p < 0.01, * *p < 0.05, *p < 0.1; t-statistics in parentheses.

TABLE 11 Conduction Effect Analysis of Heterogeneous Financial Development on Carbon emissions.

Group	Sobel (Z-value)	*p*-value	Whether there is mediating effect	Ratio of mediating effect to total effect
I	4.593	0.000	Partial mediating effect	47.51%
II	1.86	0.063	Partial mediating effect	11.48%
III	2.376	0.017	Partial mediating effect	4.49%
IV	0.000	1.000	No mediating effect	—

(III) The industrial structure upgrading in urban agglomeration exerts a catalytic impact of financial development upon carbon emissions, but poor financial development and high-caliber industrial structure upgrading (II) High-caliber financial development and poor industrial structure upgrading (IV) Urban agglomeration does not have a moderating role.

According to Table 11, high-caliber financial development and high-caliber industrial structure upgrading (I), poor financial development and high-caliber industrial structure upgrading (II), poor financial development and poor industrial constitution promotion (III) Urban agglomeration with high-caliber financial development and high-caliber industrial structure upgrading (I), the ratio of medium impact in overall effect is the highest. However, high-caliber financial development and poor industrial structure upgrading (IV) There is no mediating effect between the industrial constitution promotion of urban agglomeration and financial development upon carbon emissions.

5 Conclusions and suggestions

5.1 Research conclusion

Data concerning 283 Chinese cities from 2006 to 2019 is gathered in this article. We selected a more appropriate model to empirically analyze the effect of financial development on carbon emissions based on a series of spatial econometric tests. Synchronously, the advanced industrial constitution is looked on as the moderating variable and mediator variable to explore whether there is a moderating and conductive effect between carbonous emissions and financial development.

The results of empirical analysis show that the financial development measured by loans from financial institutions/GDP wields an active effect over carbon emissions, and the industrial constitution upgrading wields an active effect over carbon emissions. When the financial development and promotion of industrial constitution act as interaction items, upgrading of industrial constitution exerts a prohibitive impact upon financial development and carbon emissions. While the upgrading of industrial structure is used as a mediating channel, there exists a partial mediating effect between carbon emissions and financial development.

All cities are split into four parts of urban agglomerations in this paper, according to the degree of the industrial constitution upgrading and the level of the financial development. In addition, the heterogeneity is also analyzed. The financial development of urban agglomerations with high financial development level, along with high industrial constitution promotion (I), urban agglomerations with low financial development level, along with high industrial constitution promotion (II) and urban agglomerations with low financial development level, along with low industrial constitution promotion (III) wields an evident active effect over carbon emissions, especially in the domain of urban agglomerations of category III. Secondly, industrial structure upgrading of urban agglomeration (I) with high financial development level and high industrial constitution upgrading exerts a prohibitive impact upon financial development on carbon emissions, while the upgrading of industrial structure of urban agglomeration (III) with low financial development level and low industrial constitution promotion exerts a promoting effect on financial development on carbon emissions, but other urban agglomerations have no moderating effect. In addition, the high-caliber financial development and industrial structure upgrading of urban agglomeration (I), the poor financial development and the high-caliber industrial constitution promotion of the urban agglomeration (II), the poor financial development and the poor industrial constitution upgrading of urban agglomeration (III), the high-caliber industrial constitution of financial development and the poor industrial constitution promotion of urban agglomeration (III), have some mediator effects upon financial development and carbon emissions; additionally the mediator effects in category I urban agglomeration occupy the biggest percentage proportion of the total effects. However, high-caliber financial development and poor industrial structure upgrading (IV) There is no mediating effect between the industrial constitution promotion of urban agglomeration and the financial development upon carbon emissions.

5.2 Research recommendations

On the basis of the experienced consequences, this article propounds the policy recommendations below.

(1) Give play to the role of financial development in emission reduction

The interplay between industrial upgrading and financial development can inhibit carbon emissions. Financial institutions can lean towards low-carbon and green enterprises through the financial service channel of loans to help enterprises achieve industrial upgrading through technological innovation, advanced technology introduction, technology transfer and other means, with the aim of fulfilling the target of decreasing carbonous emissions. In addition, it also requires the active participation of the government, which can reduce the capital cost of enterprises by means of government subsidies, loan interest, etc., and encourage enterprises to invest in environmental pollution prevention, so as to reduce carbon emissions.

(2) Financial development should match with industrial development

Each city's industry has its own characteristics, and financial development should be combined with local industrial development to carry out financial development with local characteristics. For cities with the poor financial development and poorly upgrading of industrial structure, we should strengthen financial development, formulate financing system policies, and promote the upgrading of industries to the advanced direction through the guidance of funds; Cities with poor financial development and high-caliber industrial structure upgrading, as well as cities with a high-caliber financial development and poorly industrial structure upgrading, have seen a mismatch between financial development and industrial development. Only through two-way adjustment and coordinated development can we better achieve the emission reduction goal through the mediating of industrial structure.

(3) Strengthen financial cooperation among cities

Cities can promote financial cooperation among cities through financial information sharing, financial market resource sharing, financial supervision cooperation and other ways of boosting the free flow and the best distribution of financial elements among cities. Developed cities can also help cities in backward areas and promote the coordinated development of cities through the radiation and driving role of some urban agglomerations.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

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Conflict of interest

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Relationship between FDI inflow, CO_2 emissions, renewable energy consumption, and population health quality in China

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China has received significant foreign direct investment in the last few decades; the FDI inflow could affect the environment, income, and people's health. Therefore, this paper aims to investigate the relationship between FDI, renewable energy consumption, CO_2 emissions, and Population health quality in China for the period 1980–2020. We applied the VECM method for the data analysis for the short and long-run effects of the independent variables. In the short run, FDI and CO_2 emissions did not affect health quality in China; however, in the long run, FDI and CO_2 emissions improved life expectancy. Renewable energy has both run and long implications for the health quality in China. These results reflect that FDI creates more jobs in China and improves the overall income of Chinese citizens, contributing to more accessible healthcare services in the long run. Therefore, the government should provide incentives to increase the FDI inflow, which uses renewable energy in production. Furthermore, to mitigate the CO_2 emissions government should implement a carbon tax on the industries which has substantial CO_2 emissions in the country.

KEYWORDS

FDI inflow, CO_2 emissions, renewable energy consumption, health quality, China

1 Introduction

China gradually removed the trade restrictions and opened the economy to foreigners, and a significant amount of FDI inflow has been witnessed in last few decades. The inflow of foreign direct investment, considered to be a source of advanced technologies which leads to the technological diffusion. The foreign direct investment (FDI) provides job opportunities, makes the host country more productive and reduces unemployment. Trade liberalization and tax-reduction policy for foreign investment increase the FDI inflow in China (Li et al., 2021; Zhou and Latorre, 2021). China has focused on the FDI inflow for the last few decades to achieve its economic and social development goal. According to the Yearbook (2017) in China, 52.75% of the FDI is allocated to the secondary and manufacturing industries, while primary and tertiary industries account for 2.56% and 44.69%, respectively. Furthermore, the addition of capital stock in manufacturing industries is the main contributor to CO_2 emissions in the country. FDI in the secondary industry, i.e., Mining Industry, Construction Industry to the tertiary industry, i.e., Education Industry, Tourism, Environment, and Facilities Management, raises concerns about environmental protection and provides biases to the use exploitation of renewable energy. The relationship between FDI and CO_2 emissions are still controversial and uncertain, some researcher such as Xie et al. (2020); Salahuddinet al., 2018; Salahodjaev and Isaeva (2022) and Farooq (2022) found a positive relationship between FDI and CO_2 emissions, while other researcher such as Zhang and Zhou (2016); Faheem et al. (2022); Gyamfi et al. (2022) and Shabir, Ali, Hashmi, and Bakhsh (2022) reported a negative relationship between FDI and CO_2 emissions.

Other types of foreign inflow, such as remittances also possible sources of CO_2 emissions in the country (Jafri et al., 2022). The remittances increase the household income, which means the household owns more capital and increases energy consumption from various perspectives. For example, with higher income, people may purchase cars, consume more electricity and fuel gases in their daily life and ultimately contribute to the increased consumption and thus increase CO_2 emissions. Furthermore, the portion of foreign remittances that save from consumption will be allocated to the financial sector, which could be further used as an investment and leads to CO_2 emissions. Furthermore, according to Yang et al. (2020) the existence of FDI will cause a "Pollution Haven" which can be explained by the fact that developed countries put heavily polluting enterprises into developing countries, leading to the increased amount of CO_2 emissions. In line with this hypothesis, developed countries participating in FDI typically disseminate technologies that contribute to increasing the release of carbon dioxide emissions (Khan et al., 2019). The increase in CO_2 emissions negatively affects human health and decreases life expectancy and health quality (Ullah et al., 2019; Shah et al., 2021; Mahalik et al., 2022). Mainly, a substantial pollutant element in the air causes respiratory diseases. The kids may affect more severely by air pollution due to low resistance and immune system (Matthew, 2015). Although low CO_2 emissions could improve human health, a healthy lifestyle, better healthcare conditions, and adequate amounts of nutritious food could also improve health quality (Claessens & Feyen, 2007).

FDI inflow may affect the population's health from different aspects; firstly, FDI inflow accompanying renewable may reduce CO_2 emission and improve the health quality. Secondly, the rise enables the purchasing power of the people, and they may have access to better healthcare facilities. Thirdly FDI inflow would enhance the level of medical services, including applying advanced medical apparatus and employing elite doctors (Immurana, 2020a). Conversely, FDI may negatively affect the population's health quality in some cases, such as more FDI inflows significantly increasing the probability of purchasing harmful products like tobacco (Mckee & Schwalbe, 2005). Besides, social equality is also the main concern with FDI inflow. Foreign commercial firms with higher payment and equipment can entice people away from public facilities: an "internal" brain drain. Furthermore, the health system may become diverged with high medical quality care for the rich and that of lower for the poor. However, foreign direct investment and renewable energy consumption reduce CO_2 emissions in the country (Schwela & Haq, 2020). The expansion of renewable energy consumption due to FDI may replace traditional fossil fuel energy that emits a tremendous amount of carbon dioxide. Thus, the diseases such as respiratory diseases; lungs cancer caused by CO_2 emissions will decline. Furthermore, low CO_2 emissions will reduce adverse effects such as heat damage, food mildew, and hypoxia (Solarin et al., 2022).

Past studies have examined relationship between FDI, health and renewable energy such as Chiappini et al. (2022); Shah et al. (2022) and Burns et al. (2017) and examine health and FDI from the different aspects; however there is not study that specifically analyze the case of China. Therefore, this paper investigates the relationship between FDI inflow, CO_2 emissions, renewable energy consumption, and population health quality in China; The study adds to the existing body of knowledge in several ways; firstly, we use health quality with FDI, which has not been analyzed in the past literature especially in context of China. Secondly, we constructed an index for health quality, which has not been developed in previous studies. Thirdly, we use the VECM approach, which could provide both short and long-run estimations of FDI for the health quality and other related variables in the study. The rest of the paper is organized as Section 2 contains the literature review; Section 3 is related to the stylized facts of the study. Sections 4 and Section 5 provide the methodology, results, and study discussion, respectively. Section 6 is based on the conclusion of the study.

2 Literature review

Jafri et al. (2022) analyzed an asymmetric impact of remittances and foreign direct investment (FDI) on China's CO_2 emissions from 1981 to 2019 using the NARDL approach for data analysis. Their findings suggest that foreign remittances and CO_2 emissions have a negative relationship in the short run and long run. FDI has a negative effect on CO_2 emissions both in the short run and long run. However, the long run is more relatively effective than the short run. They concluded that the Chinese government should redesign its environmental policies to boost the country's foreign investors and local environmental quality. Li et al. (2022) analyzed China's CO_2 and FDI association. They find that the impact of the negative shock of remittances is more significant than the negative shock of FDI on CO_2 emission in China. Marques and Caetano (2022) explored the effects of FDI on CO_2 emissions in 15 OECD countries. They applied the ARDL model for analysis. Their findings reported that total fixed asset construction reduces pollution except for the mining industry. Furthermore, all OECD countries are under pressure from the tradable sector. They recommended that government should promote energy efficiency based FDI in the region. Furthermore, the host country needs to implement relevant laws and regulations to control the CO_2 emissions produced by FDI.

Mahalik et al. (2022) explore the impact of CO_2 emissions on life expectancy in developing countries from 1990–2017. They used disaggregated panel data analysis to examine the relationship between CO_2 emissions and life expectancy. The study mentioned two types of CO_2 emissions: consumption- or production-based CO_2 emissions. Furthermore, the economic level of national development is used as a controlled variable; the results conclude that there is a negative relationship between CO_2 emissions and life expectancy in emerging countries, and CO_2 emissions reduce life expectancy regardless of the source of CO_2 emissions. Their findings suggest that the positive effect of CO_2 emissions on life expectancy can be attributed to consumption, not production. In addition, an increase in income does not necessarily reduce environmental degradation and create a healthier life. Mohmmed et al. (2019) investigated the factors contributing to CO_2 emissions in the top 10 emitting countries. They used the ARIMA approach to analyze the impact of CO_2 emissions from different sectors, such as agriculture, industry, manufacturing, energy, Etc., and its effect on the Human Development Index (HDI), life expectancy, and economic growth. The results suggest a strong

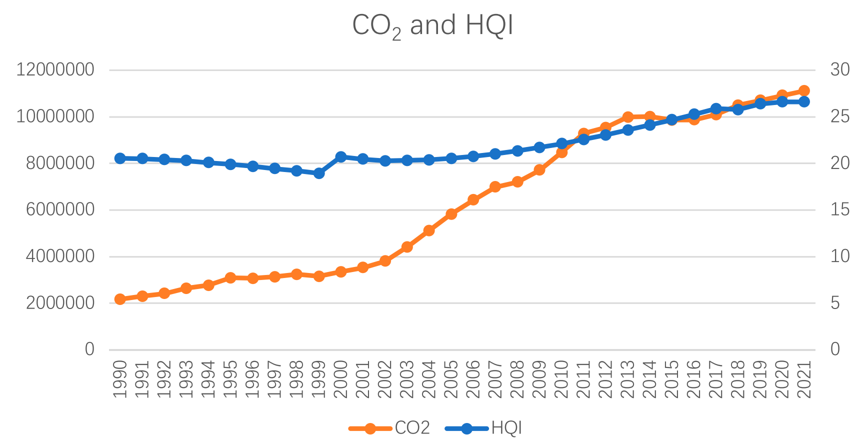

FIGURE 1
CO_2 Emissions and HQI in China. Source: WDI indicators.

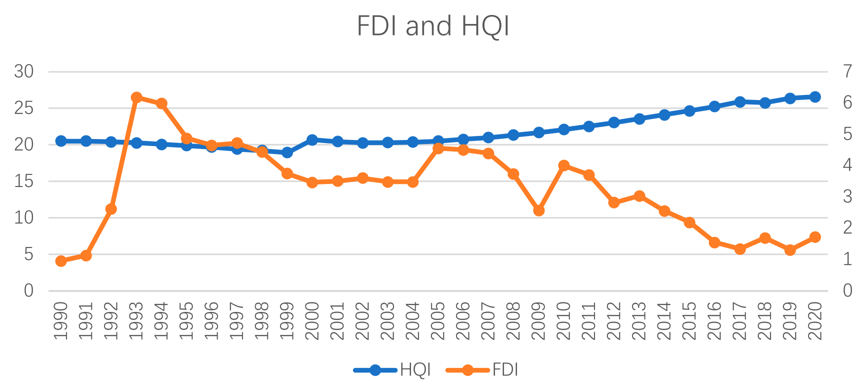

FIGURE 2
Fdi inflow and HQI in China. Source: WDI.

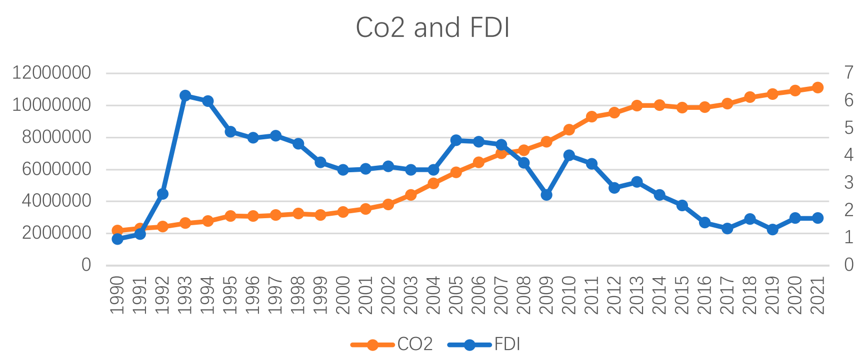

FIGURE 3
CO_2 emissions and FDI in China. Source: WDI.

relationship between included variables and CO_2 emissions in most countries. In addition, they recommended implementing environmental protection laws to provide better health quality and reduce CO_2 emissions.

Immurana (2020b) analyzed the impact of FDI on health outcomes such as life expectancy and mortality rate for 43 African countries from 1980 to 2018. They applied the fixed effects method and found that FDI improves health outcomes. Furthermore, his study

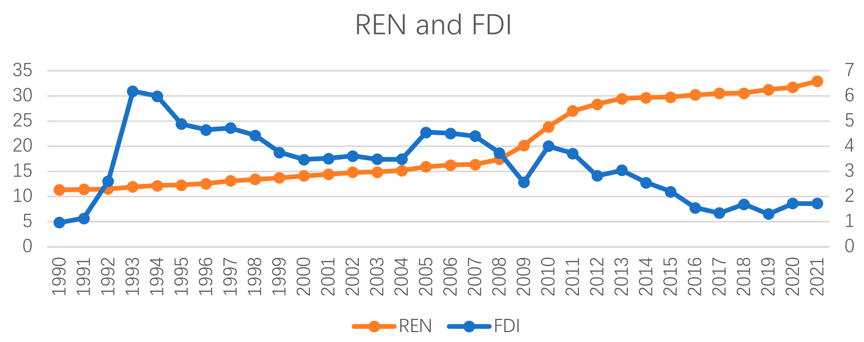

FIGURE 4
REN and FDI in China. Source: WDI.

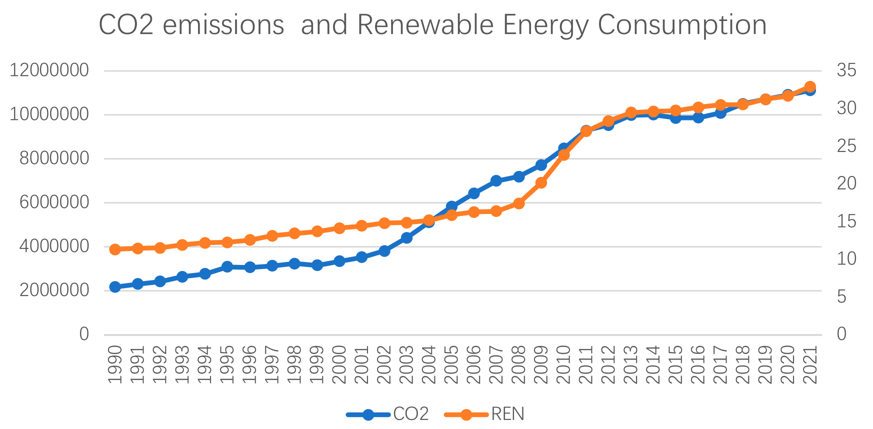

FIGURE 5
REN and CO_2 in China. Source: WDI.

has some limitations because it only covers African countries with a generally low level of economic development, and policy implications are limited to the African region. Nagel et al. (2015) in panel data for 179 countries between 1980 and 2011, found a non-linear relationship between FDI and Health. Specifically, the low-income countries found that FDI positively affects health, but this effect diminishes as income increases and even becomes negative at a high-income level. Immurana (2020a) also analyzed the impact of foreign direct investment (FDI) inflows on population health in Ghana from 1980 to 2018. Life expectancy, infant mortality, and malaria are health indicators of population health. They applied Simultaneously equation, and Ordinary least squares (OLS) method for data analysis, and their results indicate that FDI significantly affects health outcomes. They concluded that FDI inflow could improve population health in Ghana. In addition, mental health is also an essential component of life expectancy for human health.

Jiang and Chen (2022) studied the influence of air pollution on mental health by using the moderating effect of foreign direct investment in China. They applied fixed-effects panel regression and threshold models for analysis using 2015–2018 data. The results show that air pollution significantly negatively affects mental health. Furthermore, FDI has a mitigating effect on the negative association between air pollution and mental health. Air pollution and FDI impact are based on regional characteristics, including location, medical resources, technology investment, and individual traits, covering age, education level, and income. Deng et al. (2021) analyze FDI and renewable energy consumption in BRICS countries from 1990–2019 and apply ARDL-PMG and NARDL-PMG methods. According to ARDL-PMG's implication, the change in foreign direct investment has no significant effect on renewable energy consumption in the long run. At the same time, the NARDL-PMG model also shows the same result. The outcomes revealed that a negative inflow in foreign direct investment would improve the environmental quality, positively affecting the residents' health. They recommended that eco-friendly technology and innovations should be implemented in the country to increase the usage of renewable energy consumption. Li et al. (2021) also investigated the between FDI and renewable energy consumption in China using the provisional level data for 1995–1917. In provinces with high renewable energy use, FDI inflow accompanying renewable energy can reduce environmental degradation and improve health among the population. Meanwhile, some regions in China have been recommended to optimize their energy structure and implement higher renewable energy usage to improve the population's health. Most of the past studies discuss the FDI with CO_2 emissions and renewable energy consumption such as Xie et al. (2020); Salahuddin

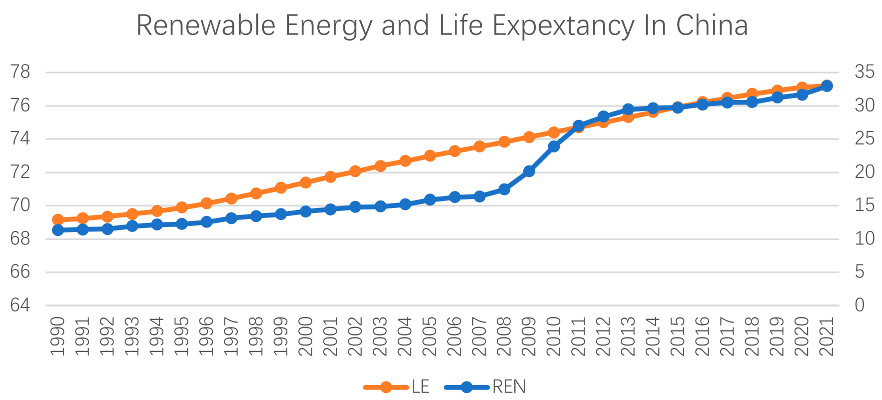

FIGURE 6
REN and LE in China. Source: WDI.

et al. (2018); Salahodjaev and Isaeva (2022) and Farooq (2022); Zhang and Zhou (2016); Faheem et al. (2022); Gyamfi et al. (2022) and Shabir et al. (2022) analyzed the relationship between FDI and CO_2 emissions. Other studies including Schwela and Haq (2020); Mirziyoyeva and Salahodjaev (2022); Saleem et al. (2022) and Qudrat-Ullah (2022) examine the renewable energy and CO_2 emission. Less attention is given to health and FDI however there are some studies related to FDI and health such as Chiappini et al. (2022); Shah et al. (2022) and Burns et al. (2017). Thus, study added the existing literature by covering FDI, CO_2 emissions and renewable energy and health quality in China.

3 FDI, renewable energy, population health in China

Figure 1 demonstrates a graphical relationship between carbon dioxide emissions and the health quality index from 1990–2021. The figure shows that from 1990 to 1999, the HQI has a minor negative relationship. However, from 2002 to 2011, both HQI and CO_2 emissions movie with comparatively faster speed, and still, the negative association persists. From 2012 to 2021, the relationship between CO_2 emissions and HQI became negative but lower rate. However, overall, the CO_2 emissions and HQI have a negative relationship. China had the lowest discharge amount of CO_2 emissions in 1990. This was primarily due to a small population, a low number of automobiles, and a slower pace of industrial development. According to Chen et al. (2019), after 1990 Chinese government developed the secondary industry, contributing to the increasing tendency of carbon dioxide emissions, which is accompanied by discharging of much more environmentally hazardous industrial waste. Although the Chinese government also promoted the development of the tertiary industry (tourism, real estate, and financial industry) in recent years, the proportion of economic profit created by the secondary industry of gross domestic profit (GDP) still accounts for almost 40% in 2020. That confirms that industrial emissions will undoubtedly keep increasing in the following years.

Figure 2 illustrates the connection between foreign direct investment (FDI) inflows and China's health quality index (HQI). The relaxation of trade restrictions brings a large amount of FDI to the country. FDI witnessed the highest rate from 1990 to 1993 and gradually declined from 1994. Despite a recovery between 2004 and 2006, some fluctuations in FDI exist, which means the variations arise due to structural changes in China. From a macro perspective, FDI shows considerable variation in the 30 years, and HQI still exhibits a decreasing tendency during this period. FDI inflow in sectors such as mining and manufacturing brings the great possibility of negative externalities which deteriorate the environment and health of the people. Immurana (2020b) suggests that harmful foreign products could affect the environment and human health. Immurana et al. (2021) have found that FDI promotes the production and consumption of toxic products such as tobacco and adversely affects human health. The deviation in the FDI and HQI does not provide an explicit association, and it is possible that in some years, FDI may have a positive or negative effect on the HQI.

Figure 3 represents a relationship between China's carbon dioxide emissions and foreign direct investment (FDI). Although it depicts the causal relationship between CO_2 emissions and FDI inflows, especially when FDI reached the highest level in 1993, FDI and CO_2 emissions still exhibit a negative correlation. The regulations of FDI in Europe and north Asia reduce the emissions in these countries. However, FDI in China has significantly increased CO_2 emissions and put pressure on environmental resources. Furthermore, the CO_2 emissions, based on fossil fuel, leading to environmental degradation and discourage future FDI inflow in the country, adversely affecting human health. CO_2 emissions have an increasing trend in China from 1990 to 2021, which implies that industrial development in the transition period leads to a constant increase in CO2 emissions in the country. This hypothesis is supported by Huang et al. (2019), who found that foreign enterprise in developing countries has a higher rate of CO_2 emissions.

Figure 4 shows the relationship between renewable energy consumption (REN) and foreign direct investment (FDI) in China from 1990 to 2021. There is a slight negative association between these two variables. This implies that FDI in China is mostly based on fossil fuels, leading to higher CO_2 emissions. However, renewable energy consumption can improve the living environment, leading to a healthy environment and labor productivity. Furthermore, increasing labor productivity will attract FDI inflow, Mustapha Immurana (2020a). Besides there are other reasons for the FDI inflow in the country besides renewable energy. FDI is not complementary to advanced

TABLE 1 Unit Root Test.

Variables	At level	First difference	Conclusion
CO_2	1.0966 (−1.9524)	−1.6755 (−1.9524)	Non-stationary at level and stationary at first difference
FDI	−0.579,234 (−1.9520)	−4.4187 (−1.9524)	Non-stationary at level and stationary at first difference
RNE	−0.1345 (−2.9677)	−2.9983 (−2.9677)	Non-stationary at level and stationary at first difference
HQI	2.8473 (−1.9520)	−4.0412 (−1.9524)	Non-stationary at level and stationary at first difference

technology from developed countries, and it causes the "Pollution Haven," which implies that foreign investment from countries possibly triggers a higher level of carbon dioxide emissions instead of stimulating renewable energy adoption. FDI in China has a deviating trend, and it is suggested that FDI and renewable energy cannot be predicted in the short run. Statistical analysis may provide more robust estimations and a clear picture.

Figure 5 illustrates China's historical trend between CO_2 emissions and renewable energy consumption (REN) from 1990 to 2018. The CO_2 emissions increasing trend from 1990 to 2018. This suggests that due to industrial and economic development, there is a constant increase in CO_2 emissions in China. China mainly uses traditional energy sources such as coal and oil for energy supply. The utilization of these energy sources accounts for more than 80% of the total usage. These types of energy sources release many gases that are harmful to the environment, such as carbon dioxide. In addition, the rapid development of China's manufacturing industry and the surge in production from 2010 to 2018 are also reasons for the high rate of carbon dioxide emissions. Therefore, the carbon dioxide emission rate accelerated from 2010 to 2014, while the impact of industrial expansion on the environment was moderated from 1990 to 2010. However, significant incentives have been provided to adopt renewable energy, such as wind and solar energy, whose contribution and production have significantly increased, reducing carbon dioxide emissions. Nevertheless, traditional energy still dominates in China and is the dominant source of energy production.

Figure 6 presents the derivation between Renewable Energy (REN) and Life expectancy. The long-term REN curve is constant, showing a mild and stable increase in renewable energy consumption from 1990 to 2008. Renewable energy follows the increasing trend from 2009 to 2012. The developing speed has declined since 2013 but still demonstrates moderate increases in subsequent years. Wind, hydro, and photovoltaic power account for major renewable energy production sources. The curve of life expectancy is flatter compared to the curve of renewable energy consumption proportion, rising steadily at the same rate overall. This symbolizes the positive impact of sustainable energy development on health levels. Moreover, the positive impact of renewable energy development on the population's health has improved life expectancy. From the figure, it can be concluded that renewable energy and life expectancy have an increasingly positive trend, and an increase in renewable energy has improved life expectancy in China.

4 Materials, model and methodology

This section presents the method and data we apply for the analysis. The data is compiled from World Bank Database for China during 1980–2020. The variable CO_2 represents *per capita* carbon dioxide emissions (Kt). In addition, FDI represents inflows of foreign direct investment *per capita* (Mert & Boluk, 2016). On the contrary, we construct the following index: HQI stands for Health Quality index and calculated by average value of some factors such as "life expectancy", HIV, Mortality, Hospital beds (per 1,000 people), People using safely managed sanitation services (% of population); RNE (renewable energy) stands for the renewable energy consumption (measured in kilotons of oil equivalent) *per capita.*

The following model contains the relationship of our study:

$$Health\,Quality\,Index = f\,(FDI, RNE, CO2\,emissions) \quad (1)$$

Following the ordinary least square model, we conduct a preliminary analysis of the basic impact of FDI, CO_2, and RNE on health quality by confirming the model's parameters and validity. This model provides the linear regressions to test whether the PHH hypothesis/EKC or the theory that the trend of FDI and RNE is positive correct or not since the ordinary least squares model can analyze the correlation of variable

$$HQI_t = \alpha_1 FDI_t + \alpha_2 CO2_t + \alpha_3 RNE_t + \epsilon_t \quad (2)$$

This study applies Vector Error Correction Model (VECM), which is based on the long run relationship and short run deviations. The model is estimated VAR framework and it assumes that all variables in the system hold same order of integration. We are using long-term time series data; it is essential to analyze the unit root parameters of the variables. It is indeed possible to get misleading results if the variables are non-stationary. The first step in VECM method is to estimate the order of integration, furthermore it is assumed that all variables should hold a same order of integration. There is different method that perform to test the unit root, Augumnetd Dickey and Fuller (1981) (ADF) and Ducky Fuller (DF) (1979). are most common methods to stationarity of the variables. The following equations represents the unit root test

$$\Delta Z = \gamma Zt - 1 + \partial t \quad (3)$$

$$\Delta Z = z_0 + \gamma Zt - 1 + \partial t \quad (4)$$

$$\Delta Z = z_0 + z1i + \gamma Zt - 1 + \partial t \quad (5)$$

Eq. (1)–(3) mainly performed to estimate γ, Dickey and Fuller (1979) test the hypothesis H0: 0, Zt is non-stationary if the γ is insignificant. Furthermore, the Dicky Fuller (DF) assumes that errors and residuals in statistics are uncorrelated. But if this error term is correlated to then DF method unable to estimate the stationary properties. Therefore, we use lag values and of dependent value which augments this equation, and Augmented Dicky Fuller (ADF) test could test the hypothesis as follow

$$\Delta Zt = x0 + \beta 1i + \gamma Zt - 1 + \Sigma\beta iZt - n + \varepsilon t \ldots \quad (6)$$

Mackinnon's critical and t (tau) statistics are used to test parameter Yt-1 in the ADF unit root test. If it reaches 0, it means there is a unit root, which indicates the variable is non-stationary, and *vice versa*. After evaluating the order of integration, the next step is the

TABLE 2 Johansen Cointegration Test.

Rank	Rank Test (Trace)		Rank test (Maximum Eigenvalue)	
	Trace statistics	Prob. value	Maximum eigen values	Prob. value
$r_0 = 0$	74.1780	0.0000	33.3112	0.0082
$r_1 \leq 1$	40.8668	0.0018	22.7689	0.0292
$r_2 \leq 2$	18.0979	0.0198	17.9817	0.0123
$r_3 \leq 3$	0.11618	0.7332	0.11618	0.7332

TABLE 3 Dependent variable: HQI.

Variable	Coefficient
CO2	−3.4208
	(0.0000)
FDI	0.32568
	(0.0000)
RNE	0.27326
	(0.0000)
R-squared = 0.9191	

estimate the long run relationship. The study test applied Johansen cointegration for the long run estimation; the primary requirement of the cointegration is the same order of integration. Engle and Granger (1987); Johansen (1991); and (Johansen, 1995). There are several ways for cointegration, including Engle and Granger (1987) and Johansen (1991); (Johansen, 1995); are the main method to test the long run relationship. The Engle and Granger (1987) method estimate the when system has two variables in the system and it cannot provide information for long run estimation. However for the multiple vectors Johansen (1991); and (Johansen, 1995) can be applied. Johansen test perform estimation based on following equations.

$$\Delta M = \mu + \sum_{i=1}^{p-1} \Gamma_i \Delta M_{t-1} + \Pi M_{t-1} + \varepsilon_t \ldots \quad (7)$$

The error term in the in Johansen techniques follow the likelihood ratios (LR) to the test the hypothesis of cointegration. The test provides two statistics, one is trade statistics and second is maximal eigen values. The first test assumes that the rank is equal to or less than the cointegrating vector (r), whereas the second uses trace statistics.

$$\lambda\,\text{trace} = -T \sum_{i=r+1}^{n} \text{In}(1 - \lambda i) \ldots \quad (8)$$

A second test will test for the maximum eigenvalue, and for the null hypothesis, it is tested for the number of cointegrating vectors as follows:

$$\lambda\,\text{max} = -T\,\text{In}(1 - \lambda_r) \ldots \quad (9)$$

VAR framework is used to test these statistics and for the optimal lag length Akike and Shward criterion is applied. If cointegration is found, the next step is to test the short run dynamics which is known as Error correction model.

$$\Delta HQI_t = \sum_{i=1}^{k} \beta_1 FDI_{t-i} + \sum_{i=1}^{k} \beta_2 CO_{2t-i} + \sum_{i=1}^{k} \beta_3 Ren_{t-i} + ECM_{1,t-1} \ldots \quad (10)$$

$$\Delta FDI_t = \sum_{i=1}^{k} \beta_5 HQI_{t-1} + \sum_{i=1}^{k} \beta_6 CO_{2t-i} + \sum_{i=1}^{k} \beta_7 Ren_{t-i} + ECM_{2,t-1} \ldots \quad (11)$$

$$\Delta CO_{2t} = \sum_{i=1}^{k} \beta_9 FDI_{t-i} + \sum_{i=1}^{k} \beta_{10} HQI_{t-1} + \sum_{i=1}^{k} \beta_{11} Ren_{t-i} + ECM_{3,t-1} \ldots \quad (12)$$

$$\Delta Ren_t = \sum_{i=1}^{k} \beta_{13} CO_{2t-1} + \sum_{i=1}^{k} \beta_{14} HQI_{t-i} + \sum_{i=1}^{k} \beta_{15} FDI_{t-1} + ECM_{4,t-1} \ldots \quad (13)$$

$\beta_{1,}\beta_{2,}\beta_3 \ldots \beta_n$ are the coefficient values of the vectors in the system and lag value of ECM presents the long run causality. Furthermore, it is assumed that significant value ECM indicates that long run causality. The data for the relevant variables are extracted from the World Bank Development Indicators, which are publicly available. However, the Health Quality Index is created by the using different health-related variables.

5 Results and discussion

4.1 Unit root test

This paper uses the VECM method for analysis; the initial step is to check the stationarity of the variables at level and first difference, more precisely, to check whether they are integrated with order two or not because the same order of integration enables them to proceed the VECM technique. We use the ADF unit root test to identify the order of integration (Wozniak, 2019). Table 1 provides the results of the ADF unit root test; the variables are tested by critical value at a 5 percent level. We concluded that all the variables are non-stationary at the level and stationary at the first difference. The results show that data of variables can be considered to proceed with the cointegration.

4.2 Cointegration test

We found that all variables are I (1); the next step is to test the cointegration among all of the variables. We use Johansen

TABLE 4 Long run and Short Run Causality.

	Short run Effect (causality)								Long effect (causality)
	D (CO_2(-1))	D (CO_2 (−2))	D (FDI (-1))	D (FDI (-2))	D (HQI (-1))	D (HQI (-2))	D (RNE (-1))	D (RNE (-2))	Ect (-1)
D (CO_2)	0.3939 (0.2167)	0.1501 (0.2108)	0.0020 (0.0345)	0.0222 (0.0360)	−0.0392 (0.0718)	−0.0074 (0.0706)	0.1036 (0.0558)	−0.0476 (0.0685)	0.05010 (0.0249)
D (FDI)	−0.8755 (0.8486)	−0.5497 (0.8253)	0.4196 (0.1352)	−0.0093 (0.1409)	−0.2529 (0.2810)	−0.3107 (0.2764)	−0.1383 (0.2184)	0.7579 (0.2681)	0.5849 (0.0976)
D (HQI)	−0.5773 (0.6746)	−0.5703 (0.6561)	−0.0837 (0.1074)	−0.0799 (0.0920)	−0.0218 (0.2234)	0.0702 (0.2197)	0.0866 (0.1737)	0.0116 (0.2131)	−0.0232 (0.0776)
D (RNE)	−0.8923 (0.6863)	1.2471 (0.6675)	−0.0934 (0.1093)	−0.0693 (0.1139)	−0.1808 (0.2273)	0.1048 (0.2235)	1.2108 (0.1766)	−0.4704 (0.2168)	0.1278 (0.0789)

cointegration to estimate the long-run relationship among variables. Johansen test are reported in Table 2; there have two statistics, trace statistics and eigenvalues, in Johansen cointegration. The result of trace statistic and eigenvalues conclude that there are at most three cointegration relations at 0.05 level and the null hypothesis of no cointegration can be rejected. The result shows strong evidence long-run relationship between HQI, Carbon dioxide emissions, foreign direct investment, and renewable energy consumption.

4.3 Long and short relationship estimation

We use ordinary least squares to find the long-term relationship among the variables. Table 3 presents the coefficient that describes the parameters of the linear regressions for the basic model. There is a positive and significant effect on the FDI on HQI. The FDI inflow, in the long run, creates more jobs and, at the same time, raises the overall income of Chinese citizens and improves the general affordable medical conditions. Furthermore, with a rise in income, people can easily do medical treatment, minimizing financial problems and ensuring better medical care. Higher-income levels can also afford better quality food. A more varied diet has also led to improved health indicators.

The results of CO_2 are negative and significant, implying that in the long run, the CO_2 emissions negatively affect the health quality and reduce the health quality. Furthermore, the renewable energy coefficient is positive and significant with health quality which suggests that an increase in renewable energy consumption improves the health quality.

The next step is to find out the short-term estimates of the co-cointegration model. Table 4 shows long-run and short-run causality—the model of D (HQI) initial target to compare with the long-term. Corresponding to the short-term results of FDI is negative but insignificant, which suggests that in the short run, FDI does not affect the HQI. This suggests that FDI does not affect health quality in the short run. However, in the long run, FDI could improve health quality; this implies that foreign direct investment in China has been shifting industries for decades. In the initial investment stage, foreign investors tend to invest in China's manufacturing industry to expand the original scale of production rapidly. At the same time, residents in the low-income stage can only get the original level of even lower medical facilities. CO_2 emissions are insignificant in the short run, while in the long run, it causes the HQI, which indicates that in the short run, CO_2 emissions do not affect HQI. This suggests that with production and trade in China, some relatively backward technologies spread, especially those not conducive to environmental protection. In the short term, such a manner would promptly increase carbon dioxide emissions, offsetting the positive income benefits. In addition, the amount of foreign investment in China has been shrinking in recent years, indicating that China has begun to pay attention to the importance of limiting carbon dioxide emissions and reforming domestic market policies. Foreign direct investment that can bring advanced technology and a clean environment will be encouraged. Moreover, more foreign direct investment is transferred from manufacturing to tertiary industries, such as tourism and finance, with low carbon dioxide emissions. It also hints at the overall rise of China's economy as the focus of capital shifts from being a source of investment to an exporter. The self-control system of the domestic market is gradually progressing. To conclude, the advantages of FDI outweigh its disadvantages, even with some potential risks. However, it is essential to emphasize that the positive health impact of FDI is not the increase in carbon dioxide emissions but the increase in income caused by carbon dioxide emissions. The REN also found an insignificant effect on the HQI in the short run, which implies that in the short run, health quality does not improve the health quality. Renewable energy has a positive and significant effect on Health quality in the short run at a 5 percent significance level. This suggests that renewable energy could improve the health quality of the people, and renewable energy has a low level of CO_2 emissions and provide a healthy environment and improve the quality of health of people. The significance of the error term tests the long-run causality test. The error term (ECT-1) is negative and significant, which implies that all variable, such as CO_2, FDI, and REN has long-run causality, implying that all variables cause health quality in the long run.

RNE is the most significant factor in the short run that reduces CO_2 emissions and substantially improves health. China's rapidly expanding renewable energy sources, such as photovoltaic, solar and wind, and power, could significantly reduce carbon dioxide emissions. Carbon dioxide can cause cardiovascular disease and other diseases caused by the greenhouse effect. Therefore, the negative effects environment can be greatly relieved. Some variable has no effect in the short run because it may be due to the slow development of the new energy industry caused by the poor economic capacity of China in the 20th century and the limitation of laggard technology. The result of this study has several implications; firstly, the FDI are mostly engaged in the production sector which contributed to CO_2 emissions. The CO_2 emission from FDI can be compensated by imposing carbon tax on foreign firm that could help to reduce the CO_2 emission in the country. Secondly the government should promote the implementation of renewable energy especially in the production process, additionally the renewable energy could provide clean energy to system but also improve the health quality of the people in the county. Thirdly the regulation for nature of FDI inflow is key aspects; tax incentives or tax exemption can be provided to those foreign that uses renewable energy in the production; which could help to achieve both environment and health objectives. Furthermore, firms need to adopt capital-intensive technology-oriented solutions rather than labor-enhanced solutions (Shahbaz et al., 2022). In addition, foreign direct investment in clean energy or cutting-edge technology could promote domestic industries and ensure the sustainable development (Doytch & Narayan, 2016). (Nepal et al., 2021). The results of this study in line with other past studies such as Shah et al. (2022); Xie et al. (2020); Salahuddin et al. (2018); Salahodjaev and Isaeva (2022); Farooq (2022); Ullah et al. (2020) and Pablo-Romero et al. (2016).

6 Conclusion

A significant amount of foreign direct investment has been attracted to China, which raises health and environmental concerns. Most of the previous studies analyzed the FDI and with CO_2 emissions or with renewable energy, however health aspect especially for Chinese economy still not address in literature. Therefore, this study investigates the relationship between FDI, CO_2, renewable energy consumption, and population health in China for the period 1980–2020. We constructed a health quality index (HQI) and used it as a dependent variable, while foreign direct investment (FDI), carbon dioxide emission (CO_2), and renewable energy consumption (REC) as independent variables in the model. We applied the VECM method for data analysis to test the short and long-run relationship between the variables. The results suggest that in the short run, only renewable energy causes the HQI, which implies that REN improves health quality in the short run. However, in the long run, all variables, such as renewable energy and FDI, improve health quality, while CO_2 emissions negatively affect health quality in China. These results have some policy recommendations; firstly, renewable energy is an essential factor that could improve health quality both in the short and long run. Therefore, government should promote renewable energy both in households and industries. The government may provide subsidies on the price of solar panels and renewable energy equipment. Secondly, the government should welcome and provide special incentives to boost FDI inflow, mainly those using renewable energy in production. The government may provide corporate tax reductions for the FDI firms that use renewable energy in the process and operation. Thirdly government should implement a carbon tax to reduce the CO_2 emissions in the country and to improve the health of the environment. Fourthly, tax revenue collected from the heavily CO_2 emitted industry could be used to provide tax relief to those industries that adopt renewable energy in the production process. Besides, to improve the quality of health, the government should improve the healthcare unit, especially in the rural and remote areas, which could improve the quality of health of the people in the country. This study has some limitations; firstly, we only discuss the case of China; consequently, we can test this hypothesis by adding multiple countries. Secondly, we constructed the HQI based on variables such as life expectancy, mortality rate, death rate, number of hospital beds, and people using safely managed sanitation services; future research may construct a stronger index by adding some new health quality-related variables. Thirdly, this study uses renewable energy consumption, CO_2 emissions, and FDI variables in the model; future studies may use additional variables to test this hypothesis.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org/country/CN.

Author contributions

ZZ: Conceptulaization FN and LD: Review the main draft and analyze the data IU: data extraction and review the main draft SX, YJ, and ZY, and CY: write the main draft.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The driving mechanisms for human settlement and ecological environment in the upper minjiang watershed, China

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The Chinese urbanization process is undergoing rapid development and intensification. There is, however, little awareness of spatial development in rural areas, particularly in watersheds that are relatively backward. Consequently, human settlements have been disrupted and environmental damage has been caused. The upper reaches of the Minjiang River are not yet aware of the limited space resources and environmental elements due to topography, climate, and other factors, resulting in an unbalanced development. Human settlements and ecological environments are examined in this paper in light of the adaptive development strategy of the upper reaches of the Minjiang River watershed. This paper establishes a "habitat-ecology" variable system for the purpose of adaptability research. The study identified 35 explanatory variables, including 17 in the category of human settlements and 18 in the category of ecological environment. A total of 12 relevant research sample areas have been selected, including five target sample areas and seven comparison sample areas. As a result of differential analysis and correlation research, explanatory variables with high significance were identified as characteristic variables. In addition, a driving mechanism between human settlement and ecological environment is determined using correlation analysis results, optimal subset equations, and independent effects of variables. The results show that in the "habitat-ecology" driving mechanism model: (1) In terms of human settlement, factors such as population density, proportion of construction land, and service scope of medical facilities are the most prominent; (2) In terms of ecological environment, factors such as regional proportion, *per capita* water area, net flow, and grassland coverage are the most prominent; (3) Based on the element configuration of the above two research subjects, the driving mechanism with human settlement as the driving force and ecological environment as the carrying capacity is obtained.

KEYWORDS

human settlement construction, ecological environment, driving mechanism model, correlation analysis, regression analysis

1 Introduction

The Upper Minjiang watershed is located in the Aba Tibetan and Qiang Autonomous Prefecture in northwestern Sichuan Province. In general, the topography is high in the northwest and low in the southeast (Zhang et al., 2021). There are plateaus, mountains, and canyons throughout the basin, and its core area includes Songpan County, Mao County, Wenchuan County, Heshui County, and Lixian County (Figure 1). Besides being characterized by a pronounced arid valley climate, severe soil erosion, and a fragile ecological environment

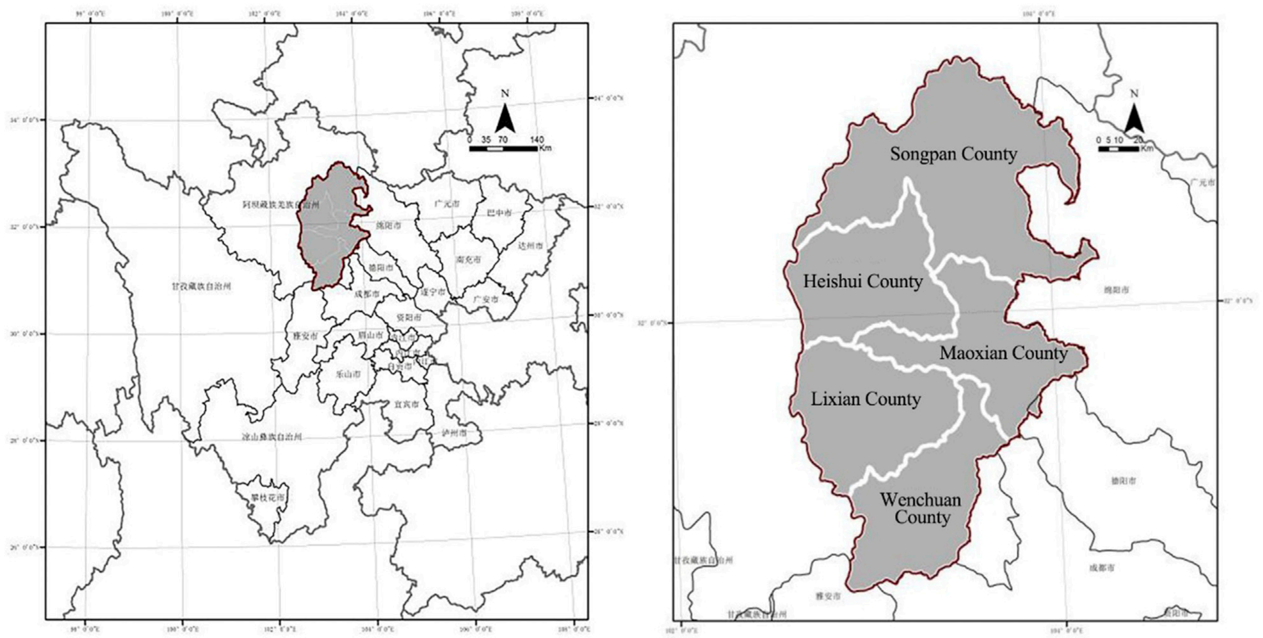


FIGURE 1
The location of core regions in Minjiang wateshed (Source: Author drawing).

(Yang et al., 2014), it is also mountainous (Guo et al., 2013). Furthermore, the region is prone to natural disasters such as earthquakes, landslides, and mudslides (Tension, 2018), making construction difficult. Moreover, the intensity of human activity in the upper Minjiang River watershed varies widely by region. For example, human activity in Heshui County is more uniform and frequent, while human activity in Lixian County and Mao County is on an average basis. Despite its better development, Wenchuan has unevenly distributed human activities, as well as a watershed dominated by Tibetans and Qiangs with their own distinct cultural systems. Due to the basin's unique ethnic culture and natural landscape, it attracts many tourists. Furthermore, the development of local hydropower stations has resulted in substantial economic growth, although there remains a significant difference in *per capita* income and *per capita* GDP.

The upper reaches of the Minjiang River have a wealth of construction guidance and policy regulations. However, there is a lack of flexible planning guidelines for adapting measures to local conditions and reconciling land use conflicts. It is intended that research focus on improving the development orientation of existing policies. This will mean complementing and improving specific suggestions for specific development areas, and strengthening the feasibility of urbanization implementation. Land conflicts have become more prevalent in the upper reaches of the Minjiang River as a result of urbanization, and man-made activities have destroyed the natural pattern in particular (Li et al., 2016). As a result of our commitment to the protection of the ecological environment, as well as enhancing the quality of life and productivity of the population, the concept of adaptability in this project is both theoretical and practical in understanding how to alleviate and create a harmonious and symbiotic relationship between the two subjects. A unique natural environment and restricted terrain characterize the upper reaches of the Minjiang River. Conflicts over land use have resulted in stagnant urbanization and slow development in this area. It should be noted that this is in comparison with the level of urban construction in the middle and lower reaches of the Minjiang River. A large portion of China's land area consists of mountains, which have specific structural characteristics. Thus, it is imperative that urbanization development methods be studied within the context of mountain topography for backward areas and areas with obvious differences in spatial characteristics. The environment has suffered severe damage, and the contradictions within the human settlement development system remain unclear. Therefore, it is imperative that we clarify their relationship in order to coordinate their interaction. In particular, we need to clarify the relationship between the construction of human settlements and the ecological environment of the upper Minjiang River. The purpose of this paper is to analyze the current urbanization problems in the upper reaches of the Minjiang River from a material and spatial viewpoint. A mechanism for adapting logic based on relevant evolution logic will be established to explain the relationship between human settlements and ecology. Moreover, the development and construction of urban spaces around watersheds are significant scientific research directions in the field of human settlements. As a result of this research, there is an urgent need to coordinate the development of natural elements with the development of society.

Watersheds have historically been significant sites for human settlement (Wang, 2009; Mao, 2019). A major tributary of the upper Yangtze River (Wang, 2009), the Minjiang River is a crucial source of water and transportation corridor for the Chengdu Plain (Man et al., 2007; Peng et al., 2007). Thus, its environmental conditions influence not only the development of local urbanization, but also the overall development of the Chengdu Plain and the greater Yangtze River basin (Zhang et al., 2014).

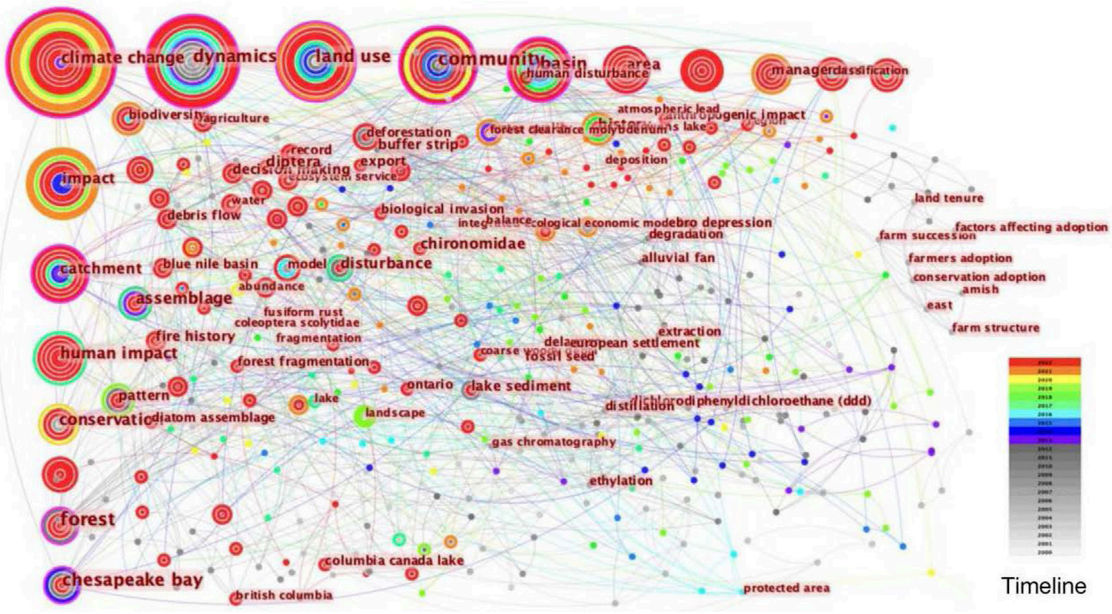


FIGURE 2
Research progress of foreign human settlement in watershed environment.

There is, however, a need to note that the characteristics of the elements in different parts of the basin vary considerably due to the unique ecological environment and topography of the upper Minjiang watershed (Zhao, 2018), and the process of urbanization proceeds slowly. It is necessary to clarify the relationship between human settlement and the ecological environment, as well as the forces that interact between them, in order to formulate a guiding model of the "habitat-ecology" driving mechanism. It is possible to optimize human settlement construction models and propose environmental compensation policies in the watershed by studying the driving mechanisms. Through the integration of theory and practice, this will contribute to the development of targeted environmental protection strategies and land development and utilization methodologies. Analyzing the inadequacies of existing development policies and providing recommendations for developing a "habitat-ecology" coordination model.

To begin with, it is crucial to identify specific elements that reflect human settlements and ecological environments, such as environmental concerns (Fang et al., 2016; Adil et al., 2020); population and water resources. Furthermore, a comprehensive index system must be developed in order to examine habitat-ecology relationships from a rational perspective through data analysis in order to study habitat-ecology relationships more accurately and rationally. As a result, most current studies utilize non-quantitative methods for analyzing data, and the research elements are not comprehensive enough. For example, there is little quantitative research on the upper Minjiang River basin, and even less quantitative research has been conducted on "ecological planning and design" (Pickett et al., 2014), "ecological spatial patterns of towns" (Sun et al., 2014), and "ecological adaptive management methods" (Zhang et al., 2017). It is through the extraction and analysis of these elements that this study provides a deeper understanding of the material and spatial characteristics of the upper Minjiang River basin. Within the scope of this study, an adaptive driving mechanism will be more appropriate and accurate based on the interaction and correlation analysis between these elements. The objective of this approach is to construct optimal combination equations. In order to identify key factors, correlation analysis and regression analysis are used. The purpose of this paper is to provide a more comprehensive analysis of the elements examined. The index system is more appropriate for the upper Minjiang watershed. Additionally, it reveals the interaction between different elements and their effect on each other.

2 Literature review

Human settlement construction has always been closely related to urbanization and natural environment protection (National Park Service, 1993; Zhao, 2018). Currently, the allocation of space resources is tense in China, and land conflicts are evident primarily in mountainous and watershed environments (Hu et al., 2007). It is essential to study the behavior of human settlements within the watershed environment under the influence of unique geological and geomorphic conditions. These conditions have a significant impact on improving the quality of human settlements. The most representative studies examine the economic development model of watershed towns, the construction of infrastructure related to water conservation projects, and the concept of building watershed environments from the perspective of disasters within a watershed environment (Zhao, 2009). High-quality human settlement research (Yu and Zhou, 2009). Furthermore, the Songhua River Basin (Sun et al., 2014). Several scholars have also conducted in-depth studies on the utilization of water resources and the corresponding social indicators in foreign countries. (Razzaq et al., 2022a; Razzaq et al., 2022b; Razzaq et al., 2022c).

10.3389/fenvs.2023.1097801

TABLE 1 Summary of explanatory variable system.

Human settlement construction	Code	Ecological environment	Code
Regional GDP *per capita*	A1	Surface water patch coverage	B1
Percentage of output value of primary industry	A2	Water surface *per capita*	B2
Coverage of farming patches	A3	Unit area runoff	B3
Percentage of output value of primary industry	A4	Woodland patch coverage	B4
Length of road *per capita*	A5	Grassland patch coverage	B5
Road network effective service index	A6	Temperature and humidity index-minimum value	B6
Bridge Service Index	A7	Temperature and humidity index-maximum	B7
Total number of public transportation lines	A8	Precipitation in the unit area	B8
Total number of towns reachable by bus station	A9	Number of days of rainfall	B9
Total number of eco-tourism sites	A10	Sunlight intensity	B10
Ecotourism area patch coverage rate	A11	Percentage of plots with suitable slope	B11
Total number of human attractions	A12	Percentage of altitude suitable areas	B12
Annual passenger traffic	A13		
Total annual tourism revenue	A14		
The proportion of tertiary industry output value	A15		
Total population	A16		
Population Density	A17		
Percentage of construction land	A18		
Construction land *per capita*	A19		
Percentage of suitable construction area	A20		
Accessibility of medical facility service coverage	A21		
Total number of schools	A22		
Number of students in school	A23		

The Chinese studies primarily focus on the upper reaches of the Yangtze River and its tributaries. Professor Zhao Wanmin of Chongqing University has conducted extensive discussions regarding practical issues such as population relocation and transfer faced by the Three Gorges reservoir area, and has linked reservoir area planning research with urbanization and planning system development. In addition to urban design, historical and cultural heritage protection, and other perspectives (Zhao, 2009). Moreover, Zhao and Zhou conducted corresponding research on the Wujiang River Basin, a second-order tributary of the middle and upper reaches of the Yangtze River, as well as the upper reaches of the Minjiang River from the perspective of comprehensive river basin development and overall planning. A monograph titled "Research on the Construction and Development of human settlements in the Three Gorges Reservoir Area-Theory and practice" examines the assessment and planning of sustainable development, the redistribution of population industries, and urban land use ecology from the perspective of watersheds, urban agglomerations, cities, and blocks. As regards the planning and preservation of historic blocks, the study systematically summarizes the relevant theories pertaining to the construction of human settlements in watersheds and establishes the basic scale and paradigm for watershed research (Zhao, 2018).

With regard to ecologically fragile watersheds, Liu started with small watersheds for soil erosion control, and proposed three different types of residential ecological units for small watersheds on the Loess Plateau: end-of-mountain types, crossing-over river corridor types, and island-surrounded types. Yu discussed the types of human settlements and the evaluation of environmental suitability in the gully area of the Loess Plateau, and defined environmental suitability based on a variety of indicators, including slope and soil type (Yu and Zhou, 2009). It is evident that the relevant research on the human settlement environment in the context of watersheds has always been an important issue in the development of urbanization, and it is also an urban planning challenge that has not been fully overcome in relatively backward areas in various countries. Using the WOS search keywords "Watershed"+"Human settlement"+"Ecological environment", 331 core literature database results were identified. Citespace software was used to summarize the relevant research over the past 2 decades (as demonstrated in Figure 2), and the international perspective of related research fields is more inclined to examine global climate change from a global perspective. Additionally, domestic development is similar, and many keywords are related to human

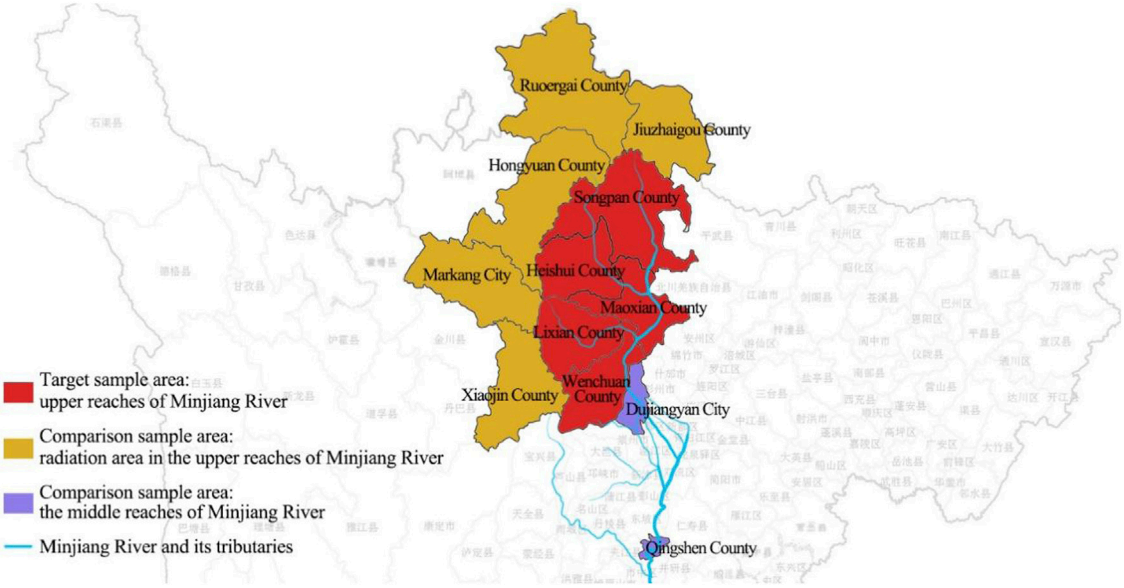


FIGURE 3
The location of sample areas.

activities, such as “human impact, commute, human distance”. In terms of research progress, human activities, variability, remote sensing, and climate are the key words for exploration. These key words are followed by climate warming, management, water sedimentation, land use, regions, rivers, biodiversity, classification, ecological services, and water resource development. Approximately one-third of the hot words are related to water, indicating that the level of foreign countries is temporarily higher than that of domestic ones with respect to the exploration of river basins.

As can be seen, the sustainable development relationship between watersheds and human settlements provides a model for the continuous construction of various indicators of human settlement and the ecological environment. According to the existing literature, the development of urbanization in a watershed requires consideration not only of the local economy and population, but also of other related variables such as topography, water resource systems, public transportation systems, and infrastructure construction (Sun et al., 2021; Xu, 2022). Consequently, the purpose of this study is to examine the driving relationship between various indicators, and to distinguish their driving roles in the upper reaches of the Minjiang River.

3 Methods and materials

3.1 The preparetion of datasets

3.1.1 The description of the statistics

In consideration of the relationship between human settlement construction and the ecological environment. In this paper, the relevant elements of “habitat-ecology” were compiled based on Zhao Bing’s “Ecological Footprint Analysis and Optimization of Habitat in the Upper Minjiang River”, “GIS-based Assessment of Habitat Climate Suitability in Hubei Province” (Zhou et al., 2015), and “Study of Road Skeleton System in Small and Medium-sized Cities” (Wang, 2009). With the assistance of local official websites, it filtered and supplemented these elements. It is intended to make these elements more consistent with the basic characteristics of the upper Minjiang watershed. It is pertinent to note that habitat elements include town construction, transportation systems, watershed economies, and cultural tourism, while ecological elements include “water”, “vegetation”, “weather”, and “topography”. The following elements (Table 1) were used to extract representative indicators to be used as explanatory variables in the later study.

3.1.2 Selection of study sample areas

Accordingly, 12 samples were selected, including those from Songpan, Mao, Wenchuan, Heshui, and Lixian counties in the upper Minjiang watershed core area and seven comparison samples, namely Jiuzhaigou, Hongyuan, Xiaojin, Ruoerge, and Markang counties in the upper Minjiang watershed radiation area and Dujiangyan and Qing Shen counties in the middle reaches of the Minjiang (Figure 3).

3.1.3 Data source

(1) Three-dimensional data are gathered from the National Basic Geographic Information Center’s Global Surface Coverage Data Product Service website and the Computer Network Information Center’s Geospatial Data Cloud Platform (Sun et al., 2021), and these vector data are processed and corrected in ArcGIS (Li et al., 2016). (2) Economic index data: data on the economy, such as population, output value, and national economic and social development statistics, are derived from the China County Statistical Yearbook and the National Economic and Social Development Statistical Bulletin. (3) Meteorological data, such as rainfall and runoff, temperature and humidity, and sun intensity. A number of methods have been used to gather these data, including the Central Weather Station, the China Meteorological Data Network, and the “Wheat-A″ tool. A variety of government websites, travel advisory

TABLE 2 Coefficient of deviation values of explanatory variables.

A1	0.36*	A7	0.29	A13	0.26	A19	0.30	B1	0.27	B7	0.31
A2	**0.33**	A8	0.28	A14	0.26	A20	**0.31**	B2	**0.31**	B8	0.29
A3	0.29	A9	0.27	A15	0.26	A21	**0.30**	B3	0.28	B9	**0.34**
A4	**0.30**	A10	0.27	A16	0.27	A22	0.27	B4	**0.34**	B10	**0.32**
A5	0.28	A11	0.29	A17	**0.36***	A23	0.26	B5	0.28	B11	**0.31**
A6	**0.31**	A12	0.29	A18	**0.32**	-		B6	**0.30**	B12	**0.33**

Note: The bold font indicates that the deviation coefficient meets the expected conditions (Deviation coefficient greater and equal to 0.3).

TABLE 3 The number of other explanatory variables with significant correlation in the Pearson coefficient.

A1	4	A7	10	A13	11	A19	17	B1	10	B7	15
A2	1	A8	9	A14	**11**	A20	**12**	B2	9	B8	**13**
A3	**11**	A9	**10**	A15	0	A21	4	B3	**21**	B9	2
A4	6	A10	0	A16	**14**	A22	**10**	B4	7	B10	5
A5	**10**	A11	0	A17	**17**	A23	**11**	B5	**20**	B11	2
A6	9	A12	3	A18	**15**	-		B6	**10**	B12	**17**

NOTE: The bold font indicates that the correlation coefficient meets the expected conditions, with correlation cofficient greater than or equal to 0.6.

TABLE 4 Spearman coefficients for other explanatory variables with significant correlations.

A1	6	A7	18	A13	2	A19	11	B1	1	B7	16
A2	1	A8	3	A14	3	A20	4	B2	**15**	B8	**14**
A3	**13**	A9	3	A15	0	A21	**11**	B3	**14**	B9	2
A4	7	A10	2	A16	9	A22	3	B4	7	B10	8
A5	7	A11	2	A17	**13**	A23	6	B5	**11**	B11	2
A6	**12**	A12	5	A18	**15**	-		B6	**13**	B12	**12**

NOTE: The bold font indicates that the correlation coefficient meets the expected conditions, with correlation cofficient greater than or equal to 0.6.

websites, etc., provide information on tourist attractions. A variety of public transportation-related data can be obtained through Xinxin Travel, Baidu Map and other transportation websites. After obtaining the basic data by the above three ways, the different explanatory variables of different sample units are then calculated and assigned.

3.2 Quantitative research methods

3.2.1 Correlation analysis method

Using correlation analysis, we can filter out useful variables, which will be synthesized later using three different computational models:

The paper introduces the concept of "deviation coefficient" to describe the variability among the explanatory variables in the study area, i.e., the standard deviation is calculated after normalizing the data for that same variable. For the purpose of this paper, X represents a set of variable values, Xs represents the normalized value of X. Xsi represents the standard deviation of X, and Xsi represents the normalization formula. A tendency towards zero indicates that the explanatory variable has less variability among samples. At the same time, it may indicate to some extent that the variable has a negligible impact on the watershed. σ is obtained from the standard deviation formula

$$\sigma = \frac{\sqrt{\sum_{i=1}^{n}(xs_i - xs)^2}}{n-1}, xs_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{1}$$

In Pearson correlation coefficients, the product-difference correlation coefficient is used to assess the linear relationship between two variables, and its value ranges between [-1, 1]. A significant correlation is one in which the absolute value of both variables is greater than 0.6, indicating that there is a strong interaction force between the two variables (Li, 2021). In this equation, Cov (X, Y) is the covariance between X and Y, $Var[X]$ is the variance of X, and $Var[Y]$ is the variance of Y.

$$r(X, Y) = \frac{Cov(X, Y)}{\sqrt{Var[X]Var[Y]}} \tag{2}$$

The Spearman correlation coefficient is calculated by using a monotonic equation, which belongs to nonparametric statistics, which has a wide range of application (Xu, 2022). Its value range,

TABLE 5 The determination of characteristic variables.

Categories	Deviation coefficient	Pearson Correlation group	Spearman Correlation group
Ecological environment	**B2**、B4、**B6***、B9、B10、B11、**B12***	B1、**B3**、**B5**、**B6***、**B8**、**B12***	**B2**、**B3**、**B5**、**B6***、**B8**、**B12***
Human settlement	A1、A2、A4、**A6**、**A17***、**A18***、**A19***、**A20**、**A21**	**A3**、A5、**A7**、A9、A13、A14、A16、**A17***、**A18***、**A19***、**A20**、A22、A23	**A3**、**A6**、**A7**、**A17***、**A18***、**A19***、**A21**

Note: Bold indicates significant variables with occurrence times ≥2, *represents significant variables common to the three groups.

TABLE 6 Collinearity Diagnostic Results.

Dependent variable	Independent Variables through Diagnosis
A3	**A7、A19、A21、B2、B5、B12**
A6	**A7、A19、A21、B2、B5**
A17	**A21、B2、B3、B12**
A18	**A7、A21、B2、B3、B5、B12**
A20	**A7、A21、B2、B3、B5、B12**

Note: Bold indicates meet the condition of flexible screening with VIF < 10" and "variance ratio < 0.9.

principle, and formula are similar to Pearson's correlation coefficient, which is omitted from this discussion.

3.2.2 Regression analysis methods

There are generally four stages in the regression calculation.

Determine the dependent and independent variables: in the equation, Y is the dependent variable, X is the independent variable, and bi is the adjustment coefficient, ε is the tolerance (Nick et al., 2005).

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 \ldots + b_nX_n + \varepsilon \tag{3}$$

Covariance diagnosis: When more variables are considered, some of the independent variables will have similar explanatory information for the dependent variable, leading to the problem of covariance encountered in multi-factor integrated analysis. It is therefore possible to eliminate unfavorable variables using the variance inflation factor (VIF), which is most effective when VIF <5, and VIF >10 when there is a serious issue of covariance. In this model, (1-R^2) represents the tolerance, and Ri represents the negative correlation coefficient of the independent variable Xi for all other variables in the model.

$$VIF = \frac{1}{1 - R_i^2} \tag{4}$$

By performing regression calculations, the most appropriate combination of variables can be determined as well as the number of key variables, which should be selected as small as possible. In general, SPSS software allows multiple optimal subsets to be derived (the number is determined by the user). The higher the adjusted R^2 value, the better the fit of the optimal subset equation. Where R_a^2 is the adjusted R^2, RSS is the sum of squared residuals after regression, and TSS is the intrinsic variance before regression.

$$R_a^2 = 1 - \frac{(1 - R^2)(n - 1)}{n - p - 1}, R^2 = 1 - \frac{RSS}{TSS} \tag{5}$$

The importance of each independent variable in the equation is ranked and the respective contribution share is determined based on the results of the regression equation for the optimal subset.

4 Results

4.1 Analysis of the correlation between human settlement construction and ecological environment

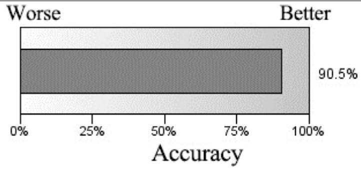
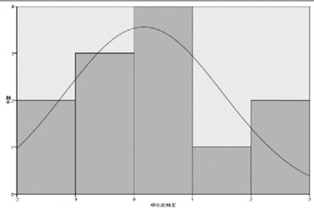
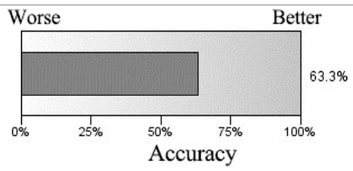
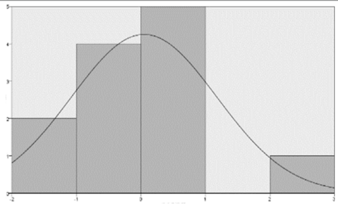
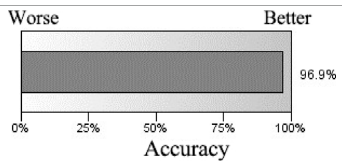
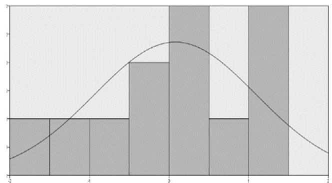
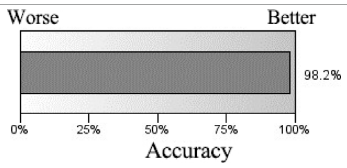
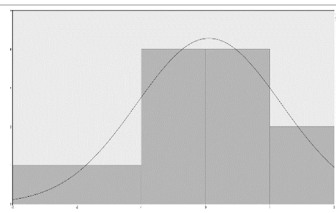
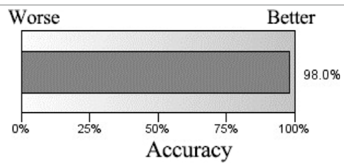
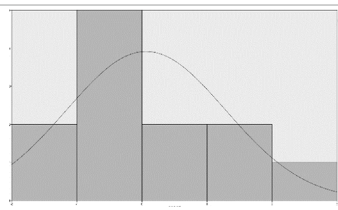
4.1.1 Analysis of variance in the explanatory variables themselves

The analysis of the variance of the explanatory variables with the help of the deviation coefficient (σ), using $\sigma \geq 0.3$ as the threshold value of the significant variables, results in 17 additional significant explanatory variables (Table 2). These include A1, A2, A4, A6, A17, A18, A19, A20, A21 in the category of human settlement construction. In addition, B2, B4, B6, B7, B9, B10, B11, B12 in the ecological environment category. Based on the overall results, "A1 - regional GDP *per capita*" and "A17 - population density" are most prominent, with $\sigma > 0.35$.

4.1.2 Pearson correlation analysis

In order to determine the preliminary screening results of the explanatory variables, the Pearson correlation matrix should be analyzed (Table 3). In this paper, when the correlation coefficient is greater than or equal to 0.6, it is considered a "significant coefficient", and when there are more than 10 significant coefficients for a single explanatory variable, it passes the initial screening condition and is considered a "significant variable". Table 3 summarizes the 20 explanatory variables that meet the conditions. A3, A5, A7, A9, A13, A14, A16, A17, A18, A19, A20, A22, and A23 are human settlement construction categories. The ecological environment construction categories are B1, B3, B5, B6, B7, B8, B12. Among the most significant variables are the total population, population density, *per capita* construction land, unit area runoff, grassland patch coverage, and the proportion of areas with suitable altitude. This shows that population plays an imperative role in the driving mechanism that is clearly influenced by the ecological environment.

TABLE 7 Optimized output model and optimal subset regression equation.

Dependent variable	Output model	Accuracy (R^2)	Residual histogram
A3	A3~ A19 + A21 + B5+B12		
A6	A6~A7+A19		
A17	A17~B2+B3+B12		
A18	A18~A7+B3+B5+B12		
A20	A20~A7+B3+B5+B12		

4.1.3 Spearman correlation analysis

Spearman correlation coefficients are calculated and screened in the same manner as Pearson correlation coefficients (Table 4). Accordingly, 14 significant variables have been screened out: the categories of human settlement construction include A3, A6, A7, A17, A18, A19, A21, the ecological environment category, B7, B8, B12, B12, B12. It is more significant, and it can be seen that it is related to "human settlement ecology."

4.1.4 Analysis of the distribution characteristics of different significant variables in each county

A study of the differential representation between indicators is conducted in order to clarify the current status of each variable in the county. We compare the results of counties in the upper reaches of the Minjiang River with those of the variable areas, including Songpan (U1), Maoxian (U2), Wenchuan (U3), Heishhui (U4), Lixian (U5), Jiuzhaigou (U6), Hongyuan (U7), Xiaojin (U8), Ruoergai (U9), Maerkang (U10), Dujiangyan (U11), Qingchengshan (U12).

The significant difference in water area *per capita* (A2) is primarily reflected in Hongyuan County and Ruoergai County. Based on the source data, it appears that the difference in the proportion of water area between the two counties is not obvious. As a result, this variable can also be explained by the fact that the populations of the two counties are clearly low. In Songpan County, Hongyuan County, and Ruoergai County, the value of forest patch coverage (A4) is evidently low. Taking into account the previous analysis, the altitude of these areas is relatively high, which makes it difficult for forests to grow; Shenxian County has a low proportion of forest land. Preliminarily, it can be concluded that the intensity of human settlements is related to the previous data. Temperature and humidity index (A6, A7): The change trend of temperature and humidity index is comparable to that

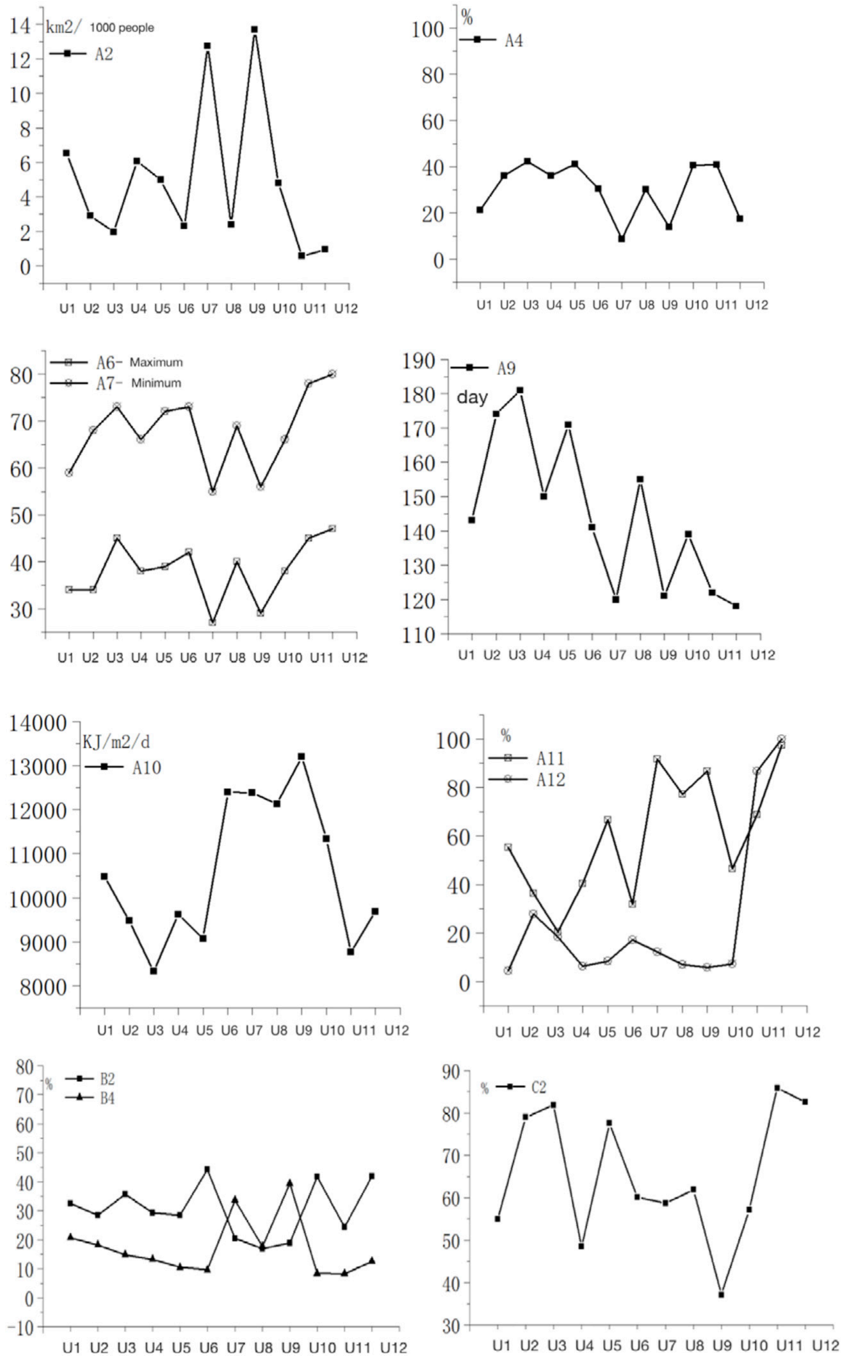


FIGURE 4
(Continued)

of forest patch coverage, with the exception of Qingshen County, where temperature and humidity will increase as a consequence of its low latitude and heavy rainfall. The number of rainy days is relatively high in the upper reaches of the Minjiang River, but as can be seen from the previous variable, the number of rainy days does not explain the real situation of rainfall in this area.

Sunlight intensity (A10): The sunshine intensity is obviously higher in the radiated areas of the upper reaches of the Minjiang River, and most of these areas are within the plateau zone. As with the change pattern of sunshine intensity, this variable reflects the proportion of plots with a suitable slope (A11). However, there are large basins, plains, or hilly terrain in the middle reaches of the Minjiang River, and the slope is relatively gentle. Suitable altitude (A12) refers to areas with lower altitudes, since these areas are more suitable for human settlements. The figure indicates that this parameter is generally low in the upper reaches of the Minjiang River, while it has improved significantly in the middle reaches. This indicates that the Minjiang River's upper reaches have a

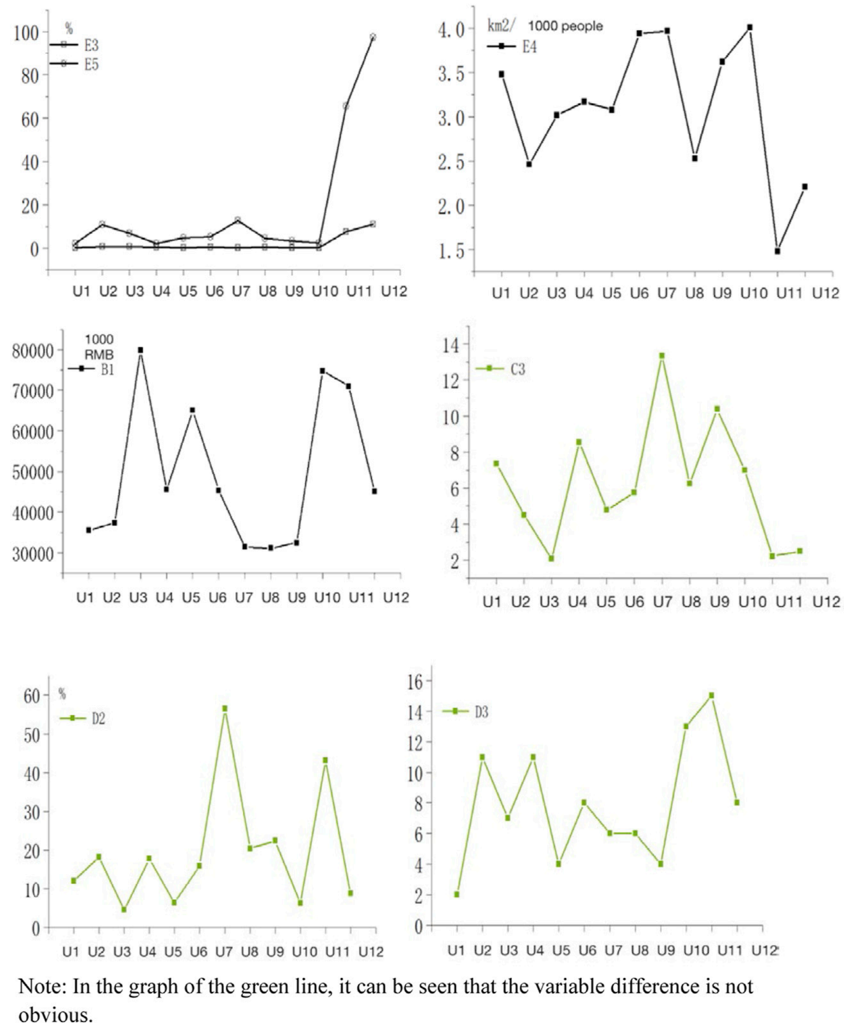


FIGURE 4
The distribution of each significant variable in the county.,

higher elevation than its middle reaches. Regional *per capita* GDP (B1): Some counties in the upper reaches of the Minjiang River have low *per capita* GDP, but Wenchuan County and Li County have significantly higher *per capita* GDPs than other counties. There is no significant geographical preference for the proportion of employees in secondary and tertiary industries (B2), although there are significant differences among counties in this variable; Hongyuan County, Xiaojin County, and Ruoergai County have the lowest parameter values among them. In the upper reaches of the Minjiang River, the primary industry represents a relatively high proportion of output value (B4), particularly in Hongyuan County and Ruoergai County; however, it is less apparent in the middle reaches of the Minjiang River.

As can be seen from the figure, the Road Network Effective Service Index (C2) in Heishui County and Zoige County is low, while the values in Mao County, Wenchuan County, Li County, and the middle reaches of the Minjiang River are relatively high. The Bridge Service Index (C3) is generally higher in the upper reaches of the Minjiang River (except in Wenchuan), that is, the average distance between two bridges is larger, which indicates that the distance between two bridges in this basin is relatively long. The differential screening did not reveal any significant differences between the cultural and tourism landscapes. A study of two variables with relatively large differences was conducted in order to gain a better understanding of the phenomenon. Eco-tourism patch coverage (D2): Although this parameter varies greatly, it does not indicate a clear preference regarding the research area; Hongyuan County and Dujiangyan City appear to be the most prominent. The total number of cultural attractions (D3) is relatively low in the radiation area of the upper reaches of the Minjiang River. According to the previous data, this area is mainly characterized by ecological and natural landscapes. Although there is a significant difference in population density (E2), it is primarily reflected in the differences between the upper and middle reaches of the Minjiang River; while for the upper reaches, there is no obvious difference.

There is a similar pattern of change in the proportion of construction land (E3) and suitable construction area (E5), indicating that these two variables are closely related to population density. As can be seen from the figure, even though the algorithm for calculating the proportion of suitable construction areas is relatively objective, its potential impact on population density and the scope of human settlements can be seen. Construction land *per capita* (E4) is

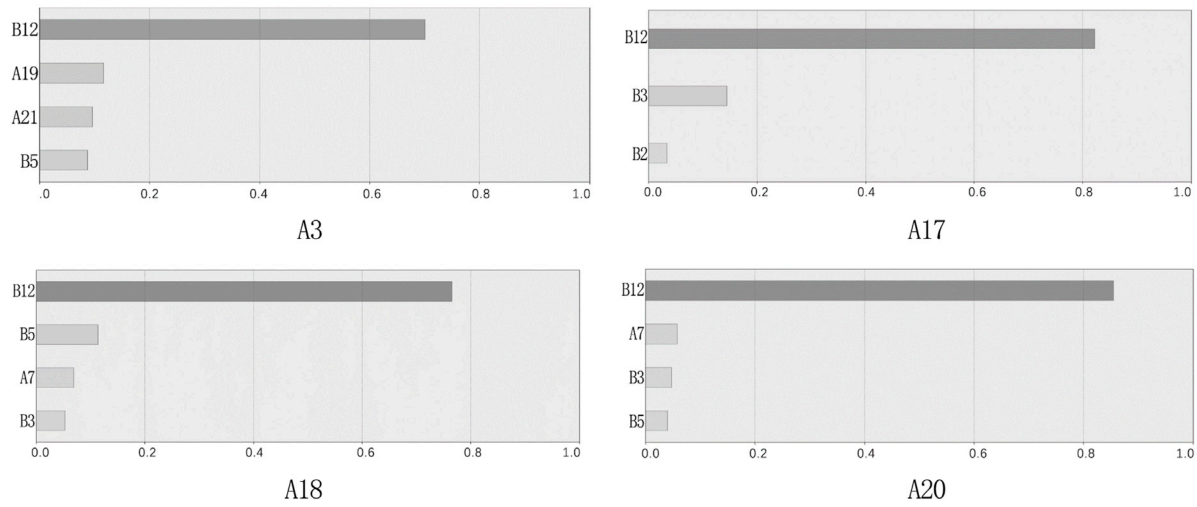


FIGURE 5
The independent effects of explanatory variables.

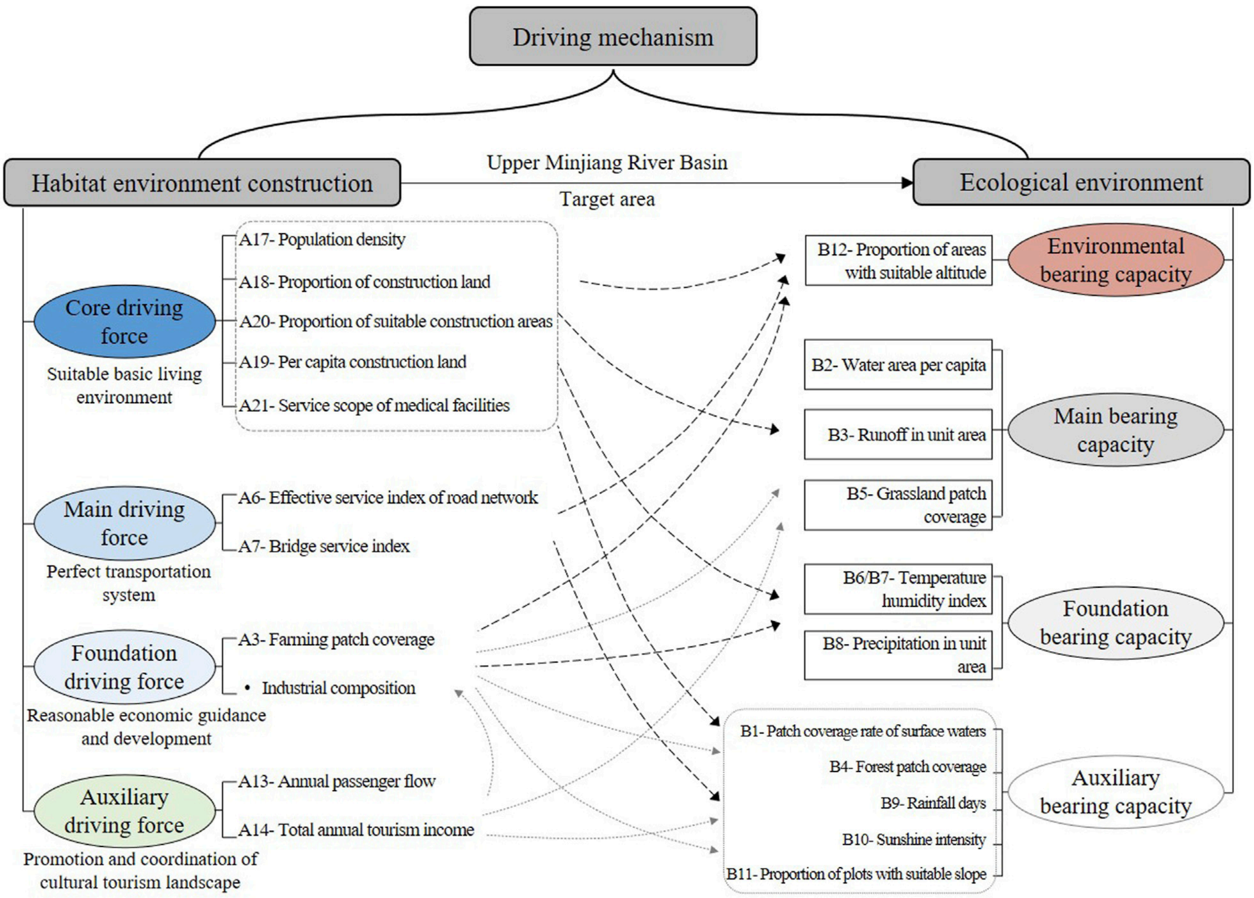


FIGURE 6
"Habitat-ecology" driving mechanism model.

significantly higher in the upper reaches of the Minjiang River, which also indicates that the intensity of construction and human activities is relatively low in this area, and urbanization is not as good as in the middle reaches. Accessibility to medical facilities and service coverage (E6): This parameter is significantly lower in the upper reaches of the Minjiang River, and the higher value of Malkang City can be attributed to its status as a county-level city; it may reflect medical care in a certain way in the upper reaches of the river. Low infrastructure configurations are present. As a result of the above analysis, it is evident that some differentiated variables exist objectively, some are artificially produced, and some are caused as a result of these objective variables.

4.2 The regression model of human settlement construction and the ecological environment

4.2.1 The determination of independent and dependent variables

The three calculation methods have been applied to obtain their respective significant variables. This paper refers to significant variables with occurrence times ≥2 as "characteristic variables" (Table 5). The following text uses these Features variables as independent variables. Table 5 shows that there are 14 characteristic variables, which are A3, A6, A7, A17, A18, A19, A20, A21, B2, B3, B5, B6, B8, B12.

In this study, the dependent variable is chosen from the characteristic variables. The construction of human settlements is the main focus, so the dependent variable is selected from the categories of human settlements. The following eight feature variables are included in this category: A3, A6, A7, A17, A18, A19, A20, and A21. Further, A6 and A7 have overlapping definitions, and the latter is generally incorporated in the former, so A7 is omitted. It is possible to calculate A19 from A17, A18 and A19, so there will be some repetition in the analysis. Therefore, we do not include A19 in the analysis. In the following regression analysis, A21 cannot calculate the optimal equation model, so it is not considered. To sum up, A3, A6, A17, A18 and A20 were selected as dependent variables.

4.2.2 Collinearity diagnosis

A variance expansion coefficient greater than 10 indicates that the variance ratios meet the requirements when optimizing the variable combination using collinearity diagnosis. Even though the VIF is greater than 5, a small number of variables are retained at this time. To facilitate Modeling, the dependent variables will not be further eliminated. With the condition of flexible screening, there are two conditions for passing the collinearity diagnostic screening: "VIF<10″and "variance ratio<0.9". Based on the results of the collinearity diagnosis, the independent variables of A7, A19, A21, B2, B3, B5, and B12 performed relatively well (Table 6).

4.2.3 Regression equation analysis of optimal subsets

As a result of performing optimal subset regression, the optimal output model can be derived for each dependent variable. "Accuracy (R^2)" and "Residual Histogram" are used to evaluate whether the fitting result is satisfactory. The accuracy of the model reaches 70% (that is, the R^2 has been adjusted to a value of over 0.7) and the residual histogram fits well with the histogram, suggesting that the model is well fitted. According to the output results (Table 7), the optimal subset regression equations for the dependent variables A3, A17, A18, and A20 fit well, while the model for the A6 variable fits poorly. Therefore, the optimal subset regression equations are A3*A19 + A21 + B5+B12, A17*B2+B3+B12, A18*A7+B3+B5+B12 and A20*A7+B3+B5+B12.

5 Discussion

Due to the fact that many studies have been conducted on the upper reaches of the Minjiang River, the conclusions of this study are similar to those of other scholars. For example, the measured changes and fluctuations of the "grassland" element in human activities are relatively large (Hu et al., 2007). Also, a wealth of documents pay more attention to the methods of data collection, rather than identifying the categories of usage for urban development (Tahir et al., 2021). As a result, no systematic index structure has been formed for the relevant spatial and material elements in the watershed environment. Several Chinese scholars have already paid attention to the development of the upper reaches of the Minjiang River 10 years ago (Zhao, 2009; Zhao, 2018). At that time, however, due to the lack of technology and the limited scope of research, many problems emerged in the implementation of the conclusions, including the overexploitation of the environment, the disordered road structure, and scattered villages. With the assistance of current research ideas and technologies, we believe we should begin to review and examine the changes in the upper reaches of the Minjiang River. Therefore, we extracted and utilized variables again. It should be noted, however, that the specific research obtained in this paper is more diverse than any other literature. This is because there are differences in research directions, ideas, and sample areas. In addition, there is a more extensive level of exploration of indicators, as well as the systematic integration of various explanatory variables in the upper reaches of the Minjiang River.

Chinese scholars are increasingly focusing more on the exploration of similar cases, such as establishing the element construction mechanism of the watershed environment from a single perspective (Guo et al., 2013; Li et al., 2016). Investigate the changing principles of social activity and ecological adaptability based on the construction of human settlements. It is interesting to note that in the related studies of watersheds, the exploration of adaptation reveals more in-depth conclusions. The potential for urbanization in a watershed can be determined, for example, by surveying the suitability of land development. The construction of large-scale villages in the vicinity of small watersheds (Mao, 2019). Watershed boundary and town size development relationship (Zhang et al., 2017). In light of the fact that the purpose of this study of variables and influencing mechanisms involves the combination of other disciplines, it can be seen that the results of the study will be enhanced when the research purpose of the watershed involves combining other disciplines. The systematic establishment of the impact mechanism structure can provide insight into the development relationships of elements, which can serve as a foundation for further research in this area. As a result of examining multiple elements and exploring the relationships between them, this article establishes 35 variable systems, which cover all aspects of human settlements and the environment. In the human settlement environment, it has been determined that "population density" and "proportion of construction land" are more prominent, and the former has 17 highly correlated variables, while the latter can reach 15; and among the eco-environmental factors, the factors that are relatively prominent include "*per capita* water area", "unit area runoff", "grassland patch coverage", and "proportion of areas suited to altitude".

5.1 Upper Minjiang River basin is primarily driven by elevation

As can be seen in the above optimal subset regression equation, each dependent variable is composed of a number of independent

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variables. The "contribution rate" represents the degree to which independent variables influence the dependent variable. The greater the significance of the independent variable, the larger and more obvious the contribution rate will be. According to the results (Figure 4), the contribution rate of B12 is the highest, exceeding 70% regardless of which model is used. Therefore, the altitude factor can have significant effects on the "human settlement-ecology" relationship in the upper reaches of the Minjiang watershed. It is worth noting that other variables with a higher contribution rate are B3, B5 and A7, in addition to the three variables A19, A21 and B2. These variables, although their contribution rates are small, can still produce better interactions than other explanatory variables.

5.2 The driving mechanism model of human settlements construction and ecological environment

Based on the previous data calculation results, the interaction force between the explanatory variables has been calculated. On the basis of the data results, and referring to the characteristics of the upper reaches of the Minjiang watershed, the relationship between "human settlement construction and ecological environment driving mechanism" can be analyzed as follows: The human settlement environment acts on the construction of the ecological environment, and when the ecological environment bears the excessive "load" of the construction of human settlements, it reacts to the human settlement environment. The following is a detailed analysis of the human settlement environment as the driving force and the ecological environment as the carrying capacity (Figure 5).

(1) In light of the above data analysis, it is evident that population density, construction land, and medical facility service scope are the most significant driving forces in the model of the driving mechanism. Therefore, these factors constitute the primary driving force. A major driving force is the distribution of the road network and the construction of bridges. Furthermore, there are factors such as farm patch coverage and industrial composition ratio, which are considered to be basic driving factors. However, the Pearson correlation coefficient indicates that annual passenger flow and tourism revenue perform better, so they are considered as auxiliary driving factors.

(2) An analysis of the carrying capacity-ecological environment has shown that the factor of "proportion of suitable altitude areas" has a strong independent significance, which is the basis for this paper's study of the driving mechanism model. Furthermore, ecological environment variables such as *per capita* water surface, runoff per unit area, and grassland patch coverage have also been included in the optimal equation model, indicating that they will undergo obvious changes due to human settlement construction; as a result, they will serve as the main carrying capacity. Moreover, the temperature-humidity index and unit area precipitation that have passed the correlation test can also be used as basic carrying capacities. Although to some extent, the five variables in the ecological environment, surface water patch coverage, woodland patch coverage, rainfall days, sunlight intensity, and proportion of suitable slopes, failed the correlation test, they remained significant to some extent. Consequently, they can be viewed as an auxiliary carrying capacity in this mechanism model, since they are influenced by the development of human settlements. Figure 6

6 Conclusion

Human settlements and ecology in the upper reaches of the Minjiang watershed are influenced by factors such as altitude, population, and construction land. Altitude has a strong impact on agricultural land, population density, construction land, the traffic network, and precipitation. Population density primarily relates to water distribution, altitude, precipitation, agricultural land, and construction land. The state of construction land will have potential impacts on traffic, vegetation distribution, and runoff.

In the upper reaches of the Minjiang watershed, the "human settlement-ecology" driving mechanism is influenced by a combination of factors. Several key elements are involved in this mechanism, such as altitude, population, construction land, etc. In contrast, each element has its own combination of influences. In the case of "construction land", its combination of influence factors is "bridge traffic + runoff + grassland distribution + altitude".

It is of great importance for urbanization and development in the context of watersheds to study how elements interact with the ecological environment. At present, China's urbanization is undergoing rapid growth, and it has transitioned from a spatially diffuse to a highly intensive development model. Considering the ecological environment, the construction concept of sustainability, environmental protection, and living balance is highlighted. In contrast to plain areas, watershed areas are still in the early stages of urbanization due to the influence of mountain altitudes and extreme weather conditions. In recent decades, a number of scholars have continuously explored how to conduct urban planning and design in such areas, achieving impressive results in the process. However, as a result of the constant changes in policies and the evolution of population needs, relevant research has been constantly re-examining the *status quo* of the watershed, particularly in regard to environmental variables. However, the mechanism of action and the corresponding model between the elements have not been systematically constructed. Therefore, in addition to constructing the index system and researching the driving mechanism based on the current situation, the research in this paper also proposes the extraction path of urban elements and variables within the research basin to provide a reference for future studies in this area.

7 The limitation of study

It is emphasized in this paper that variables are extracted and relationships are explored between material and spatial elements. There has, however, been no effective interpretation of the interaction between human activities within the watershed and the related cities. There is no doubt that we have not studied the environmental impacts of population growth and decline and whether there are corresponding countermeasures. As a result, in future research, more dynamic research strategies will be proposed. Moreover, this study has not yet proposed the model for urban design based on the findings of this study, but only focuses on the driving relationship between the various elements. In the future, a follow-up study will be conducted.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material further inquiries can be directed to the corresponding author.

Author contributions

BL: Conceptualization, Methodology, Validation, Writing—original draft, Writing—Editing, Investigation, Data curation, Funding acquisition. ZW: Conceptualization, Methodology, Validation, Data curation. JH: Validation, Data curation, Investigation. JW: Data curation, Investigation. JS: Supervisor.

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Conflict of interest

Author JW was employed by the Da Sheng Assert management group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The manufacturers' strategy selection of carbon emission reduction and pricing under carbon trading policy and consumer environmental awareness

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Carbon trading policy and consumer environmental awareness are increasingly important to manufacturers' carbon emission reduction and pricing. To analyze their strategy selection of carbon emission reduction and pricing, this paper develops three game models, where two manufacturers could choose no cooperation (NC), only cooperation in carbon emission reduction (SC), or simultaneous cooperation in carbon emission reduction and pricing (CC). By solving these models and comparing their environmental R&D levels, net carbon emissions, and profits, the paper finds strategy selection for manufacturers and its conditions. Results show that from the view of the environmental R&D level and supply chain's profit, NC and SC may be the optimal strategy and the second-best strategy, respectively. From the net carbon emission point of view, CC and SC should be the optimal strategy and the second-best strategy, respectively. As to manufacturers' profits, CC should be the optimal strategy, and NC or SC should be the second-best strategy. From comprehensive views, none of these strategies could be the optimal strategy, but SC may be the second-best strategy. This paper contributes in three aspects. First, this paper designs three strategies of carbon emission reduction and pricing for two manufacturers. Second, this paper takes the initial carbon emission allowances of the government as one of decision variables. Finally, this paper investigates the effects of different strategies and finds strategy selections for manufacturers from a single view and comprehensive views.

KEYWORDS

carbon trading policy, consumer environmental awareness, carbon emission reduction, pricing, cooperation

1 Introduction

Environmental damage caused by carbon emission has been one of the most important issues globally, and how to reduce carbon emission has drawn much attention. In recent years, the digital economy has shown a significant spatial effect on carbon emission reduction (Yi et al., 2022; Li and Wang, 2022). However, carbon tax policy (CT) and carbon trading policy (CET) have been more widely put into practice to curb carbon emissions. However, with advantages in the effect and cost of carbon emission reduction, CET is more attractive to many countries (Wang and Wang, 2015) and can increase the potential of firms to reduce carbon emissions (Chu et al., 2021). In practice, the EU, the United States, Australia, and some other developed economies have implemented carbon trading policy. As a developing country, China has been putting great emphasis on the environment issue in recent years and has made a promise to peak its carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. In practice, China is already taking strong nationwide actions toward the carbon peak and carbon neutrality targets. China' national carbon emission trading market is a good example. As of the start of 2022, there are 25 operational emission trading systems around the world, in jurisdictions representing 55% of global GDP and covering 17% of global emissions[1]. In addition, many countries continue to strengthen the concept of environmental conservation and gradually integrate the requirements of low carbon into consumers' daily life, and some consumers with strong environmental awareness may pay higher prices for low-carbon products (Chitra, 2007; Yalabik and Fairchild, 2011) and induce firms to design corporate resource allocation (Su et al., 2023) and produce low-carbon products (Basiri and Heydari, 2017). Under these backgrounds, firms should invest more in environmental R&D, and some strong firms produced many lower-emission products. For example, companies in the fashion apparel industry such as H&M and Levi's have adopted cleaner technologies to generate less carbon emissions during their production (Li and Li, 2014), and consumers with strong environmental awareness were willing to pay an average premium of 33% for green goods[2]. However, since firms non-cooperatively investing in environmental R&D will bring additional cost pressure on themselves, some of them choose to cooperate with their rivals. For example, the truck units of Toyota Motor and Volkswagen AG are forming an alliance to develop lower-emission vehicles and can spend R&D money only once instead of twice or thrice than they would when alone[3].

To summarize, it is profound for manufacturers to rethink the strategy of carbon emission reduction and pricing when they are faced with CET and consumer environmental awareness (CEA). Though previous researchers studied carbon emission reduction under CET, carbon emission reduction under CEA, and carbon emission reduction under CET and CEA, most of them considered the cooperation between the manufacturer and the retailer in the same supply chain. Taking these backgrounds into account, we consider two two-echelon supply chains consisting of two manufacturers and a common retailer, where manufacturers make decisions on environmental R&D levels and wholesale prices of products and the retailer makes a decision on retail prices of products. Then, we provide three strategies of carbon emission reduction and pricing for manufacturers including no cooperation (NC), only cooperation in carbon emission reduction (SC), and simultaneous cooperation in carbon emission reduction and pricing (CC), meaning that manufacturers make all their decisions non-cooperatively, make their decisions on environmental R&D levels cooperatively and on wholesale prices non-cooperatively, and make all their decisions cooperatively, respectively. Questions of interest in this paper are as follows: 1) what effects do the three strategies of carbon emission reduction and pricing have on the carbon emission level, net carbon emission, and profit? 2) from a single view, which strategy should be chosen by manufacturers? 3) from comprehensive views, which strategy should be chosen by manufacturers?

1 https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-2022-icap-status-report.

2 http://i.aliresearch.com/file/20160803/20160803103534.pdf

3 https://www.reuters.com/article/hino-motors-volkswagen-idINL3N1RP32F

To answer these questions, we develop three four-staged game models of the two supply chains faced with the CET and CEA from the perspective of game theory. Then, based on the equilibriums of these models, we compare the carbon emission level, net carbon emission, and profits of manufacturers and the supply chain and find the optimal strategy and the second-best strategy for manufacturers from a single view. Finally, we make a comprehensive comparison and find the second-best strategy for manufacturers and its condition from comprehensive views. Through this research, we can analyze effects of different strategies and find strategy selection from different views for manufacturers and provide a scientific basis for supply chain management and related policy improvement.

The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 describes model formulation and notation. Section 4 presents the three game models. Section 5 provides the results and discussion. Section 6 concludes this paper.

2 Literature review

2.1 Carbon emission reduction under CET

Some researchers only took manufacturers as an objective. Wang et al. (2018) divided manufacturers into under-emitter manufacturers and over-emitter manufacturers and found conditions under which the over-emitter manufacturers' decisions were identified. Given carbon emission reduction, Xia et al. (2020) divided manufacturers into low-carbon manufacturers and ordinary product manufacturers and analyzed impacts of the CET on retail prices, sales, and profits. Other researchers took the supply chain consisting of a manufacturer and a retailer as the objective. Wang et al. (2016) designed a wholesale price premium contract and a cost-sharing contract and found that these two contracts could increase the manufacturer's carbon emission reduction rate and the supply chain's profit; the cost-sharing contract could increase profits of both the manufacturer and the retailer, and the wholesale price premium contract could increase the profit of the supply chain. Yang et al. (2018) analyzed the effects of the manufacturer's promotion and the retailer's promotion through the manufacturer's channel and a retail channel. However, all these researchers only took CET into account and neglected CEA.

2.2 Carbon emission reduction under CEA

CEA could prompt the supply chain to provide green products (Zhang et al., 2020) and always benefit the manufacturer (Li et al., 2021). Under the three structures, Liu et al. (2012) constructed three models where the manufacturer (manufacturers) decided carbon emission reduction and wholesale prices and the retailer (retailers) decided the retail prices of products separately and analyzed the impacts of CEA on the supply chain players. In a supply chain compromised of a manufacturer and a retailer, Du et al. (2015) found that compared to the wholesale-price contract, both the revenue-sharing contract and the quantity-discount contract could increase the supply chain's profit, and the carbon emission reductions in the decentralized supply chain could be the same as those in the centralized supply chain. Zhang et al. (2019) found that retailer's fairness concerns would not change the carbon emission reduction but could influence the wholesale price and retail price. Liu and Li (2020)

TABLE 1 Meaning of parameters, variables, and functions.

Note	Meaning
q_m	Production of the manufacturer m
ω_m	Wholesale price of a product sold by the manufacturer m to the retailer R who sells the product to consumers with a retail price
p_m	Retail price of a product produced by the manufacturer m and sold by the retailer to consumers
x_m	Environmental R&D level for the manufacturer m
e_m	Net carbon emission of the manufacturer m
β	Environmental R&D spillover rate
D	Environmental damage caused by carbon emission
CS	Consumer surplus
$\bar{e}_m$	Government's free allocation of carbon allowance for the manufacturer m
p_e	Clear price of a carbon allowance in the carbon trading market
θ	Sensitive parameter to measure consumers' environmental awareness
π_i	Profit of a firm $i\,(i = m, r)$
W	Welfare of the government

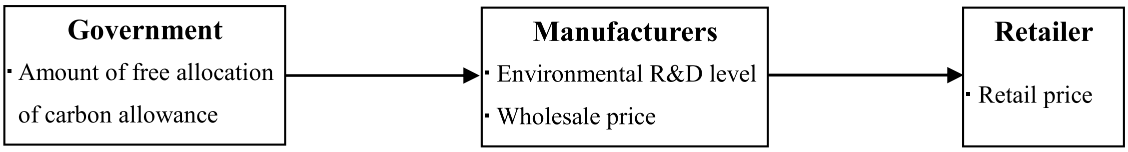

FIGURE 1
Game rules for each carbon emission reduction and pricing strategy.

found that the introduction of CEA could increase the carbon emission reduction of the supply chain, both the carbon emission reduction and profit of the supply chain in the centralized scenario are higher than those in the decentralized scenario, and the bilateral cost-sharing contract could effectively encourage the manufacturer and the retailer to engage in carbon emission reduction. Wang et al. (2021) found that both carbon emission reduction and production in the centralized model are much higher than those in the decentralized model. However, all these researchers only took CEA into account and neglected CET. Xia et al. (2022) found that either with or without a cost-sharing contract, the carbon emission reduction in the decentralized scenario was no more than that in the centralized scenario.

2.3 Carbon emission reduction under CET and CEA

Luo et al. (2016) considered two manufacturers with different carbon reduction efficiencies and constructed two models where manufacturers made decisions cooperatively or non-cooperatively. They found that manufacturers who made decisions cooperatively could increase profit and decrease total carbon emissions. However, they neglected the cooperation in pricing. Cao et al. (2017) analyzed the impacts of CET on the production and carbon emission reduction level of the manufacturer.

In the supply chain consisting of a manufacturer and a retailer, Xia et al. (2018) considered that the manufacturer decided the emission reduction rate and the retailer decided the promotion level and investigated their optimal decisions and profits. Wang et al. (2020) designed several contracts and found that the one-way cost-sharing contract was beneficial for the supply chain, the two-way cost-sharing contract could also achieve this effect if the sharing rate is small, and the joint carbon-emission reduction could be an optimal choice for the supply chain. Liu et al. (2021) provided three carbon emission reduction modes and found that the carbon emission reduction level was the highest in the joint carbon emission reduction, and firms would prefer the single carbon emission reduction or the joint carbon emission reduction under different conditions. However, these studies analyzed the interaction between the manufacturer and the retailer and were not able to investigate the cooperation between manufacturers.

In the two two-echelon supply chains, each of which consists of a manufacturer and a retailer, Yang et al. (2017) found that compared to the structure in which both chains were decentralized, vertical cooperation could increase carbon emission reduction but decrease retail prices and horizontal cooperation could damage retailers' profit. In the supply chain consisting of a supplier and a manufacturer, Bai et al. (2018) found that compared to the decentralized scenario, the centralized decision scenario could increase the supply chain's profit and decrease its carbon emission. However, these studies neglected the cooperation in pricing and took initial carbon emission allowances of the government and the price of carbon emission trading as given.

Our key contributions lie in the following aspects. First, this paper designs three strategies of carbon emission reduction and pricing for two manufacturers, which can be better to describe the operation practice. Second, this paper takes the initial carbon emission allowances of the government as one of decision variables, which can extend the existing game models to four-staged ones. Finally, this paper investigates the effects of different strategies and finds strategy selections for manufacturers from a single view and comprehensive views, which contributes to explaining various strategies between manufacturers.

3 Model formulation and notation

This paper considers two two-echelon supply chains consisting of two manufacturers producing a homogeneous product and a common retailer. The production of the manufacturer $m\,(m = 1, 2)$ is q_m and is sold to the retailer R with a wholesale price ω_m; then, the retailer R sells the product to consumers with a retail price p_m. During the production, the production of a one-unit product produces one-unit carbon emission. Under CET and CEA, the manufacturer invests in environmental R&D to reduce carbon emission. For carbon emission reduction and pricing, the manufacturer m can choose NC, SC, or CC. In each carbon emission reduction and pricing strategy, the government and members in the two supply chains play a four-staged game, which is shown in Figure 1. At the first stage, the government decides the amount of free allocation of carbon allowance for each manufacturer. At the second stage, each manufacturer decides the environmental R&D level. At the third stage, each manufacturer decides the wholesale price. At the last stage, the retailer decides the retailer price. The meaning of parameters, variables, and functions in this paper is given in Table 1.

3.1 The cost structure

For simplicity, the marginal production cost of each manufacturer is neglected. To reduce carbon emission, the manufacturer m can invest in environmental R&D. The cost of environmental R&D for manufacturer m is $C_m = x_m^2/2$ (Bai et al., 2018), where x_m is the environmental R&D level of manufacturer m. Then, net carbon emission of manufacturer m is $e_m = q_m - x_m - \beta x_n$, $m, n = 1, 2$, $m \neq n$, where $\beta\,(0 < \beta < 1)$ is the environmental R&D spillover rate.

3.2 The demand function

Based on Katsoulacos et al. (2001), consumer surplus is $CS = (q_m + q_n)^2/2$, and we introduce a sensitive parameter $\theta\,(0 < \theta < 1)$ to measure consumers' environmental awareness, and the product is sold to consumers at a retail price $p_m = 1 - q_m - q_n - \theta e_m$. Then, consumers' demand function can be obtained as follows:

$$q_m = [\theta - (1+\theta)p_m + p_n + \theta(1+\theta)(x_m + \beta x_n) - \theta(\beta x_m + x_n)]/[\theta(2+\theta)]. \tag{1}$$

3.3 The CET

Carbon emission damages the environment, and environmental damage caused by carbon emission is $D = (e_m + e_n)^2/2$ (Poyago-Theotoky, 2007). The government's free allocation of carbon allowance for the manufacturer m is $\bar{e}_m$. The manufacturer m needs to buy additional allowance from the carbon trading market if $e_m > \bar{e}_m$; otherwise, the manufacturer m can sell additional allowance on the carbon trading market, and the clear price of carbon allowance in the carbon trading market is p_e.

Therefore, profit functions of the retailer and the manufacturer m are shown as follows:

$$\pi_r = (p_m - \omega_m)q_m + (p_n - \omega_n)q_n, \tag{2}$$

$$\pi_m = \omega_m q_m - x_m^2/2 - p_e(e_m - \bar{e}_m). \tag{3}$$

The welfare function of the government is $W = \pi_m + \pi_n + \pi_r + CS - D$, which is as follows after arranging:

$$W = p_m q_m + p_n q_n + (q_m + q_n)^2/2 - (x_m^2 + x_n^2)/2 - (e_m + e_n)^2/2. \tag{4}$$

4 Model solutions

With backward induction, we obtain solutions for the aforementioned models.

4.1 Model solutions for NC

In the last stage, the retailer determines retail prices to maximize its profit. Substituting (1) in (2), the problem of optimal retail prices can be described as follows:

$$\begin{aligned}\max_{p_m, p_n} \pi_r = &\{(p_m - \omega_m)[\theta - (1+\theta)p_m + p_n + \theta(1+\theta)(x_m + \beta x_n) - \theta(\beta x_m + x_n)] \\ &+ (p_n - \omega_n)[\theta + p_m - (1+\theta)p_n + \theta(1+\theta)(\beta x_m + x_n) - \theta(x_m + \beta x_n)]\} \\ &/[\theta(2+\theta)].\end{aligned} \tag{5}$$

Combining $\partial \pi_r/\partial p_1 = 0$ and $\partial \pi_r/\partial p_2 = 0$, the optimal retail price for the product of the manufacturer m can be solved as follows:

$$p_m^* = [1 + \omega_m + \theta(x_m + \beta x_n)]/2. \tag{6}$$

Substituting (6) in (2), consumers' demand function for the product of the manufacturer m can be rewritten as follows:

$$q_m^* = \{\theta - (1+\theta)\omega_m + \omega_n + \theta[(1+\theta)(x_m + \beta x_n) - (\beta x_m + x_n)]\}/[2\theta(2+\theta)]. \tag{7}$$

In the third stage, the problem of the optimal wholesale price of the product of the manufacturer m under the NC model can be described as follows:

$$\max_{\omega_m} \pi_m = \omega_m q_m^* - x_m^2/2 - p_e(q_m^* - x_m - \beta x_n - \bar{e}_m). \tag{8}$$

Combining $\partial \pi_m/\partial \omega_m = 0$ with $\partial \pi_n/\partial \omega_n = 0$, the optimal wholesale price for the product of the manufacturer m can be solved as follows:

$$\begin{aligned}\omega_m^* = &[\theta(3+2\theta) + (1+\theta)(3+2\theta)p_e + \theta(2\theta^2 + 4\theta + 1)(x_m + \beta x_n) - \theta(1+\theta)(\beta x_m + x_n)] \\ &/[(1+2\theta)(3+2\theta)].\end{aligned} \tag{9}$$

In the second stage, the problem of the optimal environmental R&D level of the manufacturer m under the NC model can be described as follows:

$$\max_{x_m} \pi_m = \omega_m^* q_m^* - x_m^2/2 - p_e\left(q_m^* - x_m - \beta x_n - \bar{e}_m\right). \quad (10)$$

Combining $\partial\pi_m/\partial x_m = 0$ with $\partial\pi_n/\partial x_n = 0$, the optimal environmental R&D level of the manufacturer m can be solved as follows:

$$x_m^* = -\left[\theta\alpha_1\left(\alpha_2 - \beta\alpha_1\right) + \left(\alpha_3\alpha_4 + \beta\theta\alpha_1^2\right)p_e\right] \Big/ \left(\alpha_5 + \beta\theta^2\alpha_1\alpha_6\right), \quad (11)$$

where $\alpha_1 = 1 + \theta, \alpha_2 = 2\theta^2 + 4\theta + 1, \alpha_3 = 2\theta^2 + 6\theta + 3, \alpha_4 = 3\theta^2 + 6\theta + 2, \alpha_5 = 2\theta^5 - 2\theta^4 - 31\theta^3 - 53\theta^2 -31\theta - 6, \alpha_6 = 2\theta^2 + 3\theta - \alpha_1\beta\theta$. Taking into account the clear condition of the carbon trading market ($e_m - \bar{e}_m + e_n - \bar{e}_n = 0$), its clear price is solved as follows:

$$p_e^* = \{\alpha_1\left[2\theta\alpha_1\beta^2 - 2\theta^2\left(2\alpha_1 + 1\right)\beta - 4\theta^2\alpha_1 + 3\left(2\alpha_1 - 1\right)\right] + \left(\alpha_5 + \beta\theta^2\alpha_1\alpha_6\right)\left(\bar{e}_m + \bar{e}_n\right)\} \Big/ \left[2\theta\alpha_1^2\beta^2 + (2\alpha_1 + 1)\alpha_7\beta + \alpha_8\right], \quad (12)$$

where $\alpha_7 = 4\theta^3 + 19\theta^2 + 17\theta + 4, \alpha_8 = 8\theta^4 + 52\theta^3 + 99\theta^2 + 68\theta + 15$.

In the first stage, the problem of optimal allocation of carbon allowance under the NC model can be described as follows:

$$\max_{\bar{e}_1,\bar{e}_2} W = \sum_{m=1}^{2} p_m^* q_m^* + \left(\sum_{m=1}^{2} q_m^*\right)^2 \Big/ 2 - \sum_{m=1}^{2} \left(x_m^*\right)^2 \Big/ 2 - \left(\sum_{m=1}^{2} e_m^*\right)^2 \Big/ 2. \quad (13)$$

Combining $\partial W/\partial\bar{e}_1 = 0$ and $\partial W/\partial\bar{e}_2 = 0$, the optimal allocation of carbon allowance under the NC model can be solved as follows:

$$\bar{e}_m^{nc} = -\alpha_1\left(2\alpha_1 - 1\right)\left(2\alpha_1 + 1\right)\left[4\theta^2\alpha_1^2\beta^3 + 4\theta\alpha_9\beta^2 + \alpha_{10}\beta - (\alpha_1 - 2)\alpha_{11}\right] \Big/ \left(2\Delta_1\right), \quad (14)$$

where $\Delta_1 = 4\beta^4\theta^2\alpha_1^4 - 2\beta^3\theta\alpha_1^2\left(2\alpha_1 + 1\right)\alpha_{12} - \beta^2\alpha_{13} - 2\beta\alpha_{14} - \alpha_{15}, \alpha_9 = 4\theta^4 + 24\theta^3 + 41\theta^2 + 24\theta + 4, \alpha_{10} = 32\theta^5 + 180\theta^4 + 288\theta^3 + 139\theta^2 + 3\theta - 6, \alpha_{11} = 16\theta^4 + 92\theta^3 + 162\theta^2 + 103\theta + 21, \alpha_{12} = 2\theta^4 - 5\theta^3 - 37\theta^2 -34\theta - 8, \alpha_{13} = 32\theta^9 + 224\theta^8 + 156\theta^7 - 2522\theta^6 - 9281\theta^5 - 14824\theta^4 - 12731\theta^3 - 6038\theta^2 - 1476\theta - 144, \alpha_{14} = 32\theta^9 + 204\theta^8 + 24\theta^7 - 2887\theta^6 - 9921\theta^5 - 15722\theta^4 - 13700\theta^3 - 6706\theta^2 - 1722\theta - 180, \alpha_{15} = 32\theta^9 +120\theta^8 - 812\theta^7 - 6372\theta^6 - 17839\theta^5 - 26404\theta^4 - 22448\theta^3 - 10964\theta^2 - 2853\theta - 306$. Substituting 14 in 12, 11, 9, 7, and 6, the equilibrium clear price of carbon allowance (p_e^{nc}), environmental R&D level (x_m^{nc}), wholesale price (ω_m^{nc}), production (q_m^{nc}), and retail price (p_m^{nc}) under the NC model can be solved. It is easy to find that when $\beta, \theta \in (0, 1)$, $x_m^{nc} > 0, \omega_m^{nc} > 0, q_m^{nc} > 0, p_m^{nc} > 0$ will always hold, and $\mathrm{sign}(\bar{e}_m^{nc}) = \mathrm{sign}(-(4\theta^2\alpha_1^2\beta^3 + 4\theta\alpha_9\beta^2 + \alpha_{10}\beta - (\alpha_1 - 2)\alpha_{11}))$. Figure 2 shows conditions where $\bar{e}_m^{nc} = 0$, $\bar{e}_m^{nc} > 0$, and $\bar{e}_m^{nc} < 0$ can satisfy. Let $4\theta^2\alpha_1^2\beta^3 + 4\theta\alpha_9\beta^2 + \alpha_{10}\beta - (\alpha_1 - 2)\alpha_{11} = 0$, we can get the solution $\theta = g_1(\beta)$; then, we have $\bar{e}_m^{nc} = 0$. If $\theta < g_1(\beta)$, $4\theta^2\alpha_1^2\beta^3 + 4\theta\alpha_9\beta^2 + \alpha_{10}\beta - (\alpha_1 - 2)\alpha_{11} < 0$ will hold; then, $\bar{e}_m^{nc} > 0$ will hold; otherwise, $\bar{e}_m^{nc} < 0$ will hold.

4.2 Model solutions for SC

Solutions for the optimal retail price and wholesale price under the SC model are the same as those under the NC model shown in 6 and 9; then, we solve the second stage and the first stage under the SC model.

In the second stage under the SC model, manufacturers determine environmental R&D levels to maximize their joint profit $\pi_{mn} = \pi_m + \pi_n$. The problem of the optimal environmental R&D level of the manufacturer m under the SC model can be described as follows:

$$\max_{x_m,x_n} \pi_{mn} = \omega_m^* q_m^* + \omega_n^* q_n^* - \left(x_m^2 + x_n^2\right) \Big/ 2. \quad (15)$$

Combining $\partial\pi_{mn}/\partial x_m = 0$ and $\partial\pi_{mn}/\partial x_n = 0$, the optimal environmental R&D level of the manufacturer m can be solved as follows:

$$\tilde{x}_m^* = -(1 + \beta)\left[\theta^2\alpha_1 + (3\alpha_1 - 1)\delta_1 p_e\right] \Big/ \left[\beta(2 + \beta)\theta^3\alpha_1 + \delta_2\right], \quad (16)$$

where $\delta_1 = \theta^2 + 3\theta + 1, \delta_2 = \theta^4 - 3\theta^3 - 12\theta^2 - 9\theta - 2$. The clear price of carbon allowance is solved as follows:

$$\tilde{p}_e^* = -\left\{\alpha_1\left(2\theta^2\beta^2 + 4\theta^2\beta + \delta_3\right) - \left[\beta(2 + \beta)\theta^3\alpha_1 + \delta_2\right]\left(\bar{e}_m + \bar{e}_n\right)\right\} \Big/ \left(\beta^2\delta_4 + 2\beta\delta_4 + \delta_5\right), \quad (17)$$

where $\delta_3 = 2\theta^2 - 2\theta - 1, \delta_4 = 4\theta^3 + 19\theta^2 + 17\theta + 4, \delta_5 = 4\theta^3 + 21\theta^2 + 20\theta + 5$.

In the first stage, the problem of optimal allocation of carbon allowance under the SC model can be described as follows:

$$\max_{\bar{e}_1,\bar{e}_2} W = \sum_{m=1}^{2} p_m^* q_m^* + \left(\sum_{m=1}^{2} q_m^*\right)^2 \Big/ 2 - \sum_{m=1}^{2} \left(x_m^*\right)^2 \Big/ 2 - \left(\sum_{m=1}^{2} e_m^*\right)^2 \Big/ 2. \quad (18)$$

Combining $\partial\tilde{W}^*/\partial\bar{e}_1 = 0$ and $\partial\tilde{W}^*/\partial\bar{e}_2 = 0$, the optimal allocation of carbon allowance under the SC model can be solved as follows:

$$\bar{e}_m^{sc} = \alpha_1\left(2\alpha_1 - 1\right)\left[(1 + \beta)^2\theta - 1\right]\left(2\beta^2\delta_6 + 4\beta\delta_6 + \delta_7\right) \Big/ \left(2\Delta_2\right), \quad (19)$$

where $\Delta_2 = \beta^4\delta_8 + 4\beta^3\delta_8 + 2\beta^2\delta_9 + 4\beta\delta_{10} + \delta_{11}, \delta_6 = 4\theta^3 + 17\theta^2 + 14\theta + 3, \delta_7 = 8\theta^3 + 36\theta^2 + 31\theta + 7, \delta_8 = 8\theta^7 + 30\theta^6 - 69\theta^5 - 432\theta^4 - 655\theta^3 - 438\theta^2 - 136\theta - 16, \delta_9 = 24\theta^7 + 79\theta^6 - 296\theta^5 - 1550\theta^4 - 2293\theta^3 - 1525\theta^2 - 474\theta - 56, \delta_{10} = 8\theta^7 + 19\theta^6 - 158\theta^5 - 686\theta^4 - 983\theta^3 - 649\theta^2 - 202\theta - 24, \delta_{11} = 8\theta^7 + 8\theta^6 - 251\theta^5 - 960\theta^4 - 1348\theta^3 - 892\theta^2 - 281\theta - 34$. Substituting 19 in 17, 16, 9, 7, and 6, the equilibrium clear price of carbon allowance (p_e^{sc}), environmental R&D level (x_m^{sc}), wholesale price (ω_m^{sc}), production (q_m^{sc}), and retail price (p_m^{sc}) under the SC model can be solved. It is easy to find that when $\beta, \theta \in (0, 1)$, $x_m^{sc} > 0, \omega_m^{sc} > 0, q_m^{sc} > 0, p_m^{sc} > 0$ will always hold, and $\mathrm{sign}(\bar{e}_m^{sc}) = \mathrm{sign}(-((1 + \beta)^2\theta - 1))$. Figure 3 shows conditions where $\bar{e}_m^{sc} = 0$, $\bar{e}_m^{sc} > 0$, and $\bar{e}_m^{sc} < 0$ can satisfy. Let $(1 + \beta)^2\theta - 1 = 0$, we can get the solution $\theta = 1/(1 + \beta)^2 = g_2(\beta)$; then, we have $\bar{e}_m^{sc} = 0$. If $\theta < g_2(\beta)$, $(1 + \beta)^2\theta - 1 < 0$ will hold; then, $\bar{e}_m^{sc} > 0$ will hold; otherwise, $\bar{e}_m^{sc} < 0$ will hold.

4.3 Model solutions for CC

Solutions for the optimal retail price under the CC model are the same as those under the NC model, which is shown in (6); then, we solve the third stage, the second stage, and the first stage under the CC model.

In the third stage under the CC model, manufacturers determine their wholesale prices to maximize their joint profit. This problem under the CC model can be described as follows:

$$\max_{\omega_m,\omega_n} \pi_{mn} = \omega_m q_m^* + \omega_n q_n^* - \left(x_m^2 + x_n^2\right)/2. \quad (20)$$

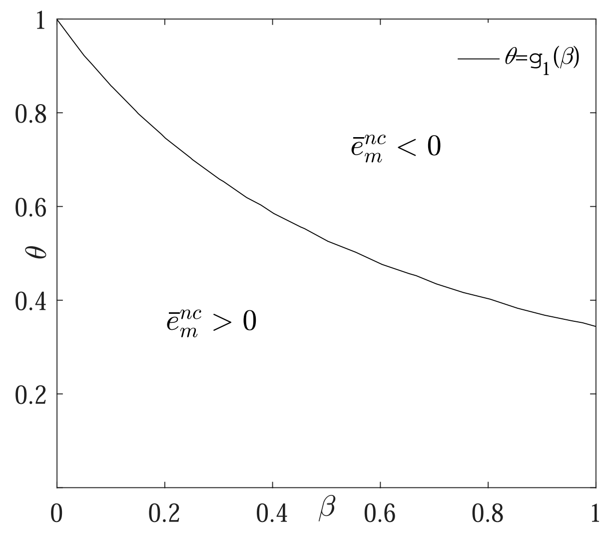

FIGURE 2
Condition for a positive solution of free allocation of carbon allowance under NC.

Combining $\partial \pi_{mn}/\partial \omega_m = 0$ and $\partial \pi_{mn}/\partial \omega_n = 0$, the optimal wholesale price of the manufacturer m can be solved as follows:

$$\tilde{\omega}_m^{**} = [1 + \theta(x_m + \beta x_n) + p_e]/2. \tag{21}$$

In the second stage under the CC model, manufacturers also determine their environmental R&D levels to maximize their joint profit. The problem of the optimal environmental R&D level of the manufacturer m under the CC model can be described as follows:

$$\max_{x_m, x_n} \pi_{mn} = \tilde{\omega}_m^{**} q_m^* + \tilde{\omega}_n^{**} q_n^* - (x_m^2 + x_n^2)/2. \tag{22}$$

Combining $\partial \pi_{mn}/\partial x_m = 0$ and $\partial \pi_{mn}/\partial x_n = 0$, the optimal environmental R&D level of the manufacturer m can be solved as follows:

$$\tilde{x}_m^{**} = -(1+\beta)[\theta + (8+3\theta)p_e] \big/ \left[\theta^2(1+\beta)^2 - 4(\alpha_1+1)\right]. \tag{23}$$

The clear price of carbon allowance is solved as follows:

$$\tilde{p}_e^{**} = -\left\{2\left[\theta(1+\beta)^2 - 1\right] - \left[\theta^2(1+\beta)^2 - 4(\alpha_1+1)\right](\bar{e}_m + \bar{e}_n)\right\} \big/ \times \left\{2\left[2(1+\beta)^2(\alpha_1+3)+1\right]\right\}. \tag{24}$$

In the first stage, the problem of optimal allocation of carbon allowance under the CC model can be described as follows:

$$\max_{\bar{e}_1, \bar{e}_2} \tilde{W}^{**} = \sum_{m=1}^{2} p_m^* q_m^{**} + \left(\sum_{m=1}^{2} q_m^{**}\right)^2 \Big/ 2 - \sum_{m=1}^{2} (\tilde{x}_m^{**})^2/2 - \left(\sum_{m=1}^{2} \tilde{e}_m^{**}\right)^2 \Big/ 2. \tag{25}$$

Combining $\partial \tilde{W}^{**}/\partial \bar{e}_1 = 0$ and $\partial \tilde{W}^{**}/\partial \bar{e}_2 = 0$, the optimal allocation of carbon allowance under the CC model can be solved as follows:

$$\bar{e}_m^{cc} = \left[\theta(1+\beta)^2 - 1\right]\left[2(2\alpha_1+5)(1+\beta)^2 + 1\right] \big/ \Delta_3, \tag{26}$$

where $\Delta_3 = 2(4+\beta)\beta^3\delta_{12} + \beta^2\delta_{13} + 2\beta\delta_{14} + \delta_{15}$, $\delta_{12} = 2\theta^3 + 3\theta^2 - 32\theta - 64$, $\delta_{13} = 24\theta^3 + 25\theta^2 - 452\theta - 864$, $\delta_{14} = 8\theta^3 + \theta^2 - 196\theta - 352$, $\delta_{15} = 4\theta^3 - 5\theta^2 - 134\theta - 228$. Substituting 26 in 24, 23, 21, 7, and 6, the equilibrium clear price of carbon allowance (p_e^{cc}), environmental R&D level (x_m^{cc}), wholesale price (ω_m^{cc}), production (q_m^{cc}), and retail price (p_m^{cc}) under the CC model can be solved. It is easy to find that when $\beta, \theta \in (0,1)$, $x_m^{cc} > 0, \omega_m^{cc} > 0, q_m^{cc} > 0, p_m^{cc} > 0$ will always hold, and $\operatorname{sign}(\bar{e}_m^{cc}) = \operatorname{sign}(-((1+\beta)^2\theta - 1))$. As under SC, if $\theta < g_2(\beta)$, $\bar{e}_m^{cc} > 0$ will hold; otherwise, $\bar{e}_m^{cc} < 0$ will hold.

Putting Figures 2, 3 together, we can get Figure 4 to get the condition for a positive solution of free allocation of carbon allowance under each model. Then, we can find $g_2(\beta) < g_1(\beta)$ when $0 < \beta, \theta < 1$. Therefore, if $\theta < g_2(\beta)$, all the equilibrium allocations of carbon allowance under the NC model, SC model, and CC model are positive, meaning that $\bar{e}_m^{nc} > 0, \bar{e}_m^{sc} > 0, \bar{e}_m^{cc} > 0$ will hold.

5 Results and discussions

5.1 Environmental R&D level

This paper first compares the environmental R&D level under the three models, and their results are summarized in Proposition 1.

Proposition 1. When $\theta < g_2(\beta)$, $x_m^{cc} < x_m^{sc} < x_m^{nc}$ will hold if $f(\beta) < \theta < g_2(\beta)$, but $x_m^{cc} < x_m^{nc} < x_m^{sc}$ will hold if $0 < \theta < \min(f(\beta), g_2(\beta))$.

Proposition 1 indicates that from the view of the environmental R&D level, CC is a dominated strategy and NC and SC may be the optimal strategy or second-best strategy, respectively. The environmental R&D level under CC is always much lower than that under NC and SC, but the environmental R&D level under NC may be much lower or higher than that under SC. Especially, the environmental R&D level under NC is much higher than that under SC if the spillover rate and consumers' environmental awareness can satisfy $f(\beta) < \theta < g_2(\beta)$. Therefore, the environmental R&D level under NC is the highest, that under SC is much higher, and that under CC is the lowest if $f(\beta) < \theta < g_2(\beta)$, meaning that NC is the optimal strategy, SC is the second-best strategy, and CC is the dominated strategy at this time. However, the environmental R&D level under SC is much higher than that under NC if the spillover rate and consumers' environmental awareness can satisfy $0 < \theta < \min(f(\beta), g_2(\beta))$. Therefore, the environmental R&D level under SC is the highest, that under NC is much higher, and that under CC is the lowest if $0 < \theta < \min(f(\beta), g_2(\beta))$, meaning that SC is the optimal strategy and NC is the second-best strategy, and CC is also the dominated strategy at this time.

5.2 Net carbon emission

This paper then compares the net carbon emission under the three models. Let net carbon emissions under NC, SC, and CC be $e_m^{nc} = q_m^{nc} - x_m^{nc} - \beta x_n^{nc}$, $e_m^{sc} = q_m^{sc} - x_m^{sc} - \beta x_n^{sc}$, and $e_m^{cc} = q_m^{cc} - x_m^{cc} - \beta x_n^{cc}$, respectively, and their comparisons are summarized in Proposition 2.

Proposition 2. When $\theta < g_2(\beta)$, $e_m^{cc} < e_m^{sc} < e_m^{nc}$ will always hold.

Proposition 2 reveals that from the view of net carbon emission, CC is the optimal strategy, SC is the second-best strategy, and NC is the dominated strategy. Compared to NC, the manufacturer m chooses SC or CC that can decrease net

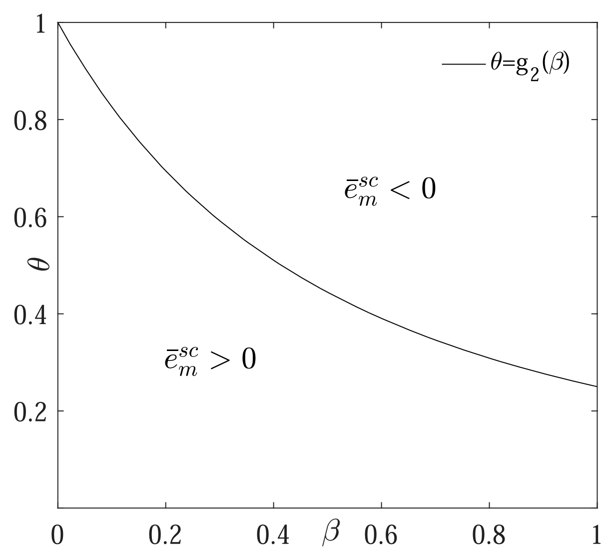

FIGURE 3
Condition for a positive solution of free allocation of carbon allowance under SC.

carbon emission and chooses CC that can decrease more net carbon emission than NC can. Therefore, the net carbon emission under NC is the highest, that under SC is much higher, and that under CC is the lowest, meaning that NC is the dominated strategy, SC is the second-best strategy, and CC is the optimal strategy.

5.3 Profit

This paper next compares profits of each manufacturer and the supply chain under the three models.

5.3.1 Manufacturer's profit

Profit comparison results of the manufacturer m under the three models are summarized in Proposition 3.

Proposition 3. When $\theta < g_2(\beta)$, $\pi_m^{nc} < \pi_m^{sc} < \pi_m^{cc}$ will hold if $\rho_1(\beta) < \theta < g_2(\beta)$, but $\pi_m^{sc} < \pi_m^{nc} < \pi_m^{cc}$ will hold if $0 < \theta < \min(\rho_1(\beta), g_2(\beta))$.

Proposition 3 indicates that from the view of profit of the manufacturer m, CC is the optimal strategy and both NC and SC may be the second-best strategy or dominated strategy under certain conditions, respectively. Compared to NC and SC, the manufacturer m chooses CC that will always increase profit. Especially, profit of the manufacturer m under SC is much higher than that under NC if the spillover rate and consumers' environmental awareness can satisfy $\rho_1(\beta) < \theta < g_2(\beta)$, meaning that profit of the manufacturer m under CC is the highest, that under SC is much higher, and that under NC is the lowest. Therefore, CC is the optimal strategy, SC is the second-best strategy, and NC is the dominated strategy under $\rho_1(\beta) < \theta < g_2(\beta)$. However, profit of the manufacturer m under SC is much lower than that under NC if the spillover rate and consumers' environmental awareness can satisfy $0 < \theta < \min(\rho_1(\beta), g_2(\beta))$, meaning that profit of the manufacturer m under CC is the highest, that under NC is much higher, and that under SC is the lowest. Therefore, CC is the optimal strategy, NC is the second-best strategy, and SC is the dominated strategy under $\rho_1(\beta) < \theta < g_2(\beta)$.

5.3.2 Supply chain's profit

Let supply chain's profits under NC, SC, and CC be $\pi^{nc} = \pi_m^{nc} + \pi_n^{nc} + \pi_r^{nc}$, $\pi^{sc} = \pi_m^{sc} + \pi_n^{sc} + \pi_r^{sc}$, and $\pi^{cc} = \pi_m^{cc} + \pi_n^{cc} + \pi_r^{cc}$, respectively, and their comparisons are summarized in Proposition 4.

Proposition 4. When $\theta < g_2(\beta)$, $\pi^{cc} < \pi^{sc} < \pi^{nc}$ will hold if $0 < \theta < \min(\rho_2(\beta), g_2(\beta))$, but $\pi^{cc} < \pi^{nc} < \pi^{sc}$ will hold if $\rho_2(\beta) < \theta < g_2(\beta)$.

Proposition 4 reveals that from the view of the supply chain's profit, CC is a dominated strategy and both NC and SC may be the optimal strategy or second-best strategy, respectively. Especially, the supply chain's profit under CC is always much lower than that under NC and that under SC. If the spillover rate and consumers' environmental awareness can satisfy $0 < \theta < \min(\rho_2(\beta), g_2(\beta))$, the supply chain's profit under NC is much higher than that under SC, meaning that the supply chain's profit under NC is the highest, that under SC is much higher, and that under CC is the lowest. Therefore, NC is the optimal strategy, SC is the second-best strategy, and CC is the dominated strategy under $0 < \theta < \min(\rho_2(\beta), g_2(\beta))$. However, if the spillover rate and consumers' environmental awareness can satisfy $\rho_2(\beta) < \theta < g_2(\beta)$, the supply chain's profit under SC is much higher than that under NC, meaning that the supply chain's profit under SC is the highest, that under NC is much higher, and that under CC is the lowest. Therefore, SC is the optimal strategy, NC is the second-best strategy, and CC is the dominated strategy under $\rho_2(\beta) < \theta < g_2(\beta)$.

5.4 Environmental R&D level, net carbon emission, and profit

Finally, this paper makes a comprehensive comparison of the environmental R&D level, net carbon emission, and profit under the three models, and results are summarized in Proposition 5.

Proposition 5. When $\theta < g_2(\beta)$, $e_m^{nc} > e_m^{sc} > e_m^{cc}$ will always hold; $x_m^{cc} < x_m^{sc} < x_m^{nc}, \pi_m^{nc} < \pi_m^{sc} < \pi_m^{cc}$ and $\pi^{cc} < \pi^{sc} < \pi^{nc}$ will hold if $f(\beta) < \theta < g_2(\beta)$, $x_m^{cc} < x_m^{nc} < x_m^{sc}, \pi_m^{nc} < \pi_m^{sc} < \pi_m^{cc}, \pi^{cc} < \pi^{sc} < \pi^{nc}$ will hold if $\rho_1(\beta) < \theta < \min(f(\beta), g_2(\beta))$, $x_m^{cc} < x_m^{nc} < x_m^{sc}, \pi_m^{sc} < \pi_m^{nc} < \pi_m^{cc}, \pi^{cc} < \pi^{sc} < \pi^{nc}$ will hold if $0 < \theta < \min(\rho_1(\beta), \rho_2(\beta))$, and $x_m^{cc} < x_m^{nc} < x_m^{sc}, \pi_m^{sc} < \pi_m^{nc} < \pi_m^{cc}, \pi^{cc} < \pi^{nc} < \pi^{sc}$ will hold if $\rho_2(\beta) < \theta < g_2(\beta)$.

Proposition 5 indicates that from the comprehensive comparison of the environmental R&D level, net carbon emission, and profit under the three models, none of the three strategies could be the optimal strategy or dominated strategy, but SC may be the second-best strategy. If $f(\beta) < \theta < g_2(\beta)$, compared to NC, the environmental R&D level, net carbon emission of the manufacturer m, and supply chain's profit are much lower, but profit of the manufacturer m is much higher under SC and CC. Compared to SC, net carbon emission of the manufacturer m and the supply chain's profit are much lower, but profit of the manufacturer m is much higher under CC. These mean that the environmental R&D level, net carbon emission of the manufacturer m, and supply chain's profit under NC are the highest, those under SC are much higher, and those under CC are the lowest, but profit of the manufacturer m under NC is the lowest, that under SC

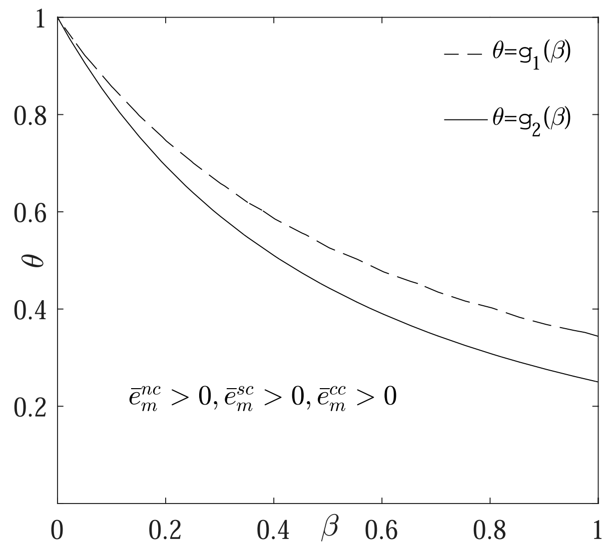

FIGURE 4
Condition for a positive solution of free allocation of carbon allowance under each model.

is much higher, and that under CC is the highest. Therefore, as a whole, there is no optimal strategy or dominated strategy, but SC can be the second-best strategy if $f(\beta) < \theta < g_2(\beta)$. If $\rho_1(\beta) < \theta < \min(f(\beta), g_2(\beta))$, compared to NC, the environmental R&D level and profit of the manufacturer m are much higher, but net carbon emission of the manufacturer m and the supply chain's profit are much lower under SC; the environmental R&D level and net carbon emission of the manufacturer m and the supply chain's profit are much lower, but profit of the manufacturer m is much higher under CC. Compared to SC, the environmental R&D level, net carbon emission of the manufacturer m, and supply chain's profit are much lower, but profit of the manufacturer m is much higher. These mean that the environmental R&D level of the manufacturer m under SC is the highest, that under NC is much higher, and that under CC is the lowest; net carbon emission of the manufacturer m and the supply chain's profit under NC are the highest, those under SC are much higher, and those under CC are the lowest; profit of manufacturer m under NC is the lowest, that under SC is much higher, and that under CC is the highest. Therefore, as a whole, there is also no optimal strategy or dominated strategy, but SC can be the second-best strategy if $\rho_1(\beta) < \theta < \min(f(\beta), g_2(\beta))$. If $0 < \theta < \min(\rho_1(\beta), \rho_2(\beta))$, compared to NC, the environmental R&D level of the manufacturer m is much higher, but net carbon emission and profit of the manufacturer m are much lower under SC. Compared to NC and SC, the environmental R&D level, net carbon emission of the manufacturer m, and supply chain's profit are much lower, but profit of the manufacturer m is much higher under CC. Therefore, as a whole, there is no optimal strategy, second-best strategy, or dominated strategy if $0 < \theta < \min(\rho_1(\beta), \rho_2(\beta))$. If $\rho_2(\beta) < \theta < g_2(\beta)$, compared to NC, the environmental R&D level of the manufacturer m and supply chain's profit are much higher, but net carbon emission and profit of the manufacturer m are much lower. Compared to NC and SC, environmental R&D level and net carbon emission of the manufacturer m and supply chain's profit are much lower, but profit of manufacturer m is much higher. Therefore, as a whole, there is also no optimal strategy, second-best strategy, or dominated strategy if $\rho_2(\beta) < \theta < g_2(\beta)$.

6 Conclusion

Three carbon emission reduction and pricing strategies of manufacturers are NC, SC, and CC. This paper develops three game models where two manufacturers could choose NC, SC, or CC to analyze manufacturers' strategies of carbon emission reduction and pricing under the CET and CEA. This paper solves these models and compares their environmental R&D levels, net carbon emissions, and profits. Results show that from the view of the environmental R&D level or supply chain's profit, manufacturers may choose NC or SC as their strategy. From the net carbon emission point of view, CC and SC should be their optimal strategy and second-best strategy, respectively. As to manufacturers' profits, CC should be their optimal innovation strategy, and NC or SC should be their second-best strategy. As a whole, manufacturers would choose none of these strategies as their optimal strategy but may choose SC as their second-best strategy.

From the aforementioned information, we propose the following management insights. First, manufacturers should select their strategy of carbon emission reduction and pricing according to their own situations. Participation in further cooperation in carbon emission reduction and pricing may damage manufacturers' benefits, even their development. As to manufacturers with weak strength, NC may be their choice. When they enhance their strength in future, SC and CC may be their choices. As to manufacturers with strong strength and social responsibility, CC may be their choice. Second, the government should a design dynamic support system based on the extent of cooperation manufacturers engaged. The government can provide more environmental R&D fund, tax reduction and exemption, financing, and other supports to manufacturers when they engage in further cooperation in environmental R&D and pricing, to lead manufacturers form and deepen their cooperation, undermine their carbon emission reduction potential, and make a greater contribution to ecological civilization construction. Finally, members in the supply chain should properly share their profits. Different cooperation strategies in carbon emission reduction and pricing cause different, even opposite, influence on members in the supply chain. Manufacturers' participation in deeper cooperation is good for the retailer to make a higher retail price on a low-carbon product, which may increase the retailer's profit but may decrease manufacturers' profits. Therefore, members in the same supply chain should design a proper profit-sharing contract and properly share their profits.

This study also exhibits several limitations. First, we focus on the carbon emission reduction and pricing strategy of manufacturers. In fact, manufacturers and retailers also cooperate in carbon emission reduction, such as retailers share carbon emission reduction costs of manufacturers, and manufacturers share low-carbon promotion costs of retailers. This leads to an extension to analyze a full cooperation between members in the same supply chain or even between different supply chains. Second, we assume that the two manufacturers have the same environmental R&D efficiency. In fact, manufacturers are different in finance, technology, and other aspects. Future research could examine the effect of different environmental R&D on strategy selection. Finally, this paper applies the backward induction to solve the game models. However, there have been many different domains where advanced optimization algorithms have been applied as solution approaches, such as carbon emission reduction (Dulebenets et al., 2017), online learning (Zhao and Zhang, 2020), scheduling (Kavoosi et al., 2019;

Dulebenets, 2021), multi-objective optimization (Zhao and Zhang, 2020), and medicine (Rabbani et al., 2017). These approaches could be more effective in solving decision problems. Future research should explore more advanced optimization algorithms for this decision problem.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YD: conceptualization and project administration; HW: investigation, resources, and data curation; HP: methodology, software, validation, formal analysis, writing—original draft preparation, writing—review and editing, and funding acquisition; and LL: visualization and supervision. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

Authors YD and LL are employed by Carbon Asset Management (Guangzhou) Co., Ltd., CSG, Guangzhou, Guangdong Province, China.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at the following links: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1120165/full#supplementary-material

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Research on the impact of equity incentives on the financial performance of new energy enterprises

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Based on the data of 253 A-share listed new energy enterprises from 2010–2021, this paper studies the correlations among equity incentives, the three contract elements of equity incentives and the financial performance of new energy enterprises by using fixed-effect regression analysis, and on this basis, Granger causality analysis is applied to determine the causal relationship, and finally, the degree of influence of equity incentives contract elements is further studied by Grey Relational Analysis. It is found that equity incentives positively affect the financial performance of new energy enterprises as a whole. In terms of the choice of equity incentive contract elements, the influence is more significant when the granting method is stock options, when the exercise duration is longer, and when the exercise conditions are stricter. As to the degree of influence, the influence of equity incentive method and exercise conditions on the financial performance of new energy enterprises is greater, but the influence of exercise duration is the lowest. Therefore, it is suggested that new energy enterprises can choose more stock options for equity incentives, create stricter exercise conditions and set the duration of the equity incentive scheme between 5 and 10 years with their own characteristics.

KEYWORDS

equity incentives, financial performance, new energy companies, contractual elements, new energy

1 Introduction

As one of the emerging strategic industries, the new energy industry is gaining more and more national attention for its ecological, environmental protection and energy-saving advantages, and the importance of the new energy industry has been mentioned in the 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives Through the Year 2035. With the innovation and development of science and technology, the new energy industry has made great achievements and reached a certain scale, and new energy enterprises are also getting more and more attention. However, new energy enterprises have encountered some obstacles in their development, such as low technology levels, high resource consumption, and not-standardized internal management. At present, there are relatively few studies on the financial performance of listed new energy enterprises at home and abroad, and the impact of corporate equity incentives on their financial performance has not been comprehensively explored. The current domestic research on equity incentives mostly takes A-share enterprises, state-owned enterprises, non-state-owned enterprises and other broad categories as research samples, but there are few studies focusing on a particular area. Due to the existence of a principal-agent relationship within each new energy enterprise, the issue of equity incentives should be paid attention to, and this paper will conduct an empirical study on the relationship between equity incentives and the financial performance of new energy enterprises, which is of certain significance to solve the principal-agent problem and thus promote the further development of new energy enterprises.

This paper takes listed enterprises of new energy as the research sample, and distinguishes between equity incentive or not, equity incentive method, exercise duration and exercise conditions based on incentive theory and residual claim theory, and tests the hypotheses by fixed effects regression model. Then, this paper conducts one-way causation analysis on the impact of equity incentives on the financial performance of new energy enterprises on basis of Granger causality analysis approach, and also further investigates the degree of impact of equity incentive contract elements on the financial performance of new energy enterprises by Grey Relational Analysis. Based on the above analysis, this paper proposes feasible suggestions for the future equity incentive schemes of new energy enterprises.

The contributions of this paper include the following: First, in terms of research method, this paper uses fixed-effect regression analysis, Granger causality analysis and gray correlation analysis, the combination of the three research methods increases the breadth and depth of this paper and enhances the credibility of the conclusion. Secondly, in terms of the research aims, most of the existing researches focus on A-shares, and few focus on equity incentives of new energy enterprises. New energy enterprises are significant to the strategic emerging industries, therefore, the importance of research on the equity incentives of new energy enterprises is self-evident.

This paper is structured as follows: Part I is the introduction, Part II is the literature review and hypothesis development, Part III is the research design, Part IV is the empirical results, Part V is the research conclusion and recommendations.

2 Literature review and hypothesis development

2.1 Literature review

Foreign scholars started to study the financial performance evaluation of enterprises earlier than Chinese scholars, and the early evaluation methods were the Balanced Score Card, DuPont Analysis, Economic Value Added Approach, *etc.* With further research, more and more scholars have integrated multiple factors in their studies to evaluate enterprise financial performance, such as Flynn (Flynn, 2010) and Miller and Breton (Miller and Breton, 2011) who integrated multiple financial performance indicators to assess financial performance comprehensively. Domestic scholars mainly focus on various ratios after relevant calculation processing by using accounting data, Zhou Yunbo and Zhang Jingwen (Zhou and Zhang, 2020) selected ROA and ROE adjusted by annual industry mean value as a measure of financial performance indicators. Wang Tao and Hu Minjie (Wang and Hu, 2015) selected six indicators of financial performance such as ROA, ROE and TAG. However, there are also many people who believe that financial performance indicators are complex, and that is not very accurate to judge financial performance with a few simple indicators alone. Therefore, a number of scholars have established financial performance indicator models through factor analysis (Yu et al., 2022a). For example, Cheng Longyun and Yue Chunmiao (Cheng and Yue, 2008) used factor analysis to calculate the comprehensive evaluation value of financial performance of enterprises each year. Hou Xiangding (Hou, 2021), Tong Yuanke and Wei Yunjie (Tong and Wei, 2021) all used factor analysis to extract the financial performance characteristic factors to construct the index system.

There is no unified view on the impact of equity incentives on financial performance, and the common views are divided into four categories: positive, negative, non-significant and curvilinear relationship between equity incentives and financial performance. The majority of scholars agree that equity incentives are positively related to the enterprise financial performance (Yu et al., 2022b). Early foreign scholars, represented by Jensen and Meckling (Jensen Michael and Meckling William, 1976), put forward the convergence of interests hypothesis, which deems that equity incentives provide executives with residual claims on corporate assets, which leads to the formation of a community of shared interests between executives and shareholders and can improve corporate performance. Domestic scholars Shen Xiaoyan and Wang Yuetang (Shen and Wang, 2015) studied 577 listed companies that implemented equity incentives between 2006 and 2010 and found that the financial performance of the companies improved after the implementation of equity incentives. Ma Lianfu and Ding Zhensong (Ma and Ding, 2017) empirically studied the impact of equity incentives on the financial performance of state-owned enterprises and found that executive shareholding could significantly contribute to the improvement of return on total assets. Chen Wenqiang (Chen, 2018) and Zhang Jinsong (Zhang and Zhang, 2021) both found that equity incentives can improve the financial performance of enterprises at growth stage.

At present, domestic and foreign researches on the equity incentive contract elements mainly contains three key elements: equity incentive method, exercise duration and exercise conditions. Regarding the research on equity incentive method, scholars have different views. For example, Sheikh (Sheikh, 2012), Liu Guangsheng and Ma Yue (Liu and Ma, 2013) found that the incentive effects of stock options on R&D investment is better than that of restricted stock. Xiao Shufang et al. (Xiao et al., 2016) concluded that listed companies should develop different equity incentive schemes by combining the characteristics of incentive objects. As to the research on the exercise duration, most scholars believe that equity incentive schemes with longer exercise duration tend to have better financial performance. Chang et al. (Chang et al., 2015) and Wang Shuxun et al. (Wang et al., 2017) discovered that equity incentive schemes with exercise duration longer than 5 years can bring more significant implementation effects to listed companies. Shi Qi et al. (Shi et al., 2020) maintained that the design of stock option contract elements with longer incentive duration can better exploit the stock option's risk-taking effect and affect corporate performance. There is no unified view on the study of exercise conditions, but some scholars believe that strict exercise conditions should be set, Chen Shengjun et al. (Chen et al., 2016) argued that enterprises can set stricter performance conditions in order to achieve better results, but some scholars do not think so. Bettis et al. (Bettis et al., 2010) suggested that less strict conditions for the use of equity incentive schemes can make the impact of equity incentives more effective, and He Yan et al. (He et al., 2019) argued that a reasonable exercise price can produce optimal incentive effects by selecting panel data for almost a decade.

In general, scholars have conducted a detailed study on equity incentives, but few scholars have further studied the degree of influence of equity incentive contract elements on enterprises, and there is still a lack of in-depth research on new energy enterprises in terms of sample selection. Based on the existing literature, this paper takes the listed enterprises of new energy as the research object, adopts factor analysis to design financial performance indicators, studies the influence of equity incentives on financial performance, conducts one-way causation analysis based on Granger causality analysis, and further studies the degree of influence of equity incentive contract elements, in order to enhance the effect of equity incentives and improve the financial performance of new energy enterprises.

2.2 Hypothesis development

2.2.1 The impact of equity incentives on the financial performance of new energy enterprises

According to the content of incentive theory, equity incentives as a long-term incentive method, avoid the short-sighted behaviors brought by short-term incentive effect (Cao and Zhan, 2003), and it can mobilize employees' motivation, manipulate and guide their behaviors, make the owner and operator's goals consistent, and in order to obtain a generous return of equity incentives, the operator should work in the direction of enterprise value enhancement and improve the performance of the enterprise, and thus maximize their own interests and achieve a win-win situation for both shareholders and operators (Lin and Liu, 2017). According to the view of residual claim, if executives and core employees do not enjoy residual claim, the compensation they receive will depend on the short-term performance of the enterprise, and the existence of moral hazard and adverse selection leads them to have higher expectations of good short-term performance, then their goals will be different from those of shareholders. The implementation of the equity incentive plan makes the shareholders not the only recipients of the residual income, but the management and employees of the enterprise jointly gain the right to share the corporate income (Ruan and Yang, 2013), and employees also become the beneficiary of the residual income, and in the long run, the goals of the employees and shareholders are aligned and work together to maximize the interests of the enterprise (Shen and Wang, 2015). It is unclear whether the domestic market can get the same impact of equity incentives as the foreign market. However, a large number of scholars have done relevant studies as of today, most of whom believe that equity incentives can have a positive impact on corporate financial performance (Zhang and Zhang, 2021). As an incentive, equity incentives are not only beneficial to the stability of talents in new energy enterprises, but also enable management to look farther, develop advanced technology, strive to improve corporate governance, and pay attention to long-term development, thus enhancing corporate financial performance. Based on the above analysis, Hypothesis 1 was put forward.

H1: In listed enterprises of new energy, equity incentives positively affect the financial performance of new energy enterprises.

2.2.2 The impact of the equity incentive methods on the financial performance of new energy enterprises

In China, the restricted stock incentive method and stock option incentive method are more favored by China's listed new energy enterprises, and the sample size of enterprises choosing other equity incentive methods is small, so this paper only studies the effect of these two incentive methods on corporate performance.

The existing literature generally agrees that the two types of incentives can positively affect the financial performance of enterprises. However, there is no unanimous conclusion as to which of the two types of methods is more effective, but most scholars believe that stock option is more effective than restricted stock (Sheikh, 2012; Liu and Ma, 2013; Xiao et al., 2016). The grantees of stock options must ensure that the corporate performance can grow after meeting the exercise conditions in order to obtain potential gains, and the basic characteristics of stock options determine that they are more motivating than restricted stock. The grantees of restricted stock usually purchased the company's restricted stock at a discount and they are only allowed to dispose of these stock if their performance goals and years of service meet the contractual requirements. Unlike the valuation of restricted stock, stock options are call options. For call option holders, an increase in the stock price can be profitable and the maximum loss is limited if the stock price falls, while an increase in stock price volatility increases the value of the call option. In other words, an increase in the company's stock price and an increase in stock volatility can add the value of the call option, so its incentive effect may be more effective. Therefore, Hypothesis 2 was proposed in this paper.

H2: In listed new energy enterprises, the incentive effect of equity incentives on financial performance is more significant when the granted method is stock options.

2.2.3 The impact of exercise duration on the financial performance of new energy enterprises

The longer the duration of the equity incentives is, the higher the requirements for the ultimate exercise by the incentive recipients is. This is because that each business cycle is linked to the performance conditions for the incentive recipients, and the performance targets set in the performance conditions may be achieved by means of manipulating revenue or costs in the short term, but in the long term, it is difficult to realize continuous manipulation due to the restrictions of supervision and disclosure. The new energy industry is at the early stage of development, and its demand for technology research and development is relatively higher and requires a certain level of innovation capability. An innovation project often takes a long time from the initial investment to the final return, which is particularly evident in the energy sector. Longer incentive schemes allow employees to share the long-term benefits of innovative activities more effectively and encourage the incentive recipients to focus more on the long-term performance of the new energy enterprises, rather than just try to achieve better short-term results. From the human capital perspective, a longer operating period is beneficial for enterprises to retain valuable human capital because innovative activities are usually not achieved overnight and require a long-term track to realize. Shuxun Wang et al. (Wang et al., 2017) found through their study that longer exercise duration of equity incentives can promote the increase in innovation output and thus improve corporate performance. Equity incentives usually have a long waiting period, and the incentive recipients must work for the company long enough for the waiting period to take effect (Chang et al., 2015). Theoretically, the longer the exercise duration of the equity incentives, the longer the time the equity incentives are used to promote innovation, and the more consistent the incentive recipients' personal interests are with the long-term value of new energy enterprises, and therefore the better the financial performance of the enterprises. Based on the above analysis, Hypothesis 3 was put forward.

H3: In listed new energy enterprises, the longer the exercise duration of the equity incentive scheme, the more beneficial it is to improve the financial performance of the enterprises.

2.2.4 The impact of exercise conditions on the financial performance of new energy enterprises

Exercise conditions are the performance targets that the incentive recipients of the equity incentive scheme must achieve within the performance period, which can be divided into strict and loose targets, and the incentive effects of equity incentives vary under different exercise conditions (Lv et al., 2009). Shengbao Zhai and Ziwei Chen (Zhai and Chen, 2016) argued that the incentive recipients are likely to use their power to influence the board of directors to design a scheme that is favorable to them in the process of designing an equity incentive scheme. According to the existing literature, most scholars believe that equity incentive schemes with strict exercise conditions are more effective, because strict exercise conditions bind the incentive recipients to a certain extent, and incentive recipients who wish to earn more residual income will try to maintain the company's performance and ensure the growth of financial performance, therefore bringing greater and long-term benefits to the enterprise (Lu et al., 2013). Meanwhile, many scholars have proposed a combination of multiple indicators for assessment as to how to set strict exercise conditions, and the indicators should preferably include multiple types (Dechow and Sloan, 1991; Sautner and Weber, 2006; Lu et al., 2013). According to the above views, this paper argues that if the equity incentive exercise conditions are too loose, it is equivalent to giving welfare to the incentive recipients, so enterprises will find it difficult to curb the self-interest of the management. In order to avoid the fraudulent behavior of managers and to achieve a better effect of equity incentive implementation, enterprises should establish more strict performance conditions. Therefore, Hypothesis 4 was proposed in this paper.

H4: In listed new energy enterprises, setting relatively strict exercise conditions for equity incentive schemes is more conducive to improving the financial performance of enterprises.

3 Study design

3.1 Sample selection and data sources

In 2016, the State Council released the "Thirteenth Five-Year Plan for the Development of National Strategic Emerging Industries", emphasizing the importance of strategic emerging industries, of which the new energy industry is a member, and its importance cannot be overstated. With the global emphasis on energy transformation and China's "double carbon" goal, developing new enterprises and increasing the proportion of new energy in energy discipline has been the key goal. To develop new energy, technical talents are indispensable. For enterprises, they need to inves in R&D and keep core talents through equity incentives. Therefore, this paper takes the listed new energy enterprises as the research object to study the equity incentive and its contractual elements, so as to make a more reasonable equity incentive plan for new energy enterprises and improve the efficiency of equity incentive of new energy enterprises.

The research sample selected in this paper is the data of 253 new energy enterprises listed on A-share in China from 2010 to 2021. New energy enterprises refer to all enterprises involved in the complete new energy industry chain, including research and development, equipment manufacturing, production and supply, comprehensive utilization, *etc.* Considering that some new energy enterprises are still at the initial stage, their data is not informative, so a total of six industries are selected: photovoltaic, wind power, nuclear energy, energy saving, geothermal energy and new energy vehicles. As a variety of sample data is required to measure the financial performance of enterprises, this paper removes a-year sample when a variable of sample enterprise is missing. In addition, some samples with abnormal and missing data are deleted to ensure the validity of the data. The specific data treatment is as follows: 1) The research sample of this paper only includes A-share listed enterprises. 2) Enterprises that receive special treatment from China Securities Regulatory Commission are removed from sample data. 3) Enterprises that have implemented equity incentives in forms other than restricted stock and stock options are also removed. Finally, a total of 2,258 valid observations are obtained.

The financial data involved in this paper are mostly derived from Wind database, and some of the missing financial data are manually compiled from CSMAR database, and the relevant analysis and empirical process uses Excel and StataSE15 software.

3.2 Research methodology

3.2.1 Construction of a factor analysis model for financial performance of new energy enterprises

In this paper, we use factor analysis to determine the final financial performance indicators, and through factor analysis, these multiple indicators are formed into a comprehensive indicator FP for subsequent analysis. Let X_i be the measurable variable, and F_1, F_2 F_m to be searched for are the common factors; ε_i is the special factor of X_i, which indicates the difference of variables that cannot be revealed by the common factors, then the model is shown in Eq. 1.

$$X_i = a_{i1}F_1 + a_{i2}F_2 + \cdots + a_{im}F_m + \varepsilon_i \tag{1}$$

3.2.2 Constructing a fixed-effects model of the impact of equity incentives on the financial performance of new energy companies

In this paper, we use the composite financial performance indicator FP as the dependent variable and select equity incentive, equity incentive method, exercise period and exercise condition as the independent variables to study their effects on financial performance.

In order to test the four hypotheses proposed in the previous paper, the following four fixed-effects models are constructed to analyze the relationship between the dependent and independent variables.

$$FP_{i,t} = \alpha_0 + \alpha_1 POST_{i,t} + \alpha_2 ES_{i,t} + \alpha_3 CPS_{i,t} + \alpha_4 OC_{i,t} + \alpha_5 IBR_{i,t} + \varepsilon_{i,t} \tag{2}$$

$$FP_{i,t} = \beta_0 + \beta_1 SO_{i,t} + \beta_2 ES_{i,t} + \beta_3 CPS_{i,t} + \beta_4 OC_{i,t} + \beta_5 IBR_{i,t} + \varepsilon_{i,t} \tag{3}$$

$$FP_{i,t} = \gamma_0 + \gamma_1 Duration_{i,t} + \gamma_2 ES_{i,t} + \gamma_3 CPS_{i,t} + \gamma_4 OC_{i,t} + \gamma_5 IBR_{i,t} + \varepsilon_{i,t} \tag{4}$$

$$FP_{i,t} = \delta_0 + \delta_1 Duration_{i,t} + \delta_2 ES_{i,t} + \delta_3 CPS_{i,t} + \delta_4 OC_{i,t} + \delta_5 IBR_{i,t} + \varepsilon_{i,t} \tag{5}$$

Eq. (2) is used to test hypothesis 1, whether equity incentives positively affect financial performance in listed new energy companies.

Eq. (3) is used to test hypothesis 2, whether the incentive effect of equity incentive on financial performance is more significant when the granting method is stock options in listed new energy enterprises.

Eq. (4) is used to test hypothesis 3, whether the longer the validity period of the equity incentive program is, the more beneficial it is to improve the financial performance of the enterprise in listed new energy enterprises.

Eq. (5) is used to test hypothesis 4, whether the longer the exercise period of the equity incentive program is, the better the financial performance of the listed new energy companies.

3.2.3 A causal analysis model of the impact of equity incentives on the financial performance of new energy companies

The causal analysis model used in this paper is the Granger causal analysis model. Granger (2003) indicates that the purpose of testing causality between panel data is to verify that the causal relationship between all cross-sections corresponding to each other holds. This hypothesis has a high intensity. In this regard, in this study, the panel Granger causality test proposed by Dumitrescu and Hurlin (2012) is chosen, and this method is based on the cross-sectional Wald statistic, which provides a comprehensive analysis of the link between cross-sections and panels, and provides a reasonable explanation of whether the causal relationship between the panel data holds.

In the Granger causality test, two panel data sets, $x = (x_{i-k}, \ldots x_{i,0})'$ and $y = (y_{i,-k}, \ldots y_{i,0})'$ are defined, where both $x_{i,t}$ and $y_{i,t}$ are observable and known data. At moment t, the variable of the i th cross-section takes the value $y_{i,t}$. Thus, the regression model can be obtained.

$$y_{i,t} = \alpha_i + \sum_{K=1}^{K} \gamma_i^{(K)} y_{i,t-k} + \sum_{K=1}^{K} \beta_i^{(K)} x_{i,t-k} + \varepsilon_{i,t} \tag{6}$$

In the above model, the number of lag orders is K and all cross-sectional fixed effects intercept terms are α_i. It is assumed that the panel is balanced and K is consistent for all cross-sections. In addition, there is no correlation between time t and the autoregressive coefficients $\gamma_i^{(K)}$ and $\beta_i^{(K)}$. Also, differences in different cross-sections are allowed to exist.

3.2.4 A model of the degree of influence of equity incentive contract elements on the financial performance of new energy companies

In this paper, the gray correlation analysis method (Deng, 1990), pioneered by Professor Deng Julong in 1982, is used to study the degree of influence of the equity incentive method, exercise period and exercise conditions on the financial performance of new energy companies.

The analysis steps are as follows.

First, determine the evaluation objects and evaluation criteria. Let there are m evaluation objects and n evaluation criteria, the reference series is $x_0 = \{x_0(k)|k = 1, 2, \ldots, n\}$, the comparison series is $x_i = \{x_i(k)|k = 1, 2, \ldots, n\}, i = 1, 2, \ldots, m$.

Next, the reference and comparison series are dimensionlessized. Let the dimensionless reference series be $x_0' = \{x_0'(k)|k = 1, 2, \ldots, n\}$, and the dimensionless comparison series be $x_i' = \{x_i'(k)|k = 1, 2, \ldots, n\}, i = 1, 2, \ldots, m$. Determine the weight of each index value corresponding to weight $w = [w_1, w_2, ..., w_n]$.

Where w_k $(k = 1, 2, \ldots, n)$ is the weight corresponding to the k th evaluation index.

Again, the gray correlation coefficients are calculated as follows.

$$\xi_i(k) = \frac{\min(s)\min(t)|x_0'(t) - x_s'(t)| + \rho\max(s)\max(t)|x_0'(t) - x_s'(t)|}{|x_0'(k) - x_s'(k)| + \rho\max(s)\max(t)|x_0'(t) - x_s'(t)|} \tag{7}$$

To compare the correlation coefficients of the series x_i to the reference series x_0 at the k th index, where $\rho \in [0, 1]$ is the resolution coefficient, call $\min(s)\min(t)|x_0'(t) - x_s'(t)|$, $\max(s)\max(t)|x_0'(t) - x_s'(t)|$ are the two-level minimum difference and the two-level maximum difference, respectively. The resolution becomes larger as ρ increases and *vice versa*.

Then, the gray weighted correlation is calculated, and the gray enhanced correlation is calculated as:

$$r_i = \sum_{k=1}^{n} w_i \xi_i \tag{8}$$

where r_i is the gray weighted correlation of the i th evaluation object as the ideal object.

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TABLE 1 Composition of comprehensive financial index system.

Type	Indicator	Symbol	Calculation formula
Profitability	Total assets net profit margin	X_1	Net profit/average balance of total assets
	Return on net assets	X_2	Net profit/average balance of shareholders' equity
	Net operating margin	X_3	Net profit/total operating revenue
	Earnings per share	X_4	(Net income for the period - preferred stock dividends)/weighted average annual total equity
Operating Capacity	Current Asset Turnover Ratio	X_5	Operating Income/Average Balance of Current Assets
	Total asset Turnover days	X_6	365/Total asset turnover ratio
	Total Assets Turnover Ratio	X_7	Operating income/total assets average balance
Debt Service Capacity	Current Ratio	X_8	Current Assets/Current Liabilities
	Quick Ratio	X_9	(Current Assets - Inventory) Current Liabilities
	Gearing Ratio	X_{10}	Total Assets/Total Liabilities
Development capacity	The Growth rate of total assets	X_{11}	(total assets at the end of the period - total assets at the end of the previous year)/total assets at the end of the previous year
	Operating revenue growth rate	X_{12}	(Current period operating revenue - Previous period operating revenue)/Previous period operating revenue
	Capital preservation ratio	X_{13}	Owner's equity at the end of the period/owner's equity at the beginning of the period

Finally, the analysis is evaluated based on the magnitude of the gray weighted correlation.

3.3 Variable categories and metrics

3.3.1 Measures of explained variables

The explanatory variable in this paper is corporate financial performance, and factor analysis is used in this paper to determine the final financial performance indicators. In recent years, domestic and foreign research literature has also applied factor analysis extensively to establish the financial evaluation system (Cheng and Yue, 2008; Xu and Shi, 2010; Hou, 2021; Tong and Wei, 2021), taking into account Shu Xiaohui's "Research on the Evaluation Methodology and Visualization of Financial Performance of Listed Companies" (Shu, 2013) and the revised "Operating Rules for Enterprise Performance Evaluation" by the Ministry of Finance in 2002, and statistics on the frequency of use of each indicator, as well as the characteristics of new energy enterprises that are in the transition from the start-up period to the growth period, this paper selects a total of 13 indicators in the categories of profitability, Operating capacity, solvency and development capacity, a total of 13 indicators are selected in this paper, as shown in Table 1.

3.3.2 Metrics of other variables

(1) Explanatory variables

POST: equity incentive indicators. The research subjects in this paper are all annual indicators, and considering the lag of equity incentive, the time dummy variable here takes the value of 0 before the implementation of the equity incentive plan, and takes the value of 1 in the year of the implementation of the equity incentive plan and the next 3 years.

SO: Equity incentive method indicator. Classification according to the Company Law of the People's Republic of China, It takes 1 for companies using stock options as the incentive method and 0 for companies using restricted stock as the incentive method.

Duration: the indicator of exercise period. According to the Company Law of the People's Republic of China, the exercise period refers to the period from the date of announcement of the equity incentive plan to the final expiration date.

Condition: Exercise condition indicator. Therefore, in this paper, referring to Lv Changjiang (Ruan and Yang, 2013), all the enterprises with exercise conditions higher than the first 3 years are defined as enterprises with strict exercise conditions and denoted by dummy variable 1; other companies are defined as enterprises with loose exercise conditions and denoted by dummy variable 0. When the equity incentive plan has multiple performance conditions, all performance conditions with financial ratios no lower than the average of the previous 3 years are defined as strict exercise conditions and denoted by dummy variable 1, while all exercise conditions with financial ratios lower than the average of the previous 3 years are defined as loose exercise conditions and denoted by dummy variable 0.

(2) Control variables

ES: firm size, which is expressed as the natural logarithm of the firm's total assets. The size of the company has an impact on the financing ability and R&D capability of new energy companies.

CPS: Capital structure, expressed as the gearing ratio. The capital structure of a company is one of the most important indicators for corporate assessment and one of the common

TABLE 2 Categories of variables and methods of definition.

Nature of variables	Variable name	Variable interpretation
Explanatory Variable	Financial Performance (FP)	Derived from Factor Analysis
Explanatory Variables	Equity Incentive (POST)	0 before the implementation of the equity incentive plan and 1 after the implementation of the equity incentive plan
	Stock incentive method (SO)	0 for restricted stock and 1 for stock options
	Exercise Period (Duration)	The time between the announcement date of the plan and the final expiration date
	Exercise conditions (Condition)	The exercise condition is denoted by 1 for companies with strict exercise targets and 0 for companies with loose exercise conditions
Control variables	Control variables Firm size (ES)	Expressed as the natural logarithm of total assets
	Capital structure (CPS)	Expressed as gearing ratio
	Concentration of ownership (OC)	expressed as the percentage of shares held by the top 10 shareholders
	Business growth (IBR)	expressed as the growth rate of operating revenue

control variables for regression analysis. New energy companies need to raise capital to obtain development, so they need to weigh the financing risk against the profit output.

OC: Equity concentration, expressed as the percentage of shares held by the 10 largest shareholders of the company. China's capital market is not yet perfect, and many managers of enterprises are shareholders, and this part may interfere with the formulation of specific conditions of equity incentives, from which they seek benefits for themselves and harm the interests of small and medium shareholders.

IBR: Enterprise growth, using the growth rate of operating income to express the growth of the company. The growth of the company will affect the future judgment of the incentive recipients. The incentive recipients of companies with good growth are more willing to accept the equity incentive because of the higher possibility of gaining benefits in the future, while the incentive recipients of companies with low growth may have lower confidence in the equity incentive plan.

The specific variable categories and variable explanations in this paper are shown in Table 2.

4 Empirical results

4.1 Financial performance evaluation indicators

According to the experimental design, the financial indicators were selected in total as return on net assets (X_1), net profit margin on total assets (X_2), net operating margin (X_3), earnings per share (X_4), current asset turnover ratio (X_5), total asset turnover days (X_6), total asset turnover ratio (X_7), current ratio (X_8), quick ratio (X_9), gearing ratio (X_{10}), operating income growth rate (X_{11}), total assets growth rate (X_{12}), and capital preservation ratio (X_{13}) 13 indicators were synthesized into a composite financial performance index (FP). After standardizing the original data, KMO and Bartlett's sphericity test were conducted first, and the KMO value was 0.592 by software analysis, which was greater than

TABLE 3 Component score coefficient matrix.

Name	Ingredients			
	1	2	3	4
Net Profit Margin on Total Assets	0.013	0.344	0.001	−0.031
Return on net assets	−0.068	0.316	−0.113	−0.046
Net Operating Margin	−0.038	0.359	−0.073	−0.034
Earnings per share	−0.023	0.271	0.016	0.047
Current Assets Turnover Ratio	−0.000	−0.116	0.450	0.020
Total Assets Turnover Days	0.025	0.078	0.267	−0.027
Total Assets Turnover Ratio	0.041	−0.080	0.464	0.025
Current Ratio	0.402	−0.067	0.037	−0.026
Quick Ratio	0.397	−0.068	0.038	−0.017
Gearing Ratio	0.307	0.020	0.000	−0.054
Total Assets Growth Rate	−0.068	0.060	−0.003	0.435
Operating income growth rate	−0.043	−0.071	0.027	0.432
Capital Preservation and Appreciation Ratio	0.006	−0.044	0.004	0.511

the critical value of 0.5; the Bartlett's sphericity test result was realistic, and the p-value was 0.000, which was less than 0.01, and the null hypothesis was rejected, indicating that the selected indicators were suitable for factor analysis.

Using stata software, the eigenvalues and variance contribution rates of each factor were derived, and the model extracted four common factors as F_1, F_2, F_3 and F_4, respectively, and the variance contribution rates of the four factors after rotation were 19.365%, 18.556%, 16.418% and 12.354%, and the total variance contribution rate was unchanged, and the model could explain the original variable information of 66.693%, indicating that the four extracted common factors can measure about 67% of the 13 indicators of financial performance.

TABLE 4 Descriptive statistics of main variables.

Name	N	Minimum	Maximum	Mean	Standard deviation	Median
POST	2258	0.000	1.000	0.241	0.428	0.000
SO	2258	0.000	1.000	0.188	0.391	0.000
Duration	2258	0.000	10.000	3.147	2.548	4.000
Condition	2258	0.000	1.000	0.472	0.499	0.000
ES	2258	19.625	27.547	22.589	1.296	22.192
CPS	2258	0.027	0.991	0.477	0.187	0.493
OC	2258	3.621	81.885	33.740	15.164	28.991
IBR	2258	−2.191	563.633	20.974	903.381	0.186
FP	2258	−4.875	4.966	−0.021	0.510	−0.028

The scores of each factor were calculated and the composite score was calculated as shown in Table 3.

Finally, after obtaining the formulae for the four common factors, the composite financial performance index (FP) of new energy enterprises is calculated based on the principal component coefficients to obtain Eq. (9).

$$FP = 0.290F_1 + 0.278F_2 + 0.246F_3 + 0.185F_4 \tag{9}$$

4.2 Descriptive statistics and correlation analysis

Table 4 shows the descriptive statistical analysis results of the main variables. In this paper, a total of 2258 valid observations are obtained for the A-share listed new energy enterprises from 2010–2021. Among them, the mean value of equity incentives (POST) is 0.241, so enterprises choose more restricted stock for equity incentives than stock options. The mean value of exercise duration (Duration) is 3.147, and the standard deviation is 2.528, so most enterprises have exercise duration below 5 years. The mean value of exercise conditions (Condition) is 0.472, and the standard deviation is 0.5. In general, there are more enterprises with loose exercise conditions than those with strict exercise conditions. The standard deviation of enterprise size (ES) is 1.296 after taking the logarithm, and the gap between the distribution of assets before the enterprises is obvious. The standard deviation of capital structure (CPS) is 0.187, and in general, the capital structure of the sample is relatively similar. The ownership concentration (OC) of most enterprises is below 50%, so their concentration is relatively low. The average value of corporate growth (IBR) is 20.974, and the difference between the maximum and the minimum is large. The mean value of enterprise growth (IBR) is 20.974, with a large difference between the maximum and minimum values, indicating a larger gap in growth between different enterprises. Financial performance (FP) has a maximum value of 4.966 and a minimum value of −4.875, with a large difference. This is because the factor analysis method synthesizes 13 indicators, and the data itself has large differences, and the synthesized indicators are also affected by these differences, but the data analysis is more comprehensive and is not biased.

The correlations of the main variables can be reached from Table 5, and specific analysis shows that.

Equity incentive and financial performance and three equity incentive contract elements equity incentive, equity incentive method and exercise period are significantly correlated at the 1% level, indicating that equity incentive has an impact on corporate financial performance, which initially verifies the four hypotheses content of this paper. In addition, the correlation coefficient values between equity incentives and a total of three control variables, namely, firm size, capital structure and equity concentration, show significance. However, the correlation analysis of variables can only get the preliminary relationship between variables and cannot draw accurate conclusions, and more precise relationships are to be further developed in the regression analysis.

4.3 Analysis of regression results

Hypothesis 1 is first tested and regression analysis is performed on Eq. (2). Since the model data studied in this part of the regression are panel data, the hausman test is performed first to judge the model. According to the hausman test, a p-value of 0.0001 is obtained, so the original hypothesis is strongly rejected and therefore a fixed effects model should be used.

In this section, overall equity incentive (POST) is used as the explanatory variable in Eq. 2 and the composite indicator of corporate financial performance (FP) is used as the explanatory variable in Eq. 2. The regression results are shown in Table 6.

The coefficient of equity incentives and corporate financial performance is 0.044, and the two are significantly positively correlated at the level of 0.1, indicating that there is a positive correlation between equity incentives and corporate financial performance for the sample enterprises, and the Hypothesis 1 is initially valid. The regression results show that corporate size has a negative impact on financial performance, which may be related to the characteristics that most of the new energy enterprises are in the growth period. During the growth period, the smaller the size of the enterprise is, the more the equity incentives can cover the

TABLE 5 The pearson correlation coefficient between the main variables.

	FP	POST	SO	Duration	Condition	ES	CPS	OC	IBR
FP	1								
POST	0.101***	1							
SO	0.212***	0.224***	1						
Duration	0.385***	0.161***	0.042**	1					
Condition	0.627***	0.077***	0.223***	0.475***	1				
ES	−0.043**	−0.036*	0.009	−0.071***	−0.018	1			
CPS	−0.515***	−0.011	0.003	−0.256***	−0.428***	0.203***	1		
OC	0.031*	−0.108***	−0.163***	−0.001	0.027	0.268***	−0.006	1	
IBR	−0.021	0.034*	−0.01	−0.025	−0.02	−0.005	0.037*	−0.001	1

TABLE 6 Regression analysis of equity incentives and financial performance of new energy companies.

	(1)	(2)	(3)	(4)	(5)
post	−0.039	0.015	0.033	0.045**	0.044*
	(0.028)	(0.027)	(0.023)	(0.023)	(0.023)
ES		−0.125***	−0.004	0.001	0.001
		(0.019)	(0.020)	(0.020)	(0.020)
CPS			−1.679***	−1.662***	−1.668***
			(0.131)	(0.127)	(0.127)
OC				0.641***	0.640***
				(0.119)	(0.119)
IBR					0.000***
					(0.000)
_cons	0.013	2.827***	0.882**	0.536	0.533
	(0.028)	(0.428)	(0.432)	(0.424)	(0.425)
N	2258	2258	2258	2258	2258
r2	0.008	0.022	0.269	0.301	0.301

Model (1) to (5) gradually increases the control variables, and model (5) adds all the control variables. After adding the control variables, the r-square of the model gradually becomes larger and the explanatory strength of the model increases. And it can be observed that adding control variables does not affect the significance of the equity incentive method, so the results are reliable and stable.

management and even the technological employees, and the greater the impact on the overall financial performance is. Capital structure and financial performance are negatively correlated. New energy enterprises are different from traditional enterprises with strong foundation, and if they carry too much debt, it may have a negative impact on the enterprises by putting great pressures. Ownership concentration is positively correlated with financial performance. A high degree of ownership concentration can play a better role in monitoring the behaviors of management and reducing agency costs. Enterprise growth is positively correlated with financial performance and is significant at the level of 0.01, which is consistent with the basic hypothesis that the higher the enterprise growth, the higher the incentive recipient's expectations of high future income and the motivation to work will increase, and at the same time such enterprises also face less capital pressures and can have better financial performance.

To test hypothesis 2, this section uses the equity incentive approach (SO) as the explanatory variable in Eq. 3 and the composite indicator of corporate financial performance (FP) as the explanatory variable in Eq. 3, and the regression results are shown in Table 7.

Table 7 shows the regression results of the effect of equity incentive method on corporate financial performance, after controlling for other factors, the SO coefficient is 0.151, which is significantly correlated at the 0.01 level, which means that companies that choose stock options will have better financial

TABLE 7 Regression analysis of equity incentive method and financial performance of new energy companies.

	(1)	(2)	(3)	(4)	(5)
SO	0.072***	0.091***	0.146***	0.151***	0.151***
	(0.025)	(0.024)	(0.022)	(0.021)	(0.021)
ES		−0.125***	−0.001	0.004	0.005
		(0.011)	(0.010)	(0.010)	(0.010)
CPS			−1.720***	−1.703***	−1.710***
			(0.069)	(0.068)	(0.069)
OC				0.641***	0.641***
				(0.090)	(0.090)
IBR					0.000
					(0.000)
_cons	−0.011	2.811***	0.817***	0.462**	0.461**
	(0.025)	(0.239)	(0.222)	(0.225)	(0.225)
N	2258	2258	2258	2258	2258
r2	0.021	0.030	0.290	0.321	0.321

TABLE 8 Regression analysis of exercise period and financial performance of new energy companies.

	(1)	(2)	(3)	(4)	(5)
Duration	0.067***	0.062***	0.046***	0.045***	0.045***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
ES		−0.107***	−0.002	0.004	0.005
		(0.010)	(0.010)	(0.010)	(0.010)
CPS			−1.507***	−1.495***	−1.502***
			(0.069)	(0.068)	(0.069)
OC				0.565***	0.565***
				(0.090)	(0.090)
IBR					0.000
					(0.000)
_cons	−0.204***	2.222***	0.612***	0.282	0.281
	(0.028)	(0.233)	(0.220)	(0.225)	(0.225)
N	2258	2258	2258	2258	2258
r2	0.165	0.148	0.337	0.364	0.364

performance compared to restricted stock, and also company size and capital structure are significant, and hypothesis 2 is initially valid.

In order to test hypothesis 3, this section uses the exercise validity period (Duration) as the explanatory variable of Formula (4) and the explanatory variable of the composite indicator of corporate financial performance (FP) Formula (4), and the regression results are shown in Table 8.

TABLE 9 Regression analysis of exercise conditions and financial performance of new energy companies.

	(1)	(2)	(3)	(4)	(5)
Condition	0.502**	0.474**	0.363**	0.352**	0.351**
	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)
ES		−0.060***	0.017*	0.019**	0.019**
		(0.009)	(0.010)	(0.010)	(0.010)
CPS			−1.270***	−1.269***	−1.274***
			(0.067)	(0.066)	(0.067)
OC				0.444***	0.444***
				(0.082)	(0.082)
IBR					0.000
					(0.000)
_cons	−0.245***	1.133***	0.038	−0.153	−0.154
	(0.020)	(0.213)	(0.207)	(0.209)	(0.209)
N	2258	2258	2258	2258	2258
r2	0.378	0.362	0.444	0.455	0.455

Table 8 shows the regression results of the effect of exercise validity period on the financial performance of new energy enterprises, after controlling for other factors, the Duration coefficient is 0.045, which is significantly correlated at the level of 0.01, while the four control variables capital structure and equity concentration are significant, and these regression results initially verify that hypothesis 3 holds, indicating that in listed new energy enterprises, the equity incentive program The longer the effective period, the more beneficial to improve the financial performance of the enterprise. This may be because the improvement of financial performance brought by equity incentives often requires companies to carry out technological innovation, investment projects, *etc.*, and their impact on their financial performance is time-bound, and the R&D process is longer, plus it still takes time to convert how the research results are converted into profits, so this is an important reason why the longer the validity period of equity incentive programs is more beneficial to the improvement of corporate financial performance.

In order to test hypothesis 4, this section uses the exercise condition (Condition) as the explanatory variable of Eq. 5 and the composite indicator of corporate financial performance (FP) as the explanatory variable of Eq. 5, and the regression results are shown in Table 9.

Table 9 shows the regression results of the effect of exercise conditions on the financial performance of new energy enterprises. After controlling other factors, the coefficient of Condition is 0.351, and the independent variable exercise conditions is statistically significant with the financial performance of enterprises, and hypothesis 4 is initially valid, that is, in listed new energy enterprises, setting relatively strict exercise conditions for equity incentive programs is more conducive to improving the financial performance of enterprises. For the equity incentive, the exercise conditions are difficult to achieve, which can make the employees

TABLE 10 Robustness test results1.

Explanatory and control variables	Explained variable: Return on net assets (ROE)			
	1	2	3	4
post	0.074**			
	(0.035)			
SO		0.058*		
		(0.038)		
Duration			0.025***	
			(0.006)	
Condition				0.036*
				(0.033)
ES	0.065***	0.067***	0.065***	0.067***
	(0.014)	(0.013)	(0.013)	(0.013)
CPS	−0.720***	−0.733***	−0.629***	−0.688***
	(0.092)	(0.092)	(0.095)	(0.101)
OC	0.251**	0.228**	0.210**	0.206**
	(0.099)	(0.098)	(0.098)	(0.099)
IBR	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
_cons	−1.187***	−1.214***	−1.279***	−1.245***
	(0.280)	(0.279)	(0.278)	(0.279)
N	0.065***	0.067***	0.065***	0.067***
R^2	(0.014)	(0.013)	(0.013)	(0.013)

more motivated and really make the incentive targets operate the enterprise according to the principle of maximizing shareholders' value. If the exercise conditions are set too simple, it may become an opportunistic way to seek benefits for the incentive recipients.

4.4 Robustness test

To further confirm the effect of equity incentive and equity incentive covenant elements on corporate financial performance, a robust type test was conducted by changing the corporate financial performance variable (FP) to return on net assets (ROE) and return on assets (ROA) to re-run the regressions, and the regressions of equity incentive (POST), equity incentive method (SO), exercise period (Duration), and exercise condition (Condition) and return on net assets (ROE) are regressed in Tables 10, 11, and all three contractual elements of equity incentive and equity incentive are significantly correlated at the level of 0.1 and above.

Regression analysis with tobit regression instead of fixed effects, the regression results can be obtained in Table 12, which shows that the results are still significant and the sign is as expected, hypothesis 1, hypothesis 2, hypothesis 3 and hypothesis 4 are verified, and this paper passes the robustness test.

4.5 Causal analysis of equity incentives on financial performance of new energy enterprises

Despite of the significant results of the above regression analysis, it does not directly prove that it is indeed the equity incentives that affect the financial performance of enterprises, which is mainly due to the endogeneity of equity incentives. First of all, the relationship between equity incentives and financial performance may supplement each other, which means that equity incentives can improve financial performance and that only enterprises with good financial performance are more likely to choose equity incentives to reward employees. Second, some of the key variables may not be considered in the model. Finally, the selection of the sample may be biased. In view of this, Granger causality analysis is next conducted to address the possible problems.

In the analysis, if the fixed panel data is not used, the spurious regression situation is easy to occur. Therefore, before analyzing the data, the original data of equity incentives, equity incentive contract elements and financial performance were validated in order to test the stability of the data. The results are shown in Table 13.

As shown in Table 13, the original data panel of equity incentives, equity incentive contract elements, and financial

TABLE 11 Robustness test results2.

Explanatory and control variables	Explained variable: Return on assets (ROA)			
	1	2	3	4
post	0.020***			
	−0.003			
SO		0.034***		
		−0.003		
Duration			0.008***	
			−0.001	
Condition				0.049**
				−0.003
ES	0.005**	0.006***	0.005***	0.006***
	−0.001	−0.001	−0.001	−0.001
CPS	−0.132***	−0.137***	−0.102***	−0.075***
	−0.009	−0.009	−0.01	−0.009
OC	0.060***	0.054***	0.049***	0.027***
	−0.011	−0.01	−0.011	−0.01
IBR	0	0	0	0
	0	0	0	0
_cons	−0.04	−0.058**	−0.073**	−0.105***
	−0.029	−0.028	−0.03	−0.027
N	2258	2258	2258	2258
R^2	0.142	0.17	0.196	0.24

performance is stable and allows for subsequent empirical analysis. This chapter conducts Granger causality analysis for short-run (one lag), medium-run (two lags), and long-run (three lags) respectively.

First, a causal test of equity incentives on the financial performance of the firm is conducted. The results are presented in Table 14.

The test results in Table 14 show that the *p*-value is 0.014 for one lag, 0.329 for two lags, and 0 for three lags, which indicates that equity incentives and corporate financial performance, selected in this paper, exhibit the following causal relationship in terms of statistical significance: at one and three lags, for corporate financial performance, equity incentives are its Granger at 1% confidence level cause, while corporate financial performance is not the cause of equity incentives.

Next, the causality test of equity incentive approach on corporate financial performance is conducted. The results are presented in Table 15.

From the test results in Table 15, we can see that the *p*-value is 0 for one lag, 0.153 for two lags, and 0.336 for three lags, which indicates that the equity incentive approach and corporate financial performance selected in this paper exhibit the following causal relationship in statistical significance: at one lag, for corporate financial performance, the equity incentive approach is its Granger at 1% confidence level cause, while corporate financial performance is not a cause of equity incentive method.

Again, the causality test of exercise validity on corporate financial performance is conducted. The results are presented in Table 16.

The results of the test in Table 16 show that the *p*-value is 0 for one lag, 0.648 for two lags, and 0 for three lags, which indicates that the exercise validity period and corporate financial performance, selected in this paper, exhibit the following causal relationship in terms of statistical significance: for corporate financial performance at one and three lags, the exercise validity period is its Granger cause at the 1% confidence level, while corporate financial performance is not a cause of exercise expiration date.

Finally, causality tests of exercise conditions on corporate financial performance are conducted. The results are presented in Table 17.

The test results in Table 17 show that the *p*-value is 0 for one lag, 0.97 for two lags, and 0.07 for three lags, which indicates that the exercise condition and corporate financial performance selected in this paper exhibit the following causal relationship in terms of statistical significance: for corporate financial performance at one and three lags, the exercise condition is its Granger cause at the 1% confidence level, while corporate financial performance is not a cause of the exercise condition.

TABLE 12 Robustness test results3.

Explanatory and control variables	Explanatory variable: Firm financial performance (FP)			
	1	2	3	4
post	0.103***			
	−0.021			
SO		0.212***		
		−0.022		
Duration			0.055***	
			−0.003	
Condition				0.466***
				−0.018
ES	0.051***	0.050***	0.048***	0.044***
	−0.008	−0.008	−0.008	−0.007
CPS	−1.618***	−1.636***	−1.407***	−1.042***
	−0.056	−0.055	−0.055	−0.054
OC	0.516***	0.498***	0.448***	0.264***
	−0.06	−0.059	−0.057	−0.053
IBR	0	0	0	0
	0	0	0	0
_cons	−0.591***	−0.589***	−0.759***	−0.819***
	−0.17	−0.167	−0.162	−0.149
var(e.fp)	0.178***	0.173***	0.161***	0.137***
	−0.005	−0.005	−0.005	−0.004
N	2258	2258	2258	2258

TABLE 13 Unit root test.

Variables	Difference order	ADF statistic	*p*	Critical value		
				1%	5%	10%
FP	0	−7.881	0	−3.457	−2.873	−2.573
POST	0	−8.227	0	−3.457	−2.873	−2.573
SO	0	−22.207	0	−3.457	−2.873	−2.573
Duration	0	−14.162	0	−3.457	−2.873	−2.573
Condition	0	−8.91	0	−3.457	−2.873	−2.573

TABLE 14 Granger test of equity incentives on the financial performance of firms.

Lagged year	Coefficients	Standard error	z	P > z	[95% Conf	Interval]
L1	0.110465	0.045021	2.45	0.014	0.0222254	0.1987047
L2	−0.0485009	0.0496799	−0.98	0.329	−0.1458716	0.0488699
L3	−0.224132	0.047853	−4.68	0	−0.3179223	−0.1303418

TABLE 15 Granger test of equity incentive approach on corporate financial performance.

Lagged year	Coefficients	Standard error	z	P > z	[95% Conf.	Interval]
L1.	0.2184058	0.0440985	4.95	0	0.1319742	0.3048373
L2.	0.0639312	0.0446969	1.43	0.153	−0.0236731	0.1515355
L3.	0.0409777	0.042634	0.96	0.336	−0.0425834	0.1245389

TABLE 16 Granger test of equity incentive approach on the financial performance of the firm.

Lagged year	Coefficients	Standard error	z	P > z	[95% Conf	Interval]
L1	0.051228	0.0095089	5.39	0	0.0325909	0.0698651
L2	0.0042414	0.0092914	0.46	0.648	−0.0139695	0.0224523
L3	0.0401026	0.0083197	4.82	0	0.0237963	0.056409

TABLE 17 Granger test of exercise conditions on firm's financial performance.

Lagged year	Coefficients	Standard error	z	P > z	[95% Conf	Interval]
L1.	0.1699396	0.0487935	3.48	0	0.0743062	0.2655731
L2.	0.0017996	0.0477148	0.04	0.97	−0.0917198	0.0953189
L3.	0.0844666	0.0466832	1.81	0.07	−0.0070308	0.175964

TABLE 18 Results of gray correlation coefficients.

	Share incentive method	Exercise period	Exercise conditions
1	0.927	0.514	0.888
2	0.970	0.455	0.852
3	0.991	0.496	0.836
4	0.949	0.334	0.869
5	0.961	0.457	0.859
6	0.991	0.547	0.991
7	0.991	0.496	0.836
8	0.821	0.546	0.987
9	0.816	0.544	0.980
10	0.820	0.545	0.986
11	0.840	0.498	0.840
12	0.957	0.419	0.862
13	0.927	0.465	0.888
14	0.911	0.469	0.903
15	0.933	0.464	0.883

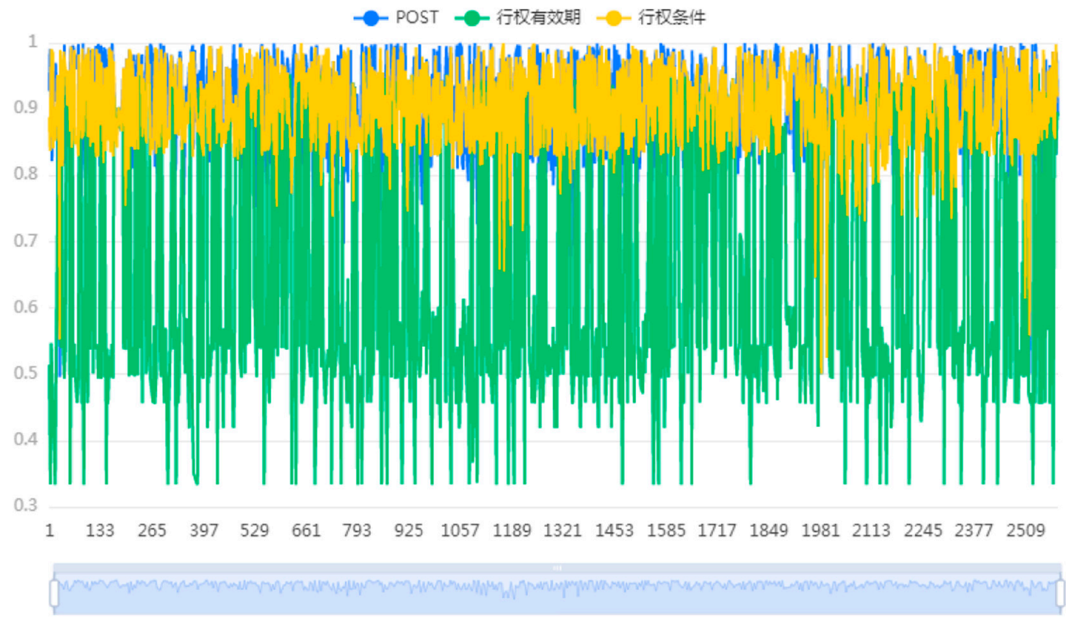

FIGURE 1
Correlation coefficient chart.

TABLE 19 Gray correlation.

Evaluation items	Relevance	Rank
Equity Incentive Method	0.913	1
Exercise Conditions	0.907	2
Exercise Period	0.649	3

4.6 Analysis of the degree of influence of equity incentive contract elements on the financial performance of new energy enterprises

In order to further determine the degree of influence of the equity incentive contract elements on the financial performance of new energy enterprises, this section conducts gray correlation analysis on 2258 data items, uses the financial performance of enterprises as the reference value, that is, the parent series, to study the correlation between the three evaluation items and the financial performance of enterprises, and provides a reference for the degree of influence of the equity incentive contract elements based on the correlation degree. When using the gray correlation analysis, the identification coefficient is 0.5, and the correlation coefficient is calculated by combining with the formula of correlation coefficient, and then the correlation coefficient is calculated based on the correlation coefficient value for the evaluation judgment. The smaller the ρ value is, the greater the identification power is, and the general value range of ρ is (0, 1), and the specific value is dependent on the situation. When $\rho \leq 0.5463$, the identification power is the best, and $\rho = 0.5$ is usually taken, as shown in Table 18.

Table 18 shows the results of the gray correlation coefficients. The correlation coefficient represents the value of the degree of correlation between the sub-series and the parent series in the corresponding dimensions, and the larger the number, the stronger the correlation. The preliminary results are that the gray correlation coefficient is the largest for the equity incentive approach, followed by the exercise conditions and the smallest exercise duration.

Figure 1 shows the graph of the results of the gray correlation coefficients, in which the values of the degree of correlation can be observed. The vertical dimension of the equity incentive method is significantly greater than the exercise conditions and the exercise period.

Table 19 shows the specifically calculated gray correlations. After further processing the data, the final correlation values are obtained and ranked for the three equity incentive contract elements including equity incentive method, exercise duration, and exercise conditions, it can be obtained that the equity incentive method has the highest degree of influence on financial performance with a correlation of 0.913, followed by exercise conditions with a correlation of 0.907, and the exercise duration with a correlation of only 0.649, which has the lowest degree of impact on financial performance.

Table 20 shows the degree of influence of gray correlations. Based on the comparison, the two elements of the equity incentive contract, namely, equity incentive method and

TABLE 20 Table of grey correlation impact degree.

Relevance range	[0,0.2]	(0.2,0.4]	(0.4,0.6]	(0.6,0.8]	(0.8,1.0]
Strength of association	Very poor	Poor	Fair	Good	Very good

exercise conditions, are very well correlated, while the exercise duration is an average correlated element. The reasonableness of the equity incentive scheme depends on the reasonableness of the equity incentive elements. The listed enterprises often need to consider many factors when formulating the equity incentive schemes, and this study finds that the two key elements, the equity incentive method and the exercise conditions, have a greater influence on the financial performance of the new energy enterprises, in other words, they have a greater impact on the whole equity incentive scheme. Therefore, when the listed enterprises formulate the equity incentive schemes, they can preferentially consider the selection of the equity incentive method and the formulation of the strict exercise conditions or not, followed by the consideration of the exercise duration, and finally ensure the feasibility of the scheme as a whole.

5 Conclusion and recommendations

This paper mainly studies whether equity incentives can improve the financial performance of A-share listed new energy enterprises in China, and further studies whether all the three contract elements of equity incentives will have the implementation effect, and whether there is a difference in the effect of the three different contract elements of equity incentives on the financial performance of enterprises, and obtains the following results:

(1) In the listed new energy enterprises, equity incentives can positively affect the financial performance of new energy enterprises as a whole.
(2) The incentive effect of equity incentives on financial performance of listed new energy enterprises is more significant when the granting method is stock options. Restricted stock is less risky, and the recipients can get restricted stock without paying cost or only need to pay a little cost, and in order to prevent the loss of interest, the recipients may avoid some high-risk and high-return projects and choose smooth transition to prevent the downward trend of the stock. And stock option is actually a kind of call option, the incentive recipients must find a way to improve the enterprise market value if they want to get a higher return.
(3) The longer the duration of the equity incentive scheme of listed new energy enterprises, the better it is to improve the financial performance of the enterprises. China stipulates that the duration of the equity incentive is generally set within 10 years, but according to the sample data, most of the enterprises choose a shorter duration, and the average duration of the sample enterprises is only 3.147, which means that the duration set by the new energy enterprises in China is relatively short, which may not be conducive to the equity incentives to play its incentive role.
(4) In the listed new energy enterprises, it is more beneficial to improve the financial performance of the enterprises by setting relatively strict exercise conditions for the equity incentive scheme. At present, China's equity incentive exercise conditions are set relatively loose, and the relevant regulatory departments do not specify the incentive conditions in the equity incentive contract elements, so that enterprises that set stricter conditions can make the incentive recipients work harder to achieve their goals.

New energy industry is one of the strategic emerging industries in the 12th Five-Year Plan for National Economic and Social Development, and its development has been paid more and more attention. New energy enterprises have encountered a lot of obstacles in the development process, such as a principal-agent relationship within the new energy enterprises and the problem of equity incentives. Therefore, it is crucial to establish an effective and reasonable equity incentive mechanism based on past data. This is not only a review and reflection on the implementation effect of equity incentives in the past, but also provides opinions and references for the formulation of equity incentives in the future.

Combined with the above findings, this paper proposes the following suggestions: Firstly, stock options are more significant to improve the financial performance of enterprises, so it is suggested that new energy enterprises can choose more stock options or combine the restricted stock and stock options in a certain proportion to jointly carry out equity incentives. Secondly, the longer the duration of the equity incentive scheme, the better it is for improving the financial performance of the enterprises. It is suggested that the new energy enterprises should set the duration of the equity incentive scheme between 5 and 10 years, but considering the degree of influence, the enterprises can finally think about the length of the exercise duration. Finally, the relatively strict exercise conditions for equity incentives are more conducive to improving the financial performance of the enterprise. It is suggested that when setting the conditions of equity incentives, new energy enterprises should set more strict conditions, and can introduce a combination of multiple indicators to fully reflect the different aspects of the enterprise. While designing the incentive conditions, the enterprise should preferably choose some benchmarks, such as industry standard horizontal comparison or vertical comparison of past years' performance, and also set some non-financial indicators as incentive conditions, such as the degree of achievement of strategic goals, innovation ability, market share, *etc.*, in conjunction with the characteristics of new energy itself.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.gtarsc.com/.

Author contributions

KC: Conceptualization, Visualization, Writing—review and editing. YY: Writing—review and editing. PJ: Methodology, Data curation, Software, Writing—original draft, Writing—review and editing. HB: Visualization, Supervision, Validation, Writing—review. TN: Writing—review, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Spectrum sensing-focused cognitive radio network for 5G revolution

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The cognitive radio network (CRN), an instrumental part of the next-generation wireless communication systems, is mainly dependent on spectrum sensing to function properly. The radio spectrum can help in clean energy transition and load capacity factors by providing a more efficient and accurate spectrum utilization. By using it, the number of spectrums that is used for communication can be optimized, which can reduce the amount of energy consumed by the network. Additionally, 5G radio spectrum sensing can be used to identify and classify different types of signals, which can help reduce the amount of interference in the network and improve the efficiency of energy utilization. It can also allow for the digitization of clean energy infrastructure and facilitate better decision-making processes that take into account environmental impacts while optimizing energy use because of its efficient characteristics like non-linearity, detection, scalability, robustness, generalization, non-stationarity in wireless environments, dynamic entity, weighted sum of Gaussian functions centered at specific frequencies, and robustness against noise and interference. It can adapt to noise and interference by adjusting its parameters, and this allows accurate distinguishing between primary and secondary users in the wireless spectrum, which is why a radial basis function is a popular choice for spectrum sensing in 5G networks. Radial basis function networks (RBFNs) can work better in 5G spectrum sensing for better signal classification, dynamic adaptation, fast detection, faster decision-making, and improved noise and interference reduction. One of the most sought-after goals in the field of wireless research is the creation of spectrum-sensing technology that is dependable and intelligent because multilayer learning approaches are inappropriate for dealing with time-series data due to the higher misclassification rate and inherent computational complexity. To address this, the study proposed the radial basis function network that learns the temporal aspects from spectral data and makes use of additional environmental statistics such as frequency, efficiency, energy, spectrum allocation, distance, and duty-cycle time, which are considered environmental data that may be used to fine-tune sensor performance. The scheme is simulated with real-time parameters, and the results are quite promising in terms of evaluation parameters.

KEYWORDS

5G, spectrum sensing, radial basis function, energy detection, cognitive radio network

1 Introduction

Spectrum development and network system compatibility are significant issues in realizing the complete vision and benefits for future generations (Ali & He, 2019; Ali et al., 2020). Furthermore, such policies may foster the development and competitiveness of innovative spectrum techniques and services that may be useful in energy management and environmental safety. A licensed spectrum can temporarily be accessed by secondary users (SUs) using a cognitive radio network, when there is no principal user. In backward induction, each SU performs the task of sensing the spectrum and conveying the details to the central controller. AI has become essential for effective communication in recent years. 5G standards are compatible with wireless equipment. Cognitive radio (CR) is a type of sophisticated scientific communication, in which the radio spectrum uses are managed (Devaraj et al., 2022). Interference during spectrum sensing, detection, and transmission requires the use of orthogonal frequency division multiplexing (OFDM) based on the cognitive radio network co-operative spectrum awareness resource allocation (CRN-CSS) (Meena & Rajendran, 2022). Ultra-dense networks (UDNs) provide high-throughput high-performance and user-centric wireless access to 5G deployments. Cognitive Radio integrates UDNs with legacy systems without allocating new airwaves, which would be expensive. The research reflects the advantages and disadvantages of the most widely known algorithm of this type, energy detection (ED), its probability, and performance evaluation (Ivanov et al., 2022). Co-operative communication in 5G networks is a rapidly evolving field that will be vital for the efficiency of future spectrums. Cognitive radio systems must recognize primary/principal (licensed) users across a large spectrum with a specified location and time. The consideration of user participation is motivated by the notion that sharing power and computing with adjacent nodes results in network energy resource savings (Banumathi et al., 2022). Wireless applications encounter spectrum overcrowding. Network obstruction causing call dropouts is another worry. These issues must be resolved for 5G and beyond to overcome spectrum overpopulation and networking. Therefore, energy detection and efficiency prediction is being determined (Eappen et al., 2022). Spectrum inadequacy causes roll-out, planning, and execution challenges for 5G and beyond. The growing number of wireless customers, traffic needs, poor spectrum distribution, and co-existence issues causes this spectrum deficit. A free wireless spectrum is essential. Using cognitive radio's spectrum-sensing functionality in-between the sub-THz band range (0.1–1 THz) for beyond the 5G communication networks, the open spectrum can be forecasted and modeled. Therefore, energy detection, prediction, accuracy, probability, and time detection are examined in this research (Kansal et al., 2022). Wireless technology reduces spectrum resources. The ability to detect and analyze signals over a broad frequency range is an essential part of cognitive radio systems. So, wideband spectrum sensing is a crucial, important, and essential part of cognitive radio technology, allowing for dynamic spectrum allocation and function properly. However, the energy detection and allocation resource technique is performed to utilize the energy resources (Ju et al., 2021). The remaining portions of this study are arranged as follows: Section 2 presents the literature review. The proposed methodology is described in Section 3. The findings and discussion in Section 4 are followed by the conclusion in Section 5.

2 Literature review

In wireless channels, it is necessary to have accurate path loss prediction models to achieve correct signal propagation and energy detection. The deterministic and empirical methods utilized to predict path loss did not produce the best possible outcomes. Support vector regression and radial basis function (RBF) models were evaluated to increase the precision of path loss predictions in the environment (Mohanakurup et al., 2022). The accomplishment of the visible light communication (VLC) system is severely hindered because of the non-linearity that is caused by light-emitting diodes (LEDs), which interferes with the regular transmission and reception processes. A post-distorter for orthogonal frequency-division multiplexing depends upon very low power communication, which solves the problem that is caused by the non-linearity of LEDs. To apply non-linearity mitigations, the radial basis function interpolation, which is well-known for being an outstanding approach for function approximation, is being examined (Ojo et al., 2022). Light-emitting diodes used in visible light communication systems are the principal causative factors behind signal distortion due to their intrinsic non-linear features. The polynomial method is used to construct the post-distorter to mitigate the non-linear effect that is caused by the LED to increase the reliability of the system. The non-linear effect can also be mitigated with the use of radial basis function interpolation, which possesses powerful processing capabilities and high levels of solution accuracy (Zhang et al., 2022). These systems use a wide range of optoelectronic components, including photodiodes. LEDs' non-linear features impose constraints on the system's performance. Meanwhile, the high peak-to-average power ratio generated with the orthogonal frequency-division multiplexing modulation worsens the non-linear distortion, which is why it is desirable to mitigate the impacts of a non-linear distortion. The authors purposed radial basis function interpolation and employed a post-distortion technique combining RBF with memory effect depression (MED), which effectively suppresses the non-linear and memory effects of LEDs. Their goal is to target the non-linear characteristics of LEDs, and to do so, we employ radial basis function interpolation (Chen et al., 2022). It is observed that the superconducting technology-based hardware implementation of signal microprocessors could be useful for a variety of specialized jobs, in which both performance and energy efficiency are of the utmost importance. Within the scope of this research, based on radial basis functions, we examine the essential components of superconducting neural networks (RBF) (Schegolev et al., 2022). Qureshi et al. (2014) presented a multiple relay selection scheme for underlay CRN in CSI. In this regard, they utilized FRBs and swarm intelligence to reduce the transmit power. The scheme seemed promising in terms of energy efficiency, but its time complexity was substantial. Therefore, we proposed a technique for intelligently reducing the transmit power in underlay CRN and multiple relay selection. The concept was inspired by the Artificial Bee Colony (ABC) (Rahman et al., 2014). The scheme was efficient in energy-saving but costly in terms of computational complexity.

RBF neural networks are considered universal optimizing networks and have been applied in the telecommunication field and other areas, and are one of the successful options for deep learning systems. In this regard, some of the most well-known algorithms in the relevant body of research are extreme learning machines (ELMs) and long short-term-based systems.

Algorithm RBF -Net (K, A, *0)* Input:
Sequence of labeled training patterns Z = ((X_1, Y_1)... (X_i, Y_i))
Number of RBF centers *K*
Regularization constant ⅄
Number of iterations *O*
Initialize:
Run *K*-means clustering to find initial values for μ_K and determine σ_{k}, $k = 1, K$, as the distance between μ_K and the closest $\mu_{i.}$ $(I \neq k)$.
Do for o= 1: *O*.
Compute optimal output weights w = $(G^T G + 2⅄/i)^{-1} G^T Y$.
Compute gradients $\frac{\partial}{\partial uk}$ E and $\frac{\partial}{\partial uk}$ *E* as in and with optimal w and form a gradient vector v

3 Proposed methodology

3.1 Algorithm overview

RBF networks are utilized in mathematical modeling. This network activates with the radial basis function. The network output is a linear combination of neuron parameters and input RBFs. RBF networks can approximate functions, predict time series, classify data, and control systems. Broomhead and Lowe, Royal Signals and Radar Establishment researchers, initially formulated them in 1988. Radial basis function networks follow the conventional organizational format of three layers (input layer, hidden layer with a non-linear RBF activation function, and output layer with a linear function), where the input layer serves as the basis for the network and the hidden layer serves as the actual activation function. An acceptable representation for the input is a vector of real values. This scalar nature of the network's output may be seen in the following equation, which relates input and output vectors:

Estimate the conjugate direction Ā with the Fletcher–Reeves–Polak–Ribiere CG method.

Perform a line search to find the minimizing step size ჯ direction Ā; in each evaluation of E recomputed the optimal output weights w as in line 1.

Update σk and μk with Ā and ჯ

Output: Optimized RBF net.

3.2 Proposed model

Figure 1 shows that the length of the packet shown the same as that of all other packets and then data are transmitted. Following that, spectrum sensing is performed again to examine the current channel's operational state. If there is still space available on the channel, it will simultaneously transmit the second packet. This process can be repeated until all packet transmissions have been completed (provided that no arrival occurred during the transmission time). Even if the presently used channel is empty, the transmitter node will seek to switch to a different channel to free up the bandwidth that is being used by the present channel. This is referred to as PHO, which stands for "Proactive Hand Off." If the user has already been using the current channel before the actual transmission, then a HO should be made in a reactive or required manner as follows: the algorithm that we discussed is displayed in this figure. For 5G communications, TDMA, OFDMA, and CDMA are used to guarantee that no customers' signals would interfere with one another. This suggested work (CDMA) is enough to serve the requirements of the people who utilize wireless networks due to the rapid expansion of mobile devices. NOMA is gaining importance in 5G networks for multi-access systems. Multiple users can share the same frequency resources. There are two primary categories of domains: code and power; both are fundamental to NOMA approaches, and both will be covered in this article. In the previous section, we established that the power domain will serve as the principal focus of our investigation. In this configuration, many users can share the same time and frequency of resources to complete their respective data transfers. By superposing the signals of several users, all of them may share the same transmission channels. Subsequent interference cancellation, or SIC, is subsequently carried out to decipher the signals that users are meant to transmit and removes interference at the receiver end.

3.2.1 Dataset

This dataset includes over-the-air observations of legitimate radio signals modulated using eleven unique modulations generated from real-world radio broadcasts. This dataset was collected to compile this information. According to the authors, the signals were produced with the help of a USRP B210, which was linked to a computer operating GNU Radio to accomplish this goal. It was crucial to employ the same data sources and source code as before, when building the numerous transmitters, as they had to be compatible with RadioML 2016.10A. It is important to mention, to provide extra clarity, that earlier versions of the RadioML dataset contained discordantly with AM modulations. As a result of this discrepancy, the RadioML dataset was updated to correct future releases.

3.2.2 Network architecture

Radial basis function networks are typically multilayer networks consisting of an input layer, a hidden layer employing a non-linear RBF activation function, and a linear output layer. RBF network is the abbreviated form of radial basis function network. It would be feasible to depict the input modeled as a vector of real numbers, x∊ Rn. After that, the network's output is a scalar function of the input vector, φ:Rn̂ →R; it is given as follows:

$$\varphi(x) = \sum_{i=1}^{N} a_i \mathrm{P}\ (\|x - c_i\|). \tag{1}$$

To determine neuron I's weight in the linear output neuron, we use the following formula: N = number of neurons in the hidden layer, Ci = neuron I's center vector, and I = neuron I's weight. Here, we figure out how many neurons reside in the deepest part of the network. The term "radial basis function" refers to the functions that are radially symmetrical about a given vector and whose behavior is

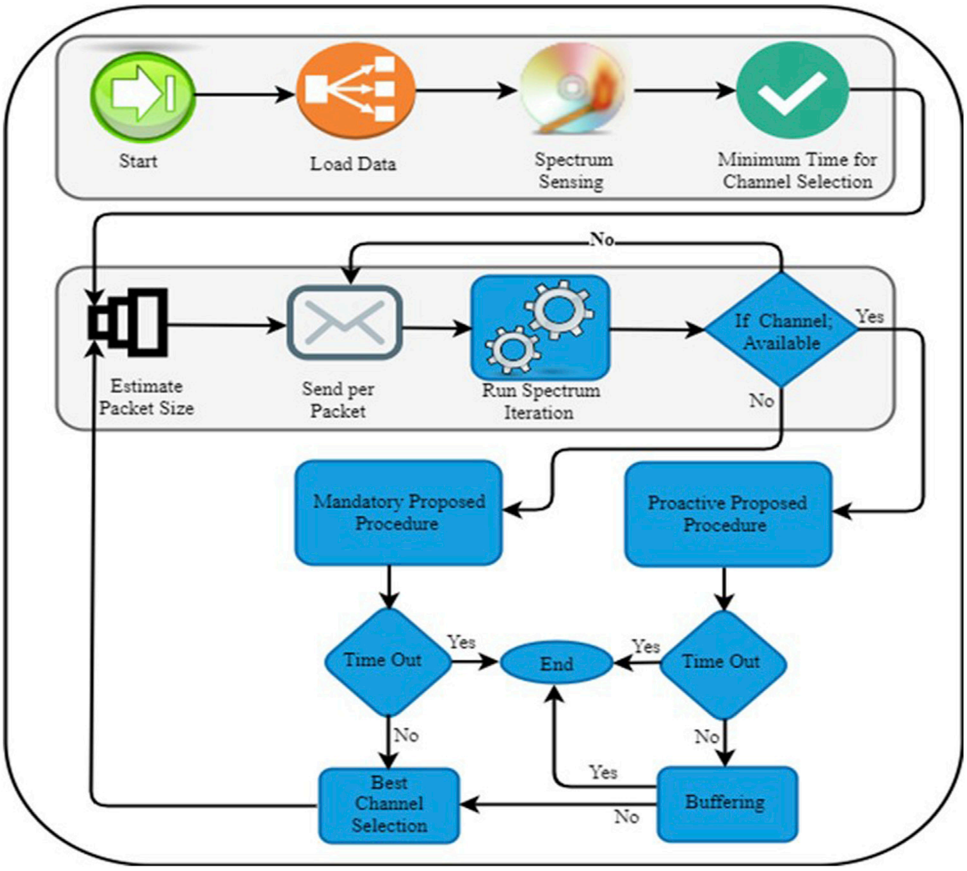

FIGURE 1
Proposed architecture for delay-sensitive image transmission in cognitive radio networks.

determined solely by the distance from a certain center vector. In its most fundamental form, each hidden neuron receives input from all the other hidden neurons. The Euclidean distance is generally considered a standard, even though the Mahalanobis distance [28] seems to perform better in pattern identification, and the radial basis function is typically considered to be the norm Gaussian function:

$$\rho(\|x - c_i\|) = \exp[\beta_i \|x - c_i\|^2. \quad (2)$$

Since Gaussian basis functions are constrained to the central vector, changing the parameters of a single neuron has a minor impact on the input values placed at the neuron's periphery:

$$\lim_{\|x\| \to \infty} \rho(\|x - c_i\|) = 0. \quad (3)$$

For a constrained region of Rn, RBF networks provide universal approximations under modest restrictions about the activation function's form. This indicates that every continuous function on a closed, limited set may be approximated arbitrarily well by an RBF network with sufficiently hidden neurons.

3.2.3 Normalized architecture

Although RBF networks are often unnormalized, they may also be normalized in the way that was previously explained. An example of such a mapping is a normalized radial basis function:

$$(\varphi)X \stackrel{\text{def}}{=} \frac{\sum_{i-1}^{N} \alpha i \rho(\|X - ci\|)}{\sum_{i-1}^{N} \rho(\|X - ci\|)} = \sum_{i-1}^{N} \alpha i u(\|X - ci\|), \quad (4)$$

where

$$u(\|X - ci\|) \stackrel{\text{def}}{=} \frac{\rho(\|x - c_i\|)}{\sum_{j-1}^{N} \rho(\|X - ci\|)}. \quad (5)$$

3.2.4 Training RBF

Generally, RBF networks are trained using pairs of input and target values, X(t), Y(t), t-1. . .by a two-step algorithm

$$K(W) \stackrel{\text{def}}{=} \sum_{t-1}^{T} K_t(W), \quad (6)$$

where

$$u(\|X - ci\|) \stackrel{\text{def}}{=} \frac{\rho(\|x - c_i\|)}{\sum_{j-1}^{N} \rho(\|X - ci\|)}. \quad (7)$$

Selecting the Ci-centers of RBFs in the hidden layer is the initial step, which may be accomplished in various ways; for instance, the centers can be selected at random from a given set of samples, or they can be established through the utilization of *K*-means clustering. We have to take into account the fact that this phase does not have any supervision. In the second stage, a linear model with coefficient Wi is applied to the outputs of the hidden layer,

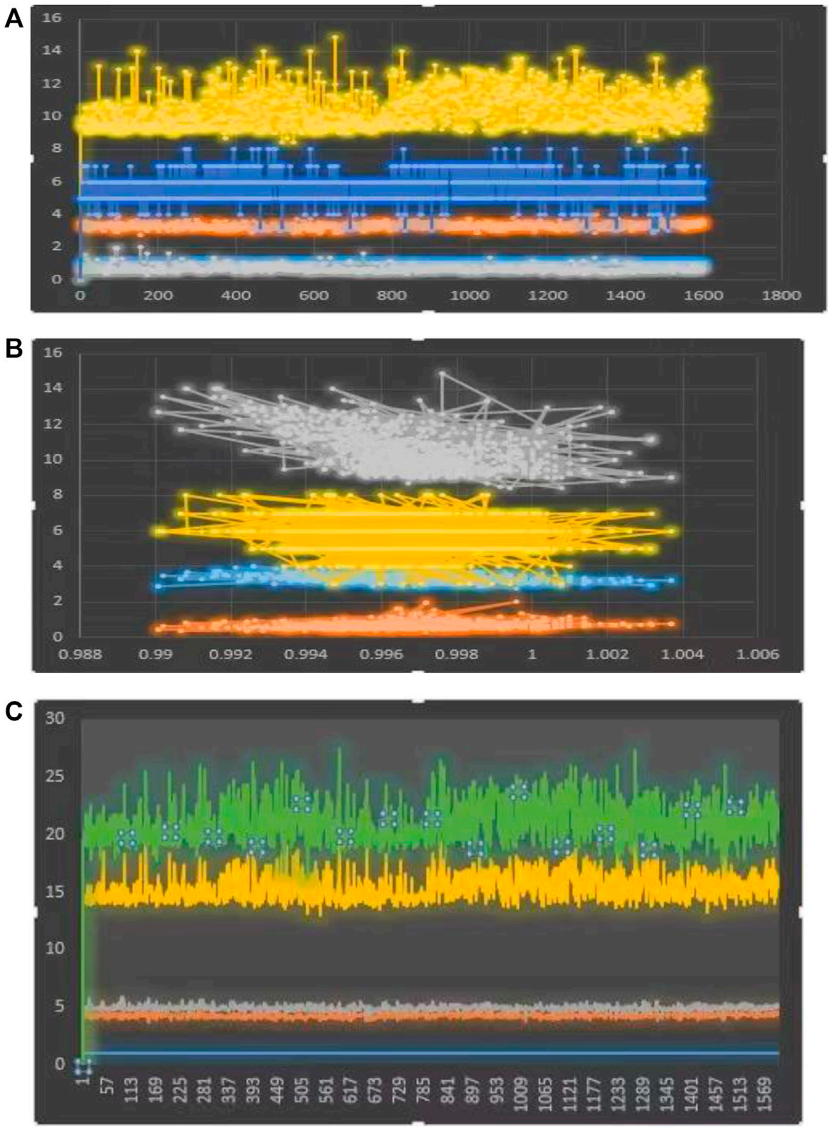

FIGURE 2
Differences in variations can be seen in Ref. (**A-C**) Signals variable parameters differences.

TABLE 1 Mathematical equations of confusion metrics.

Sensitivity	$\frac{TP}{TP+FN}$
Specificity	$\frac{TN}{TN+FP}$
Accuracy	$\frac{TP+TN}{TP+TN+FP+FN}$
Miss rate	$\frac{FN}{FN+TP}$
Fall out	$\frac{FP}{FP+TN}$
LR +	$\frac{TPR}{FPR}$
LR –	$\frac{FNR}{TNR}$
Precision	$\frac{TP}{TP+FN}$
Negative predicted value	$\frac{TP}{TP+FN}$

while considering some objective function. A common example of an objective function is the least square function, which is used in regression analysis and function estimation:

$$K_t(W) \overset{def}{=} \left[y(t) - \varphi(X(t), W)\right]^2. \tag{8}$$

Here, we explicitly included the dependency on the weights in the model. The precision of the fit can be improved by selecting the appropriate weights so that the objective function of least squares is minimized to its maximum. It is necessary to maximize not just one but several different goals, such as smoothness, in addition to accuracy. In such a scenario, maximizing a regularized objective function would be beneficial, such as the following:

$$\mathrm{H}(\mathrm{W}) \overset{def}{=} K(W) + \lambda S(W) = def \sum\nolimits_{t=1}^{T} H_t(W), \tag{9}$$

TABLE 2 Validation accuracy for the proposed algorithms.

Sr no.	Number of iterations	Validation accuracy
1	20	95
2	40	95.2
3	60	95.7
4	80	95.9
5	100	96.2
6	120	96.7
7	140	97.3
8	160	97.6
9	180	98.4
10	200	98.6

TABLE 3 Training accuracy for the proposed algorithms.

Sr no.	Number of iterations	Validation accuracy
1	20	95.3
2	40	95.4
3	60	95.8
4	80	95.9
5	100	96.2
6	120	96.8
7	140	97.6
8	160	98.9
9	180	98.8
10	200	99.3

where

$$S(W) \stackrel{\text{def}}{=} \sum_{t=1}^{T} S_t(W) \tag{10}$$

and

$$H_t(W) \stackrel{\text{def}}{=} K_t(W) + \lambda S_t(W). \tag{11}$$

4 Result and discussion

4.1 Discussion

4.1.1 Confusion metrics expression

In the context of machine learning and, more specifically, the problem of statistical classification, confusion matrices, also known as error matrices, are used to evaluate the performance of an algorithm, often a supervised learning one. Confusion matrices are also known as error matrices (in unsupervised learning, it is usually called a matching matrix, please see Ref. Table 1). Either the first permutation, in which each row of the matrix represents the instances that correspond to an actual class, or the second, in which each column of the matrix represents the examples that belong to a predicted class, can be used for the inclusion of the error matrix. Named thus because it's easy to see whether the system is confusing two categories and incorrectly labeling one as the valid target.

TABLE 4 Comparative study of algorithm performance from 45 to 2,207 MHz with a low signal-to-noise ratio (17 dBm–5 dBm) [9].

Sr no.	Algorithm	Accuracy (%)
1	Hybrid LSTM and ELM	0.984
2	Hybrid ANN-SS	0.925
3	Normal energy detector-SS	0.788
4	RF-SS	0.897
5	PALM-SS	0.937
6	LSTM-SS	0.969
7	Proposed RBFNs	99.3

Signal strength is an integer, whereas the other parameters are all expressed as floating-point numbers. Parameter 3 can assume values between 0 and 1, and the table has 1599 rows and 12 columns. Parameter 5 has a maximum allowable value of 0.6. The range of parameter 8 is quite narrow, from 0.9 to 1.004. Number 8 has the smallest standard deviation. Classifications for its 0.000187 "signal strength" are 3.5, 4.0, 5.0, 7.0, and 7.5. The mean, median, and mode are almost overlapping or too close to each other, except in parameter 7, and parameter 3 is trimodal and its signal strength is a classification variable. All of them are positively skewed. The standard deviation is the highest for parameter 7, i.e., 32.895324478299074. Class 5 has the highest count in "signal_strength." Parameters 6 and 7 are highly correlated with each other and *vice versa,* and they have 0 correlations with another parameter. Parameter 1 is positively correlated with parameter 3 and parameter 8 and negatively correlated with parameter 2 and parameter 9. Parameter 4 has a very low correlation with other parameters. Parameter 4 has the highest number of outliners, which is 155, since the high coefficient value lies between ± 0.5 and ± 1. Parameter 1 is highly correlated with parameter 3 and parameter 8. Parameters 6 and 7 are highly correlated, but since the correlation is not too high near 0.8 and above, no decrease in feature support is observed. Almost all parameters have mean, median, and mode values that are too close together or overlap, except for parameter 7. Parameter 3 is trimodal, and signal strength is a categorical variable. They are all positively slanted in one direction or another. Parameter 7 has the largest standard deviation, with a value of −32.895324478299074. The highest count may be found in the "signal strength" of class 5. The correlation between parameters 6 and 7 is substantial, and they have no association with any other parameters. There is a positive correlation between parameters 1 and 3, and between parameters 1 and 8, but a negative correlation between parameters 1 and 9. The correlation between parameter 4 and the rest of the parameters is quite poor. The largest number of planners (total 155) may be found in parameter 4. As a result, the optimal range for coefficient values is 0.5–1. There is a strong relationship between parameter 1 and both parameter 3 and parameter 8. While there is a strong relationship between parameters 6 and 7, it is not strong

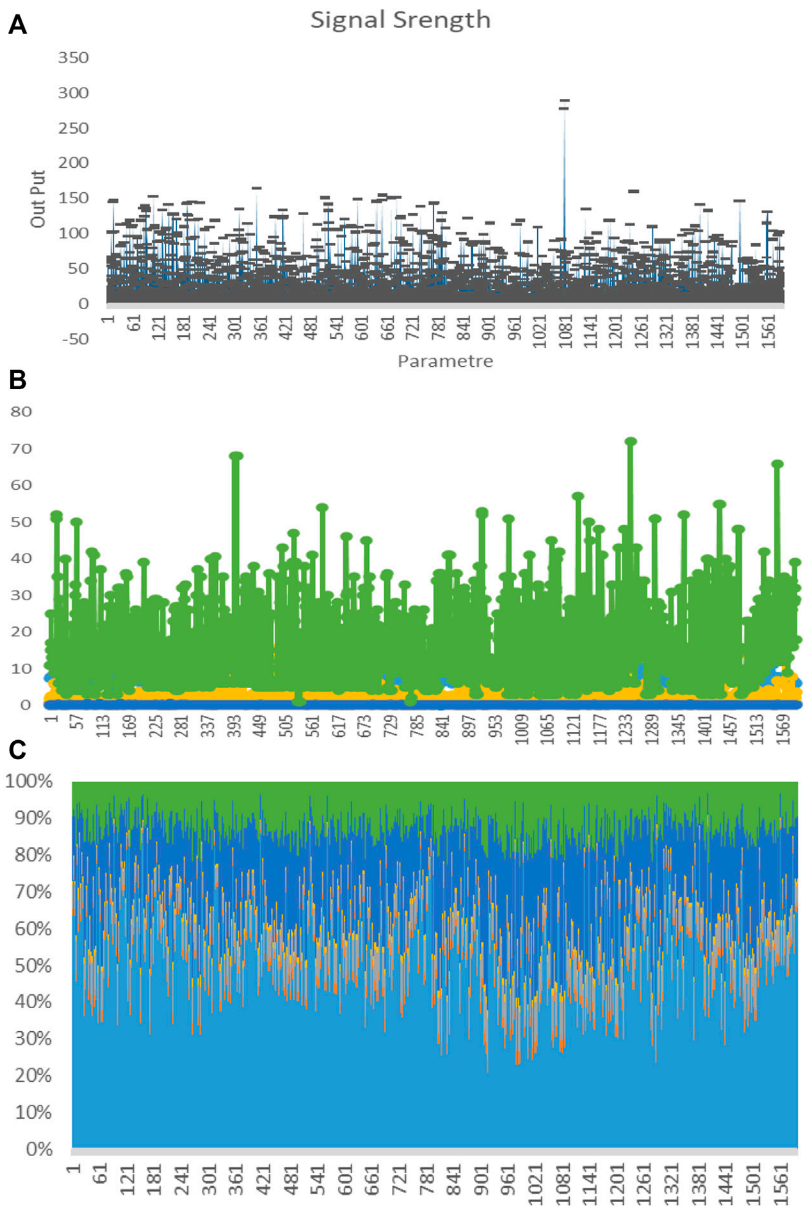

FIGURE 3
(A) Signal parameter and specific output. **(B)** Signal parameter and specific output. **(C)** Signal parameter and specific output.

enough to justify the elimination of feature support for them. The differences in variables are plotted in Figures 2A, B, C, respectively.

4.2 Results and analysis

Seventy percent of the data is used for training the proposed model, while the remaining thirty percent is used for validation. The data are fed into the model in chunks, and the output functions are computed. Table 2, Table 3, and Table 4 provide the evaluation and validation results for the proposed model's training and validation accuracies, respectively, while Figures 1, 3 provide graphical explanations of these results. The accuracy of both training and validation phases improves with an increase in iterations. Tables 3 and 4 show that the RBFN model selected has successfully dealt with the overfitting issue and is, therefore, well-suited for achieving the sought-after superior classification performance. When compared to six other algorithms, the RBFN's 99.3 percent maximum performance is far higher than that of a normal energy detector, which achieves just 78 percent. Therefore, all algorithms may agree that the RBFN performance is satisfactory.

4.3 Comparison of the proposed algorithm

Table 3 and Figure 5 analysis of existing algorithms with our proposed work at 45 to 2207 MHz and low to high SNR as −17 dBm to 5 dBm (decibel milliwatts). In Figures 4A, B, the training and

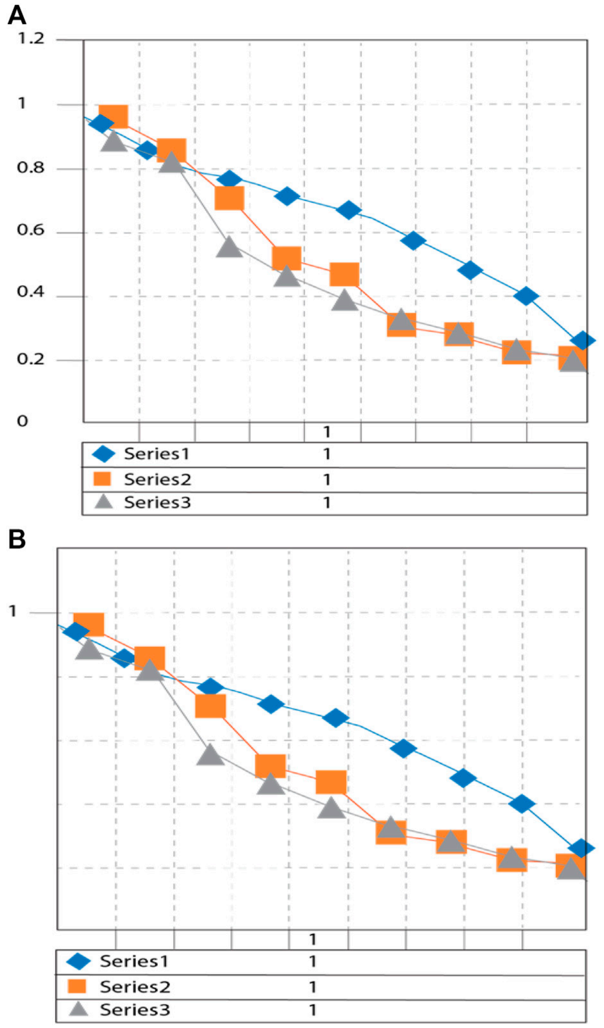

FIGURE 4
(A) Validation accuracy for the proposed algorithm. **(B)** Training accuracy for the proposed algorithm.

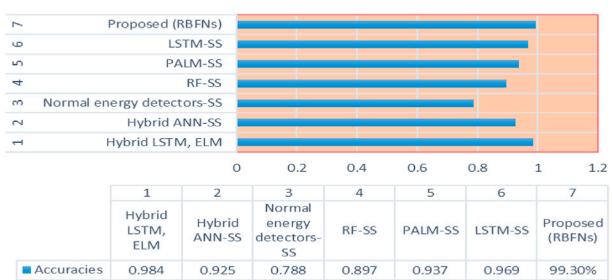

FIGURE 5
Analysis of the performance of the various methods at 45–2,207 MHz and low SNR (17 db–5 db).

validation of proposed algorithms show better accuracy than existing ones. Figure 3 shows the graphical representation of the analyzed algorithm with different bars.

5 Conclusion and future work

5G spectrum sensing can improve clean energy transition and load capacity factors by enhancing the environmental sustainability assessment through advanced statistical methods. It can allow for digitization of clean energy infrastructure and facilitate better decision-making processes that take into account the environmental impacts while optimizing energy use. Additionally, 5G spectrum sensing can help identify and analyze data related to the energy sources, their usage, and the associated environmental effects, which can provide insights that can be used to determine the best strategies for transitioning to clean energy sources and to increase the efficiency of energy networks and reduce the amount of energy used. Some of the reasons for choosing the RBFN are because it can be trained to classify different types of signals more accurately, such as differentiating between narrowband and wideband signals and detecting signal modulation schemes, noise reduction, and interference in the received signal, which can improve the accuracy of spectrum sensing. This can be carried out by training the network to recognize patterns in the received signal and filter out noise and interference. It can also be optimized to make faster decisions about the presence of primary users in the spectrum, which is important for real-time applications in 5G networks. Therefore, it can be designed to adapt to changes in the environment, such as variations in signal strength or the presence of other wireless devices by training the network on different scenarios and using adaptive learning algorithms. In this paper, we compared it to six other algorithms and found that RBFN's 99.3 percent maximum performance is far higher than that of a normal energy detector, which achieves just 78 percent. Therefore, all algorithms may agree that the RBFN performance provides satisfactory results, which are better than those of the previous studies in the literature. Additionally, the significant part of WSNs in spectrum sensing service transfer is studied, in which the RBFN performance was optimal. In addition, we also discussed the RBFN and its perspectives of frequency, efficiency, energy, and spectrum allocation. After doing a comprehensive analysis of the state of the art at the moment, we have identified several difficulties, some of which are quite remarkable, that call for more research.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Green finance and foreign direct investment–environmental sustainability nexuses in emerging countries: new insights from the environmental Kuznets curve

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The primary objective of the present study is to identify the asymmetric relationship between green finance, trade openness, and foreign direct investment with environmental sustainability. The existing research utilizes the asymmetric approach to evaluate annual data from 1980 to 2021. The findings of this study show heterogeneous results. Therefore, the outcomes of the study confirm the nonlinear (NARDL) association between the variables in Pakistan. Moreover, the study describes the positive shock of foreign direct investment (FDI) as a significant and positive relationship with environmental degradation, while the negative shock of FDI shows a negative and significant relationship with the environment. Furthermore, the study scrutinizes the positive shock of green finance as a significant and negative relationship with environmental degradation; the negative shocks also show a negative relationship with environmental degradation in Pakistan. In addition, the consequences of the study suggest that the government should implement taxes on foreign investment and that investors should use renewable energy to produce goods. Furthermore, the results suggest that the government should utilize fiscal policy and fiscal funds to enhance carbon-free projects. Moreover, green securities should be used for green technologies. However, Pakistan can control its carbon emissions and achieve the target of a sustainable environment. Therefore, Pakistan's government should stabilize its financial markets and introduce carbon-free projects. Furthermore, the main quantitative achievement according to the outcomes suggests that policymakers make policies in which they suggest to the government to control foreign investment that causes carbon emissions because of trade openness and also invest the funds in renewable energy, which helps to control the carbon emissions.

KEYWORDS

environmental degradation, trade openness, green finance, economic growth, NARDL approach

1 Introduction

Since the 1960s, global climate change has been a major issue worldwide; for example, ecological cataclysm, environmental pollution, land issues, and depletion of resources have become major worldwide concerns. These issues include total heating (Adebayo et al., 2021; Alvarado et al., 2021; Chen et al., 2021; Fu et al., 2021). Therefore, the world is facing challenges such as food shortages, global warming, environmental degradation, and depletion of resources which harm human life (Dagar et al., 2021; Pan et al., 2022; Shao et al., 2022; Alola and Kirikkaleli, 2019). Furthermore, the sea level is rising daily due to the increasing temperatures, which is an alarming situation for the whole world (Wang et al., 2021). For these challenges, the United Nations introduced the 17 Sustainable Development Goals (SDG), which include affordable renewable energy consumption, and climate activities (United Nations Development Programme, 2020). Moreover, many environmental effects have been produced by carbon and other greenhouse gas emissions in Pakistan. These emissions are producing air pollution and raising the temperature in Pakistan, and the ecosystem has been destroyed by CO_2 and GHG emissions (Apergis N., 2016; Sadiq et al., 2021). Moreover, according to the IPCC report (2014), during the previous 1,400 years, Pakistan's warmest period was from 1983 to 2012. During the last decades, energy consumption, fossil fuels, and industrial areas are the major factors in GHG emissions. Likewise, approximately 76% of greenhouse gases contribute to Pakistan's carbon emissions. Other gases like methane (16%) and nitrous oxide (6%) also contribute to air pollution. Furthermore, almost 76% of greenhouse gas emissions have increased due to forestry, agriculture, and energy production since the 1970s. Furthermore, Pakistan ranks seventh among the high carbon emission countries, indicating that Pakistan's climate condition is adverse and alarming. This condition is challenging for Pakistan's food production and energy security (economic survey, 2017). Likewise, air pollution leads to the increased incidence of many diseases such as heart disease, stroke, and lung cancer (Rahman et al., 2022). For instance, air pollution has reduced young people's intelligence levels and growth in Pakistan (World Health Organization, 2019). Moreover, according to the World Bank report (2019), 7 million people worldwide die annually due to air pollution. The IPCC report (2022) indicated that we could control 4% of CO2 emissions and 10% of greenhouse gas emissions if governments reduce subsidies for fossil fuels. As a counter to these challenges, numerous nations have started to introduce green economic development (Zeng and Eastin, 2012; Zhang et al., 2019; Lu et al., 2021; Zhang et al., 2021).

Previous international literature has scrutinized CO_2 emissions with different determinants such as poverty, economic growth, agricultural sectors, industrialization, population density, fossil fuel consumption, innovations, economic development, green bonds, green finance, financial development, foreign direct investment, spatial effects of FDI, pollution heaven, pollution hollow, international trade, export variety, globalization, renewable energy consumption, technological development, clean energy consumption, and energy consumption (Qadri et al., 2023). Therefore, foreign direct investment, green finance, trade openness, and economic growth have collectively focused less on CO_2 emissions. Thus, the main objective of this research is to analyze the effects of these macroeconomic factors collectively on carbon emissions.

In economic growth, ecological quality initially corrupts and then starts to further develop in the wake of arriving at a specific limit. This inverse U-shaped gross domestic product contamination design is additionally demonstrated in the environmental Kuznets curve (EKC) (Grossman and Krueger, 1991; Grossman and Krueger, 1995; Bekun et al., 2019; Sarkodie and, Strezov, 2019; Brown et al., 2020). Overall, the adverse consequence of financial development on ecological quality during the underlying period of improvement occurs because of the scale impact of exchange receptiveness and expanded energy utilization. In any case, this would emphatically affect the climate at the ensuing stage because of the method and organization impact (Mrabet and Alsamara, 2017; Destek and Sarkodie, 2019; Hao et al., 2022; Wu et al., 2022). Regarding the scale impact, the natural quality debases because of additional monetary exercises (transportation, modern creation, and deforestation) and energy utilization because, in the first phase of improvement, more consideration is given to development rather than ecological quality. Later, during pay level expansions in the second transformative phase under strategy impact, individuals request cleaner climates to achieve a higher expectation for everyday comforts (Grossman and Krueger, 1991; Antweiler et al., 2001; Mahalik et al., 2018; Sarkodie, 2018). In this respect, the creation of merchandise dirty innovation is supplanted by cleaner innovation or by administration areas, which decidedly affects the climate and is known as the synthesis impact (Antweiler et al., 2001; Uddin et al., 2017; Udeagha and Ngepah, 2019; Akram et al., 2022).

Previous studies have applied different methods to evaluate the results of the macroeconomic factors; these methods include regression analysis, linear frameworks, the Granger causality test (Granger and Yoon, 2002), vector error-correction models, the VAR model, quantile regression analysis, quantile-on-quantile regression, the wavelet approach, FMOLS, and DOLS approaches by Cheng, Sinha, Ghosh, and Lu (2018). Furthermore, most of the previous studies applied a linear (ARDL) approach to identify the relationships between variables. In contrast, the present study applies the nonlinear (NARDL) asymmetric approach to examine the positive and negative shocks of exogenous variables with endogenous variables with CO_2 emissions because the linear framework may show misleading results.

The benchmark of economic development in Pakistan is highly affected by foreign direct investment, which raises carbon emissions. These emissions are caused by the deterioration of environmental quality in Pakistan (Qadri et al., 2022c). Furthermore, the inflow of foreign direct investment is increasing due to world economic development and international capital flow. Furthermore, FDI increases carbon emissions in the host countries and promotes an unfriendly environment. Thus, FDI has negative and significant effects on the host country. For instance, previous studies have investigated the increase in the inflow of FDI and reported that it may increase environmental degradation in developing countries. A recent study reported that the inflow of FDI increases air pollution and harms CO_2 emissions. Moreover, several studies have shown that the pollution haven hypothesis increases the aggregate of CO_2 emissions and harmful environmental degradation (Cole, 2004; Cole et al., 2011; Ur Rahman et al., 2019; Kheder and Zugravu, 2012; Rahman et al., 2021). Moreover, some studies have reported that the inflow of FDI mitigated the carbon emissions in host countries due to clean technology projects, enhanced financial development, and helped promote a friendly environment; thus, FDI inflows have a positive and significant impact on CO_2 emissions (Nair-Reichert and Weinhold, 2001; Didas et al., 2015; Diaz and Moore, 2017; Destek M et al., 2018). Furthermore, a recent study by Huang et al. (2022) showed that the early stage of FDI inflow may increase carbon emissions; however, after reaching a threshold level, carbon emissions decrease due to increased FDI inflow. Moreover, recent studies by Manoli and Weber (2016), Mahmood and Tariq (2020), Xie et al. (2020), and Li et al. (2022) showed the negative impact of FDI on CO_2 emissions.

While green finance plays an important role, few studies have addressed this topic. In recent years, the finance sector has relied on green investments; thus, we cannot achieve sustainable economic growth (Sachs, 2015). Green finance tools can help achieve a green environment. In this way, financial brokers and markets have introduced financial tools such as green loans, green bonds, green home mortgages, and green environments. The view of green finance is not yet properly visible, and researchers are trying to reach a clear concept or definition (Zhang et al., 2019). Furthermore, green finance has inspired investment in different techniques and innovations that emerged from renewable energy (Yildiz et al., 2015; Meo and Abd Karim, 2021; Zakari et al., 2022) and green investments have positively contributed to a friendly environment. Furthermore, green finance benefits not only decreased energy consumption but also has a positive effect on economic development and CO_2 (Pao and Tsai, 2010; Rahman Z et al., 2019; Rehman et al., 2020; Shen et al., 2021; Zhu et al., 2021; Yi et al., 2023).

Trade openness plays an important role in developing countries, and each country transfers its resources and tries to enhance its export level, which is beneficial for the country's progress; however, trade openness harms the ecosystem. Furthermore, recent studies by Sarkodie and Strezov (2019), Shahzad et al. (2022), Shahbaz et al. (2018), and Shahzad et al. (2020) showed the positive and significant effects on the environment because different firms attracted to the trade are aware of spillovers upgrade to clean production through these spillovers, resulting in environmental benefits. Moreover, Salman et al. (2019) reported that trade has a significantly negative impact on the sustainable environment in Asia because when countries increase their exports, they produce more carbon emissions. Likewise, Shahzad et al. (2020) showed the negative impact on CO_2 emissions in Pakistan because the rapid expansion of trade openness has created environmental problems.

In developing countries, rapid economic growth increases energy consumption and carbon emissions through fossil fuels and crude oil. Raza et al. (2021) discussed a country that has non-renewable energy and has produced carbon emissions, and their study evaluated the negative impact of GDP on environmental sustainability. Moreover, most of the developing countries that have faced the poverty problem and want to decrease the poverty level start to increase their economic growth through industrialization; however, this rapid economic growth increases air pollution (Sadiq et al., 2021). Moreover, several studies have shown the positive impact of economic growth on environmental sustainability through the environmental Kuznets curve. Likewise, as reported by Grossman and Kruger (1991), in the first stage, the economy is interested only in economic growth; thus, in this thirst stage, carbon emissions increase, and when it gets to the threshold, it controls carbon emissions due to clean energy.

The current study presents four contributions in the context of previous literature. First, this study uses Pakistan as a sample, not by chance but due to background reasons. For instance, according to Greenpeace International (2006), Pakistan is among almost 90 countries with very high air pollution among 200 South Asian countries. Likewise, as reported by the World Economic Forum (2018), Pakistan is the highest-polluted country among the 19 highest-polluted nations worldwide. Likewise, concern about environmental pollution is a major problem among emerging countries, including Pakistan. Therefore, during the last decade, energy consumption, fossil fuels, and industrial area are the major factors in GHG emissions in Pakistan; for example, Pakistan's carbon emissions are comprised of 76% greenhouse gases, 16% methane, and 6% nitrous oxide (Economic survey, 2017). Moreover, according to Scheffen et al. (2021), carbon emissions will more than double by the end of 2050, making it the largest disaster for developing nations. Second, the basic objective of the present study is to scrutinize the nexus between foreign direct investments, green finance, trade openness, and economic growth with CO_2 emissions, as previous studies have not examined these variables with CO_2 emissions collectively. Moreover, previous studies have evaluated the environmental Kuznets curve to get a sustainable environment (Ullah et al., 2021). However, the present study evaluates other macro factors that affect the environment because of industrialization, urbanization, and energy consumption because most developing countries depend on inflows of FDI but have weak policies about FDI, which leads to environmental degradation. Moreover, the third objective of this study is to motivate Pakistan's government to invest in green projects such as renewable energy projects and green transportation. Similarly, Pakistan could reduce its carbon emissions. The novelty of the present study is its application of the asymmetric (NARDL) approach to obtain more accurate results because of the nonlinear behavior of the variables with environmental degradation. In contrast, most previous studies used symmetric linear frameworks to evaluate the macro-variables, potentially leading to misleading results because the world business and trade cycle has nonlinear behavior in real life (Ullah et al., 2020). Fourth, the present study is important for developing countries because these nations face many challenges, including environmental pollution; thus, the outcomes of the study will help policymakers to make policies that will help the government achieve a sustainable environment.

Following this introduction, the paper includes the following sections: Section 2 is the literature review, Section 3 describes the data and methodology, Section 4 evaluates the results and provides a discussion, and Section 5 presents the conclusions and policy recommendations.

2 Literature review

2.1 Foreign direct investment and environmental sustainability

As already established, FDI information can have both positive and negative effects on the environment of the host economy. As a result, the pollution haven hypothesis (PHH) is used to explain the

negative environmental effects of FDI, whereas the pollution halo effect hypothesis (PHEH) is used to understand the positive effects. According to PHH assumptions, financial globalization attracts foreign investments in unclean industrial processes, particularly in poor and emerging nations, wherein the CO_2 levels in the host economies are projected to increase. This phenomenon develops when rigid environmental regulations in developed countries force investors to invest in developing nations with flexible environmental laws; as a result, these investors take advantage of the lax environmental regulations in developing nations to invest in industries that produce large amounts of pollution. Therefore, the growth of polluting industries within the economies that welcome FDI raises those nations' respective FDI-led CO_2 emissions (Almulali et al., 2021; Qin and Ozturk, 2021). Furthermore, nations with large fossil fuel reserves can be anticipated to have a comparative advantage in the manufacturing of pollution-intensive goods. In such cases, these countries may serve as centers for luring unsavory FDIs, which increases the likelihood that their economies will develop into pollution hotspots (Banerjee and Murshed, 2020).
H_1: There is a significant relationship between foreign direct investment and environmental sustainability.

2.2 Green finance and environmental sustainability

One of the major dangers that the planet is currently facing is global warming. The Sustainable Development Goals (SDGs) of the United Nations (UN) drew attention to the growing concern over environmental contamination and the depletion of natural resources, which led to the introduction of contemporary ideas like sustainable growth. Green human resource management (HRM) practices aim to increase employee awareness of environmental issues and motivate them to take measures to decrease environmental emissions (Qadri et al., 2022a). The financial sector previously disregarded the ecosystem but has started to take environmental concerns more seriously and has launched a number of financial products explicitly aimed at environmental conservation, such as investment in renewable energy projects (Shahzad et al., 2022; Saeed et al., 2022; Hao and Chen, 2023). To date, few studies have connected economics and ecology. According to Wang and Zhi (2016), generating finance for solar energy can help achieve environmental sustainability. Environmental finance/sustainable financing is the most efficient strategy to stop environmental degradation, according to Xu et al. (2017). Green money and sustainable financing promote spending on emerging technologies and breakthroughs such as renewable energy (Jones et al., 2015).
H_2: There is a significant relationship between green finance and environmental sustainability.

2.3 Trade openness and environmental sustainability

Previous empirical studies on the relationship between foreign trade and emissions have produced conflicting findings, ranging from the claim that global trade causes CO_2 emissions to the denial of a causal connection between these two variables (Charfeddine and Ben Khediri, 2016; Shahbaz et al., 2016). Osathanunkul et al. (2018) reported that the types of indicator variables employed, the analytical methodologies used, and the study area's field of choice are the main causes of the differences in results. One cause of environmental contamination is the sharp increase in commodity production and consumption brought on by international trade (Kasman and Duman, 2015). Antweiler et al. (2001) investigated how pollutant concentrations are impacted by the global trade of products. The investigators used theoretical models to analyze three aspects of trade's influence on pollution: scale, composition, and technique. To identify connections between carbon emissions, urbanization, economic development, trade, energy depletion, and financial expansion, Dogan and Turkekul (2016) carried out a similar analysis in the United States. Their results showed that increased commerce benefits the US environment. However, there was no proof that emissions and world trade were causally related. The variables used by Dogan and Turkekul (2016) were also utilized by Farhani and Ozturk (2015) to investigate the link in Tunisia between 1971 and 2012. The "cointegrating Frontier" test, which demonstrates the long-term relationship between variables, was used to conduct the investigation. Many studies also employed a panel technique to conduct an empirical analysis of the causal linkage between similar factors used in industrialized economies by Hao (2023a), Dogan and Turkekul (2016), and Farhani and Ozturk (2015). The study discovered that variables are cointegrated using the Fisher panel cointegration approach. The causality test, however, did not identify any long-term causal nexuses between the variables. Despite these results, the study also discovered one-way causation between trade openness and short-term environmental carbon emissions. Toda and Yamamoto's Granger causality and the vector autoregression approach were both used by Michieka et al. (2013) to analyze the causative relationships among CO_2 emissions, coal use, and export commerce in China from 1970 to 2010.
H_3: There is a significant relationship between trade openness and environmental sustainability.

2.4 Economic growth and environmental sustainability

The argument over whether environmental degradation and economic advancement are possibly related began with the study of Grossman and Krueger in 1995. This influential work inspired numerous academics, leading to an increase in empirical studies on the environmental effects of economic growth (Dinda, 2004; Shahbaz et al., 2014; Shahbaz et al., 2017; Carvalho et al., 2018; Sarkodie, 2018; Adu and Denkyirah, 2019; He et al., 2021; Li et al., 2021; Shan et al., 2021; Yuping et al., 2021). The connection between economic development and the environment is based on the assumption that economies at an initial stage of growth concentrate on increasing production because their main goal is to advance economically as this can result in human welfare. This emphasis on development has a scale impact. Individual green values moderate employee behavior for better environmental performance (Li et al., 2023). Due to the scale effect, resource consumption in countries increases as a result of production without pollution control measures, which in turn exacerbates

Title	Author	Result
Do foreign direct investment inflows affect environmental degradation in BRICS nations?		FDI ↑ EP ↓
Does foreign direct investment asymmetrically affect the mitigation of environmental degradation in Malaysia?		FDI ↑ EP ↓
Role of environmental degradation and energy use for agricultural economic growth: Sustainable implications based on ARDL estimation		EG ↑ EP ↓
The influence of energy consumption and economic growth on environmental degradation in BRICS countries: an application of the ARDL model and decoupling index		EG ↑ EP ↓
Does trade openness mitigate the environmental degradation in South Africa?	Udeagha and Ngepah (2019)	TOP ↑ EP ↑
Environmental innovation, trade openness, and quality institutions: an integrated investigation about environmental sustainability	Khan et al. (2022)	TOP ↓ EP ↑
The role of green finance in reducing CO2 emissions: An empirical analysis	Saeed et al. (2022)	GF ↓ EP ↓
Nexus between green finance and climate change mitigation in N-11 and BRICS countries: empirical estimation through difference in differences (DID) approach	Nawaz et al. (2021)	GF ↑ EP ↓

ecological footprint (EF) and environmental degradation (Ulucak and Bilgili., 2018; Ahmed and Le, 2021). The scale effect is substantially influenced by globalization, which makes it possible for countries to generate more, even while domestic markets are experiencing a decline in demand (Ahmed and Le, 2021). Additionally, a well-developed financial system supplies capital to businesses, enabling them to generate more items (Saud et al., 2019). When the protection of environmental regulations is lax, FDI also increases foreign financial inflow, which can amplify the scale effect (Ahmed and Le, 2021; Soylu et al., 2021; Udemba et al., 2021). After this early phase, systemic modifications to the economic structure begin to take place and, because of the composition effect, countries gradually shift toward industrialized economies until finally becoming service economies. Since the service sector does less environmental harm, this structural change helps lower environmental strain (Qadri et al., 2022b). This point also marks the beginning of countries that produce less energy-intensive goods (Danish et al., 2019; Adebayo and Kirikkaleli, 2021; Bekun et al., 2021). In the third stage, advanced nations benefit from knowledge and creativity to produce superior technology. Additionally, economic development begins to reduce pollution levels while environmental concerns take precedence over economic goals, creating an inverted U-shaped relationship between disposable income and ecological decline (Ahmed and Wang, 2019; Kirikkaleli and Adebayo, 2021).

H_4: There is a significant relationship between economic growth and environmental sustainability.

3 Data and methodology

3.1 Data and variables

The present study uses a total of five variables, including environmental sustainability such as foreign direct investment, green finance, trade openness, and economic growth with carbon emissions. The annual data for Pakistan were obtained from the World Development Indicators from 1980 to 2021. We measured green financing in terms of the percentage of renewable energy consumption because Landenberg (2014) explained green investment in terms of renewable energy consumption in a broad sense. According to this, we can determine an environmentally sustainable goal after financial investment in environmental products, sustainable development projects, and policies that motivate the development of a sustainable economy (Nawaz et al., 2021). Furthermore, the present study measured the FDI as net inflow (% GDP), environmental pollution (Kt of CO_2 equivalent), GDP (GDP annual growth), and trade openness (export plus import of goods and services, % GDP), as shown in Table 1.

3.2 Methodology

3.2.1 Econometric form of the model

The present study uses the following table from Nawaz et al. (2021) and takes the logarithmic form of all variables and applies the asymmetric (NARDL) approach to identify the positive and negative shock effects of the variables on environmental pollution.

$$\Delta ES_t = \alpha_0 + \sum_{i=1}^{Z}\beta_1 \Delta ES_{i-1} + \sum_{i=0}^{Z}\beta_2 \Delta FDI_{t-i} + + \sum_{i=0}^{Z}\beta_3 \Delta GF_{t-i} + \sum_{i=0}^{Z}\beta_4 \Delta TOP_{t-i} + + \sum_{i=0}^{Z}\beta_5 \Delta EG + \pi_1\, lnES_{t-1} + \pi_2\, lnFDI_{t-1} + \pi_3\, lnGF_{t-1} + \pi_4\, lnTOP_{t-1} + \pi_5\, lnEG_{t-1} + \varepsilon_t.$$

This study scrutinizes the long-term linear relationships among variables such as foreign direct investment (FDI), green finance (GF), trade openness (TOP), and economic growth (EG) with carbon emissions (CO_2). This study postulates the following linear equation:

$$ES_t = \beta_0 + \beta_1 (FDI_t) + \beta_2 (GF_t) + \beta_3 (TOP_t) + \beta_4 (EG_t) + \varepsilon_t. \quad (1)$$

In this equation, ES, FDI, GF, TOP, and EG represent environmental sustainability, foreign direct investments, green finance, trade openness, and economic growth, respectively. While previous studies have also performed evaluations using linear frameworks, the existing study utilizes the asymmetric (NARDL) approach to identify the exact results for the variables.

TABLE 1 Descriptive statistics.

Variable	Symbol	Proxies/measurement of variables	Data source
Environmental sustainability	ES	(kt of CO_2 equivalent)	World development indicator
Foreign direct investment	FDI	(net inflow, % GDP)	World development indicator
Green finance	GF	(renewable energy consumptions, %)	World development indicator
Trade openness	TOP	(exports of goods and services, % GDP)	World development indicator
		(imports of goods and services, % GDP)	
Economic growth	EG	(annual GDP growth, %)	World development indicator

The reasons may be related to form, as according to Granger and Yoon (2002), a) the presence of hidden co-integration exists in a linear framework and b) the symmetric (ARDL) approach does not show structural breaks in the data. Therefore, the primary objective of the present research is to evaluate the asymmetric association among the variables, i.e., foreign direct investment, green finance, trade openness, and economic growth with environmental sustainability. The nonlinear equation is as follows.

$$ES = f\left(FDI^{+}, FDI^{-}, GF^{+}, GF^{-}, TOP^{+}, TOP^{-}, EG^{+}, EG^{-}\right). \quad (2)$$

3.2.2 Asymmetric (NARDL) approach

Previous literature has already shown the different outcomes of linear frameworks, such as the Granger causality co-integration test and the vector error correction model (VECM) by Olajide (2013), Wang and Wang (2018), and Lu (2018) which scrutinized the linear framework between the FDI, GF, TOP, and EG with CO_2 emissions. However, they did not clarify the results of exogenous variables and showed some misleading results (Pesaran et al., 2001). The asymmetric (NARDL) bounds testing approach changes the variables into negative and positive shocks and also shows the long-run and short-run results (Shin et al., 2014); moreover, this approach shows the dynamic NARDL graphs and CUSUM and CUSUM square graphs to describe the model stability. This study scrutinizes the long-term relationship between the explained variables as follows:

$$\begin{aligned} ES_t = {} & \theta_0 + \theta_1\left(FDI^{+}\right) + \theta_2\left(FDI^{-}\right) + \theta_3\left(GF^{+}\right) + \theta_4\left(GF^{-}\right) \\ & + \theta_5\left(TOP^{+}\right) + \theta_6\left(TOP^{-}\right) + \theta\left(EG^{+}\right) + \theta_8\left(EG^{-}\right) + \varepsilon_t. \end{aligned} \quad (3)$$

Eq. 3 shows that φ_i is the long-term parameter. The nonlinear (NARDL) impacts of foreign direct investments, green finance, trade openness, and economic growth are indicated as positive FDI^{+}, GF^{+}, TOP^{+}, and EG^{+}. Similarly, the negative shocks are presented as FDI^{-}, GF^{-}, TOP^{-}, and EG^{-}, respectively. FDI^{+}, FDI^{-}, GF^{+}, GF^{-}, TOP^{+}, TOP^{-}, EG^{-} are the positive and negative partial sums of foreign direct investments, green finance, trade openness, and economic growth. However, Eq. 1 shows only a long-term relationship; therefore, we re-specify Eq. 1 under the correction of the error term as follows:

$$\begin{aligned} \Delta ES_t = {} & \delta_0 + \sum_{l=1}^{m}\delta_{1k}\Delta ES_{t-k} + \sum_{l=1}^{m}\delta_{2k}\Delta FDI_{t-k} + \sum_{l=1}^{m}\delta_{3k}\Delta GF_{t-k} \\ & + \sum_{l=1}^{m}\delta_{4k}\Delta TOP_{t-k} + \sum_{l=1}^{m}\delta_{5k}\Delta EG_{t-k} + \psi_1 ES_{t-1} + \psi_2 FDI_{t-1} \\ & + \psi_3 GF_{t-1} + \psi_4 TOP_{t-1} + \psi_5 EG_{t-1} + \varepsilon_{t.} \end{aligned} \quad (4)$$

The error term provides the short-run and long-term coefficients in Eq. 4, while Δ_i represents a short-run coefficient and $\psi_1, \psi_2, \psi_3, \psi_4, and\ \psi_5$ indicate the long-term coefficients in the aforementioned equation. Moreover, the equation is assumed to have an asymmetric association among the explained variables. Thus, the primary objective of the present study is to evaluate the asymmetric relationship of FDI, GF, TOP, and EG in Pakistan. Therefore, this study finds the nonlinear effects of the projected variables and considers the asymmetric equation as follows. However, the decomposition of the equation is $\boldsymbol{c_t} = \boldsymbol{\theta^{+} d_t^{+}} + \boldsymbol{\theta^{-} d_t^{-}} + \boldsymbol{\varepsilon_t}$; therefore, $\theta^{+}\ and\ \theta^{-}$ are the long-term coefficients, and the $\boldsymbol{d_t}$ decomposition of the vector regressors is as follows:

$$d_t = d_t^{+} + d_t^{-}. \quad (5)$$

The current study decomposes the independent variables to find the changes in the partial sums of the positive and negative changes as $\boldsymbol{d_t^{+}}\ and\ d_t^{-}$ (Meo et al., 2018). Equations 6–13 indicate the partial sums of the positive and negative changes in foreign direct investments, green finance, trade openness, and economic growth.

$$FDI^{+} = \sum_{l=1}^{m}\Delta FDI^{+} = \sum_{l=1}^{m} max\left(\Delta FDI_i, 0\right), \quad (6)$$

$$FDI^{-} = \sum_{l=1}^{m}\Delta FDI^{-} = \sum_{l=1}^{m} min\left(\Delta FDI_i, 0\right), \quad (7)$$

$$GF^{+} = \sum_{l=1}^{m}\Delta GF^{+} = \sum_{l=1}^{m} \max\left(\Delta GF_i, 0\right), \quad (8)$$

$$GF^{-} = \sum_{l=1}^{m}\Delta GF^{-} = \sum\nolimits_{l=1}^{m} min\left(GF_i, 0\right), \quad (9)$$

$$TOP^{+} = \sum_{l=1}^{m}\Delta TOP^{+} = \sum_{l=1}^{m} max\ \left(TOP_i, 0\right), \quad (10)$$

$$TOP^{-} = \sum_{l=1}^{m}\Delta TOP^{-} = \sum_{l=1}^{m} min\ \left(TOP_i, 0\right), \quad (11)$$

$$EG^{+} = \sum_{l=1}^{m}\Delta EG^{+} = \sum_{l=1}^{m} max\left(EG_i, 0\right), \quad (12)$$

$$EG^{-} = \sum_{l=1}^{m}\Delta EG^{-} = \sum_{l=1}^{m} min\left(EG_i, 0\right). \quad (13)$$

After this stage, the study changes the variables of FDI, GF, TOP, and EG in Eq. 4 by the $FDI^{+}, FDI^{-}, GF^{+}, GF^{-}, TOP^{+}, TOP^{-}, EG^{+}\ and\ EG^{-}$ variables to complete the asymmetric formula:

TABLE 2 Descriptive statistics.

	ES	FDI	GF	TOP	EG
Mean	11.637	20.767	3.897	6.016	0.597
Median	11.683	20.738	3.873	6.701	0.768
Maximum	12.247	22.444	4.062	6.705	1.628
Minimum	11.007	19.317	3.731	3.114	−2.806
Std. dev.	0.343	0.909	0.085	1.414	0.939
Skewness	−0.165	0.104	0.040	−1.551	−1.917
Kurtosis	2.107	1.984	2.451	3.408	7.635
Jarque–Bera	1.094	1.342	0.370	12.652	39.207
Probability	0.578	0.511	0.830	0.331	0.233

$$\begin{aligned}\Delta ES_t = \theta_0 &+ \sum_{l=1}^{m}\theta_{1l}\Delta ES_{t-l} + \sum_{l=1}^{m}\theta_{2l}\Delta FDI^{+}_{it-l} + \sum_{l=1}^{m}\theta_{3k}\Delta FDI^{-}_{it-l}\\ &+\sum_{l=1}^{m}\theta_{4l}\Delta GF^{+}_{i-l} + \sum_{l=1}^{m}\theta_{5l}\Delta GF^{-}_{it-l} + \sum_{l=1}^{m}\varphi_{6l}\Delta TOP^{+}_{it-l}\\ &+\sum_{l=1}^{m}\theta_{7l}\Delta TOP^{-}_{it-l} + \sum_{l=1}^{m}\theta_{8l}\Delta EG^{+}_{it-l} + \sum\nolimits_{l=1}^{m}\theta_{9l}\Delta EG^{-}_{it-l}\\ &+\psi_1 ES_{t-1} + \psi\, FDI^{+}_{it-1} + \psi_3\, FDI^{-}_{it-1} + \psi_4\, GF^{+}_{it-1}\\ &+\psi_5\, GF^{-}_{i\,t-1}\psi\gamma_6\, TOP^{+}_{it-1} + \psi_7 TOP^{-}_{it-1} + \psi_8 EG^{+}_{it-1}\\ &+\psi_9\, EG^{-}_{it-1} + \varepsilon_t. \end{aligned} \tag{14}$$

After scrutinizing Eq. 13, Shin et al. (2014), the present study applied the bounds test approach, which was estimated by Pesaran et al. (2001). Therefore, Pesaran's approach for bounds testing is suitable for Eq. 13 and Eq. 4 to decompose the projected variables into positive and negative changes, a model called the asymmetric (NARDL) model. The asymmetric model is an extension of the ARDL symmetric approach, which has many advantages over cointegration as the traditional model. For instance, it is easy to approach stationary limitations, while the traditional ARDL approach restricts at the same order stationary level (Engle and Granger., 1987), but the ARDL approach can easily be applied when all variables are stationary at I (0) and I (1) difference and or mixed results. Moreover, it is appropriate for small sample sizes and provides long- and short-term results (Panopoulou and Pittis, 2004).

3.3 Dynamic cumulative multiplier

This study utilizes the asymmetric (NARDL) model to develop the cumulative dynamic multipliers, which indicate the change in units as $x^{+}\, and\, x^{-}$. $x^{+}\, and\, x^{-}$ show as decomposed variables (Rahman et al., 2022).

$$C^{+}_{k} = \sum_{h=0}^{q}\frac{\partial x_{i-h}}{\partial x^{+}_{i}},$$

$$C^{-}_{k} = \sum_{h=0}^{q}\frac{\partial x_{i-h}}{\partial x^{-}_{i}}, \quad k = 0, 1, 2, 3, 4 \ldots\ldots..$$

As $K \rightarrow \infty, c^{+}_{l} \rightarrow \beta^{+}$ and $c^{-}_{l} \rightarrow \beta^{-}$, where β^{+} and β^{-} are the asymmetric long − run coefficients and calculated as follows:

$$\beta^{+} = \frac{-\theta^{+}}{q} \text{ and } \beta^{-} = \frac{-\theta^{-}}{q}, \text{ respectively.}$$

3.4 Econometric strategy

This study uses the asymmetric ARDL approach presented by Shin et al. (2014) for time series data for emerging countries, including Pakistan. This technique is used to control the limitations of traditional approaches. Moreover, the present approach shows the positive and negative effects of the variables on environmental degradation. This flexibility allows heterogeneous results, which are useful for policymakers. Furthermore, the traditional ARDL regression approaches have not been used to show the positive and negative effects of macroeconomic variables in terms of environmental sustainability.

4 Empirical findings and explanations

The initial stage of the study involves scrutinizing the descriptive analysis. After that, we evaluate the unit root test to check that the variables are stationary using the ADF and PP tests. Finally, the asymmetric or nonlinear (NARDL) approach is applied to examine the long- and short-term relationships among the variables (Shin et al., 2014).

Table 2 demonstrates the results of the descriptive statistics. FDI has the highest mean value, while EG has a lower mean value. Furthermore, the results of the Jarque–Bera test show that the data are normal because all variable values are greater than the 1% level of significance (0.578, 0.511, 0.830, 0.331, and 0.233 > 0.001). Moreover, Table 2 describes the highest standard deviation value for TOP and the lowest value for GF, which means that there are different magnitudes of mean values. Therefore, the characteristics of the outcomes show the dependency on the asymmetric (NARDL) procedure.

The outcomes of the unit root test are displayed in Table 3. The aim of the first stage of the study is to confirm that no variables are stationary at I (2) because if any variables were to be stationary at the second difference, we would not be able to proceed with the

TABLE 3 Unit root test.

Variable	Augmented Dickey–Fuller		Phillip–Perron		Conclusion
	I (0)	I (1)	I (0)	I (1)	
ES	0.005***	0.000***	0.007***	0.000***	I (0)
FDI	0.129	0.01***	0.269	0.01***	I (1)
GF	0.02***	0.000***	0.02***	0.000***	I (0)
TOP	0.665	0.001***	0.228	0.001***	I (1)
EG	0.006***	0.000***	0.006***	0.000***	I (0)

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

TABLE 4 Zivot and Andrews (1992) test for unit root.

Variable	Unit root at level I (0)	Years break	Unit root test at first difference (1)	Years break
	t-statistic		t-statistic	
ES	0.300	2012	0.00***	1996
FDI	0.01**	2003	0.01***	2009
GF	0.97	2006	0.06***	2000
TOP	0.12	2008	0.03***	2004
EG	0.22	1998	0.00***	2001

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

asymmetric (NARDL) approach (Shin et al., 2014). Therefore, the asymmetric approach can be applied when the variables are stationary at 1 (0), I (1), or mixed. For this purpose, the present study utilizes the augmented Dickey and Fuller (1997) and Phillips–Perron (1988) tests. The study outcomes show that all variables are stationary at I (0) and I (1) and gave mixed results; thus, we are able to proceed with the long-term and short-term asymmetric approach.

The pragmatic suggestions made by the PP, Zivot, and Andrews tests are equivalent. According to Perron (1990), the stationary test for units should consider that traditional unit root tests may produce biased (one-sided) observational results. The root problem of the series may be the source of underlying aberrations. The unit root tests may acknowledge this by describing those cycles as stationary; a false null hypothesis is introduced, yet structural breaks can occur. The difficulty of encouraging unit root analysis and structural breaks is made worse by bias. In addition, Kim and Perron (2009) argued that traditional unit root tests produce dubious results because they deal with low instructive force and low magnitude circulation as an asymmetrically non-individual null hypothesis but similarly accessible alternative assumption in the absence of primary breaks. Utilizing unit root practice, which contains a single identifiable structural break, closes this gap (Zivot and Andrews, 1992). Additionally, both the null and alternative hypotheses of this experiment require a primary break point in the example work with an ambiguous date. The test results are shown in Table 4.

Table 5 reports the results of the symmetric (ARDL) and asymmetric (NARDL) analyses. The F-statistic values are shown in Table 4. The F-statistic value for asymmetric (ARDL) is 2.135, which is less than the lower bound of a 1% level of significance; thus, it is inconclusive. Table 4 demonstrates the result of asymmetric (NARDL). The F-statistic value is 4.256, which is greater than the upper bounds at the 1% level of significance, which means that hidden co-integration exists between the carbon emission and other explained variables, such as FDI, GF, TOP, and EG. However, the result of the bounds test pushes toward the asymmetric long-term and short-term procedure.

Table 6 reports the results of cumulative dynamics estimation. First, among the diagnostic tests, the results of the Breusch–Godfery and Breusch–Pagan–Godfery tests showed that the data were free from the serial and hetero-problem at a 5% significance level. Table 6 shows the R-squared value of 0.890, which indicates the high power of the independent variable of the model and evaluates the changes in independent variables. Table 6 also shows that the F-statistic value is greater than the probability value, which means our model is a good fit.

Table 7 shows the outcomes of the short-run estimation of the independent variables. The short-run table demonstrates the results of the speed of adjustment or cointegration values such as the value of ES (−1) as 0.575 (between 0 and 1). The negative sign shows how much time will take to return to the equilibrium point and the significance at the 1% level for all conditions is fulfilled; thus, we can say that long-term asymmetric (NARDL) exists among the variables. Moreover, the coefficients of FDI_POS and FDI-NEG are −0.575 and 0.021, respectively, and are significant at a 1% level of significance, which means that a 1% increase in FDI_POS will lead to a 0.57% increase in CO_2 emissions in Pakistan in the short term and has an inverse relationship between them. The FDI-NEG is also significant at a 1% level of significance, which means a 1% decrease in FDI will decrease the CO_2 emissions by

TABLE 5 Bound cointegration for linear and non-linear tests.

Test-statistic	F-statistic	Sig. level	Critical value bounds	Upper bound at 5%	Decision
			Lower bound at 5%		
Linear ARDL	2.135	1%	2.62	3.77	Inconclusive
Asymmetric ARDL	4.256	5%	1.11	3.15	Cointegration exists
		10%	1.85	3.85	

Note: The symmetric (ARDL) critical observation is derived from (Pesaran et al., 2001). ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Moreover, F-statistic values greater than the upper bound confirm asymmetric long- and short-term relationships among the variables. However, $p = \theta^+ = \theta^- = 0$ represents the null hypothesis of asymmetric cointegration.

TABLE 6 Dynamic non-linear estimation of environmental sustainability.

Variable	Coefficient	Std. error	t-Statistic	Prob.*
ES (-1)	0.425**	0.163	2.526	0.023
FDI_POS	0.021***	0.013	2.761	0.010
FDI_NEG	−0.015**	0.014	−2.754	0.046
GF_POS	−1.026***	0.331	−3.031	0.007
GF_NEG	−1.818***	0.213	−8.484	0.000
GF_NEG (-1)	0.582	0.437	1.335	0.208
TOP_POS	−0.070*	0.051	−2.367	0.098
TOP_POS(-1)	0.071	0.001	1.492	0.153
TOP_NEG	0.086**	0.375	3.216	0.031
TOP_NEG (-1)	−0.919**	0.403	−2.269	0.040
GDP_POS	0.012*	0.001	1.911	0.074
GDP_NEG	−0.003	0.005	−0.810	0.444
GDP_NEG (-1)	0.037***	0.045	2.909	0.013
C	6.351**	1.858	3.435	0.045
R-squared	0.890			
F-statistic	19.918			
Prob. (F-statistic)	0.000			
Serial correlation	0.221**	(0.041)		
heteroscedasticity	0.271**	(0.023)		

Note: "POS" and "NEG" indicate the cumulative positive and negative sums, respectively. $\beta^+ = \frac{-\theta^+}{q}$ and $\beta^- = \frac{-\theta^-}{q}$ indicate the positive and negative long-term coefficient relationships in the given model, respectively. "Breusch–Godfery" and "Breusch–Pagan–Godfery" were evaluated as serial correlations and heteroscedasticity tests, respectively. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

0.021%, and has a direct relationship because when foreign investment in developing countries primarily wants to earn, profit, environmental impact is not considered; hence, FDI increases CO_2 emissions according to the environmental Kuznets curve in the first stage and technologies cannot mitigate the CO_2 emissions. Moreover, green finance in the short-run is insignificant, which means that in the short-run, the government or investors may not have invested in projects in Pakistan; thus, GF-POS is insignificant in the short-run. GF-NEG shows significance at the 1% level, which means that a 1% decrease in green finance will decrease carbon emissions by 1.226% in the short term (Khan et al., 2022). Furthermore, TOP-POS and TOP-NEG are significant at 1% and 5% levels of significance, respectively, which means that a 1% increase in TOP-POS will increase the carbon emissions, while a 1% decrease in TOP-NEG will decrease carbon emissions in Pakistan and TOP-POS harms the environment. Furthermore, EG_POS and EG-NEG are significant at the 10% and 5% levels of significance, which means that a 1% increase in EG will increase carbon emission in the short term, while a 1% decrease in EG will decrease CO_2 emissions in the short term (Table 8).

The results of long-run NARDL are shown in Table 7 and demonstrate the positive and negative changes of independent

TABLE 7 NARDL short-term results.

Variable	Coefficient	Std. error	t-Statistic	Prob.
C	6.355***	1.858	3.4305	0.005
ES (-1)*	−0.575***	0.163	−3.413	0.000
FDI_POS**	0.021***	0.013	2.761	0.010
FDI_NEG**	−0.015	0.019	−0.754	0.466
GF_POS**	1.026***	0.331	−3.031	0.007
GF_NEG (-1)	1.226***	0.431	−2.856	0.016
TOP_POS(-1)	6.945	0.008	−0.011	0.915
TOP_NEG (-1)	−0.833**	0.290	−2.832	0.019
EG_POS**	0.012*	0.001	1.911	0.074
EG_NEG (-1)	0.025**	0.070	2.498	0.020
D (GF_NEG)	−1.818***	0.213	−8.484	0.000
D (TOP_POS)	−0.070***	0.051	−2.367	0.008
D (TOP_NEG)	0.086**	0.375	2.216	0.031
D (EG_NEG)	−0.043	0.005	−0.810	0.434

*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. "POS" and "NEG" indicate positive and negative changes in explanatory variables, respectively. The null hypothesis of the short-term series is denoted as $\sum_{h=0}^{q} x_i^+$ and $\sum_{h=0}^{q} x_i^-$, respectively.

TABLE 8 NARDL long-run results.

Variable	Coefficient	Std. error	t-statistic	Prob.
FDI_POS	0.051**	0.225	2.290	0.031
FDI_NEG	−0.019*	0.270	−4.694	0.093
GF_POS	−1.771**	0.792	−2.221	0.046
GF_NEG	−2.133***	0.260	−8.158	0.000
TOP_POS	0.021*	0.990	−5.016	0.095
TOP_NEG	0.478**	0.628	−2.390	0.032
EG_POS	0.025**	0.165	4.559	0.049
EG_NEG	0.048***	0.253	3.716	0.018
C	11.058***	0.022	3.898	0.000

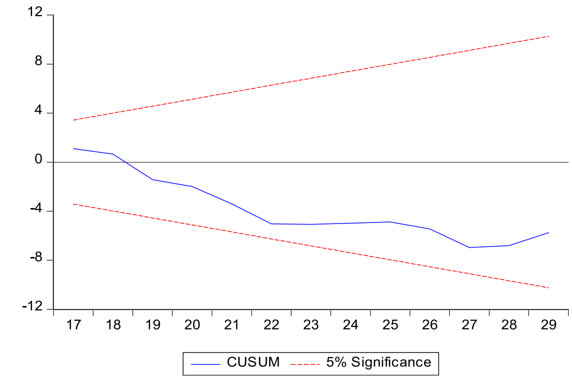
Notes: ***, **, and * denote significance levels at 1%, 5%, and 10%, respectively. The *p*-values are shown in parentheses.

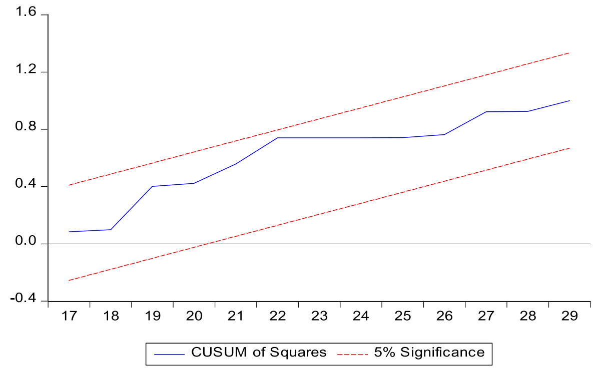
variables on the dependent variable. Therefore, the coefficients of FD-POS and FDI-NEG are 0.051 and −0.019, respectively, and are significant at the 5% and 10% levels, respectively. These results confirm the asymmetric relationship between the variables in the long term. Moreover, a 1% increase in FDI-POS will lead to a 0.051% increase in carbon emissions in Pakistan, consistent with previous results (Lin and Ma, 2022). Thus, in developing countries, when foreign projects and firms start their projects, they will produce more carbon emissions, which is harmful to Pakistan because Pakistan is already suffering from poor climate conditions. Therefore, FDI-NEG shows that a 1% decrease in FDI will reduce carbon emissions by 0.019%, and it has a direct relationship with carbon emissions. Likewise, the coefficient of GF-POS is −1.771 and is significant at a 5% level of significance, which means that a 1% increase in green finance will decrease the carbon emissions in Pakistan by 1.77% (Khan et al., 2022). GF-NEG shows a coefficient of 2.133, which is significant at a 1% level of significance, which means that a 1% decrease in green finance will increase carbon emissions by 2.133% (Meo and Abd Karim, 2021; Li et al., 2022; Zakari et al., 2022) and has an inverse relationship. Moreover, the coefficients of TOP-POS and TOP-NEG are 0.025 and 0.478, respectively, and are significant at the 10% and 5% levels, which means that a 1% increase in trade openness will increase carbon emissions by 0.025% in Pakistan, while a 1% decrease in TOP-NEG will decrease the carbon emissions by 0.478%, and negative change is very effective in Pakistan compared to positive shock. 4. The empirical analysis portion needs (Hao, 2023b; Matar et al., 2023). Likewise, EG-POS and EG-NEG have coefficients of 0.025 and 0.048 and are significant at the 5% and 10% levels, respectively. The positive shocks show that a 1% increase in economic growth will lead to a 0.025% increase in carbon emissions. The negative shocks show that a 1% decrease in economic growth will lead to a 0.048% decrease in carbon emissions in Pakistan (Xie et al., 2022).

One major hazard the world is facing today is global warming. The Sustainable Development Goals (SDGs) of the United Nations (UN) focus on rising concerns about environmental degradation and the depletion of natural resources, which have opened the door for the introduction of contemporary ideas like sustainable growth. The financial sector previously disregarded the ecosystem, but it has started to take environmental concerns more seriously and has launched several financial products explicitly aimed at environmental conservation, such as green bonds. However, to our knowledge, no research has been conducted that empirically analyzes the relationship between green financing and CO_2 emissions using an asymmetric ARDL technique. Previous studies have examined the association between CO_2 emissions and other macroeconomic factors. The link between green financing, foreign direct investment, and CO_2 emissions might depend on the economic cycle as well as the amount and type of green finance, making this strategy particularly intriguing in this context (renewable energy consumption). As a result, with other controlled variables, it is anticipated that CO_2 emissions will react differentially to both positive and negative changes in green finance and foreign direct investment. Because of both positive and negative changes in green finance and foreign direct investment, CO_2 emissions are anticipated to react differently. CO_2 emissions often remain high during periods of strong economic boom and fall during periods of economic contraction. The nature of the relationship between CO_2 emissions and green finance can vary depending on the state of the economy, even though CO_2 is a complex and multifaceted phenomenon whose relationships with green finance and foreign direct investment depend on many factors (expansion or recession). Therefore, positive rather than negative changes in green finance and foreign direct investment may have a greater impact on CO_2 emissions because renewable energy can mitigate the carbon emissions from the environment (Hao et al., 2022). According to the theory of the environmental Kuznets curve, in the first stage, carbon emissions increase due to economic growth, but after this stage, they become environmentally friendly because of clean energy or technological innovation. According to the outcomes, positive shocks show that carbon emissions are increasing due to production, while negative shocks show decreased CO_2 emissions after using clean energy.

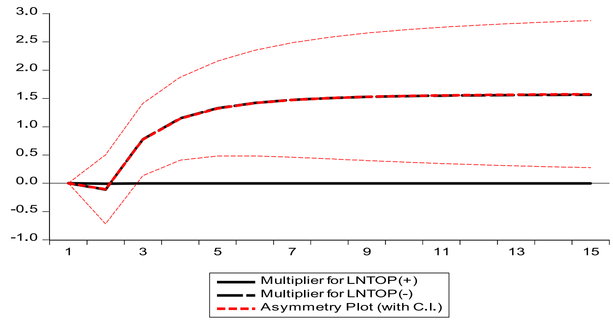
4.1 Model stability test

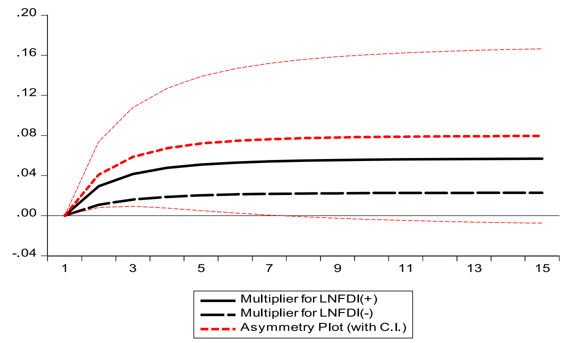
CUSUM and CUSUM-SQUARE tests are used to examine the stability of the model. The blue lines of both are between the lower and upper bounds, which means that all variables are stable in the data (Brown and Vincent, 1987).

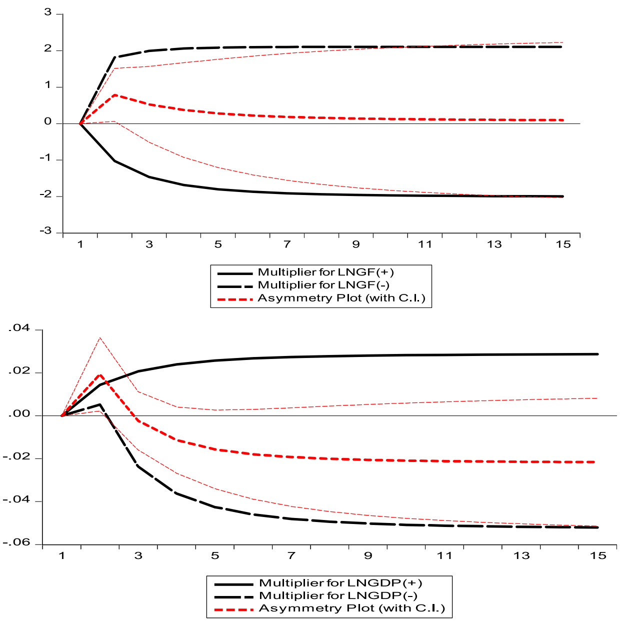




4.2 Dynamic multiplier graphs







4.3 Dynamic multiplier effects

The effects of multipliers show the condition of speed of adjustment and the behavior of adjustment before shock and after shock. However, the present study scrutinizes the asymmetric short- and long-term effects through dynamic multiplier graphs. These graphs evaluate the short- and long-term positive and negative changes in FDI, GF, TOP, and EG on CO_2 emissions. Moreover, the graphs show the dynamic multiplier effects among FDI, GF, TOP, and EG with carbon emissions. For instance, solid black lines describe the positive changes of FDI, GF, TOP, and EG, while the negative shocks of independent variables are indicated by dotted black lines. On the other hand, dark dotted red lines indicate a nonlinear relationship, while thin red lines indicate critical bounds. Therefore, the results of all graphs confirm the dynamic nonlinear relationship that exists among the variables.

5 Conclusion and policy recommendation

Although previous literature has classified different macro-determents with carbon emissions in Pakistan, none have described the nonlinear effects of foreign direct investment on a sustainable environment. The present study scrutinizes the asymmetric short- and long-term effects on environmental conditions in Pakistan. Additionally, previous studies have not provided sufficient dynamic results on the relationship of foreign direct investment with environmental conditions because while most of these studies explain sustainable environment with the "environmental Kuznets curve" in Pakistan, none explain the dynamic asymmetric effects of FDI on the sustainable environment with another controlled variable, such as green finance, trade openness, and economic growth. However, the present study applies the dynamic asymmetric approach described by Shen et al. (2021) to data from 1986 to 2021. Therefore, this study shows how host companies and multinational companies produce carbon emissions in developing countries like Pakistan. Moreover, the present research evaluates the effects of "green finance" on CO_2 emissions and explains the importance of these effects in Pakistan, which is a developing country already suffering poor financial conditions that affect its environmental conditions. Furthermore, the augmented Dickey and Fuller (1997) and Phillips–Perron (1988) tests were applied to check that the variables were stationary, which showed mixed results. The following bound cointegration test and the F-statistic value were significant at a 1% level of significance. This study also investigates diagnostic tests like serial correlation and heteroscedasticity tests to show that the data were free from all these conditions and that the model was normal by the Jarque-Bera Test. Furthermore, this study investigates the short- and long-term results. In the long term, positive shocks of FDI increase carbon emissions and negative shock shows a decrease in carbon emissions but has a negative relationship. Furthermore, green finance plays an important role in the long term because positive shocks show that a 1% increase in green finance will increase environmental sustainability and reduce carbon emissions in Pakistan. On the other hand, negative shock shows that decreased green finance increases carbon emissions. Moreover, the positive shocks of TOP and EG increase carbon emissions and their negative shocks decrease carbon emissions in Pakistan. Furthermore, the results indicate that economic expansion in Pakistan increases environmental pollution and has an adverse effect on the improvement of environmental quality and confirm the EKC hypothesis of an inverted U-curve interaction.

5.1 Policy recommendations

Pakistan has the highest carbon emissions among the top 10 countries with high CO_2 emissions, which is dangerous for Pakistan's climate. The present study suggests some implications for the government and policymakers.

The results of this study suggest that the government of Pakistan should impose maximum tariffs and taxes on foreign companies, investors, and foreign projects associated with the production of high carbon emissions in the host areas. The results of the current research recommend that policymakers should make policies about clean technologies and carbon-free production, implicating that the government should give incentives and reduce taxes on clean technologies for the investors of Pakistan. Moreover, Pakistan's government should apply limitations and restrictions on foreign investors because foreign countries coming into a host country want only to earn profit and do not care about the environmental impact of their investment. Moreover, developing countries already suffer from different problems like poverty, unemployment, and many other issues; therefore, they also do not care about the environment and want primarily to profit from foreign projects. Furthermore, the results of this study suggest that the government should develop projects within the country to help investors to invest their income in the country's production and reduce foreign investments, which are the main cause of environmental pollution. Pakistan's government is required to develop a clean environment for foreign direct investment; thus, it would achieve stronger economic performance and be able to reduce environmental pollution.

Nowadays, the global task is to reduce the negative impact of external human economic activities. Many researchers and policymakers strongly support the consequences of green finance on the environment, which helps reduce carbon emissions without compromising economic growth and also helps lessen external human activities. Furthermore, based on the negative association of green finance with environmental quality, the present study provides some suggestions to help increase green finance development. Moreover, the study suggests that Pakistan's government should utilize fiscal policies for the development of green finance, use fiscal funds for carbon-free projects, and promote green finance as green securities and social capital as green investment. Furthermore, the government should provide green securities, in the form of green bonds, to investors and recommend that investors use these green securities for green technologies. For instance, the government should use its fiscal funds in underdeveloped areas and give securities as green bonds to investors in these regions. Moreover, the government should improve its financial market conditions; the study shows that green finance would help the country to control carbon emissions. The government should also give loans to investors at lower interest rates to increase production growth. Likewise, the findings suggest that developing countries should promote their fiscal funds for low carbon emission production and should start green investments in clean energy projects, which benefit the environment.

This study's proposal for policymakers is to develop policies involving exports so that the government can control its investment in import production and increase its exports and domestic production because trade openness negatively affects the environmental condition of Pakistan. Furthermore, the heterogeneous results of trade openness recommend that policymakers and scholars study imports and exports separately because exports help the country to reduce carbon emissions. The results of this study also suggest that policymakers should scrutinize the heterogeneous effects of international trade on carbon emissions and separately consider import and export when formulating policies for achieving the goal of a sustainable environment.

Moreover, the results of this study suggest that policymakers should make policies for governments and investors wherein they advise that the government balance the demand and supply ratio because economic growth is the main mitigating factor of environmental damage in developing nations. Furthermore, the outcomes of this research recommend that governments promote low-carbon-emission technology to produce goods and develop strategies for producers to help promote clean energy production. Furthermore, the government should apply limitations on the supply side. This study has various limitations. First, the sample size is small; from 1980 to 2021, only 42 data samples from Pakistan were available, which leaves out important factors like geographical heterogeneity and economic disparity. Second, the ecological footprint and other environmental pollutants (such as sulfur dioxide (SO_2), nitrous oxide (N_2O), Freon, and methane (CH_4)) are not considered in this analysis; only CO_2 emissions are. Third, the model for how FDI spending affects CO_2 emissions does not consider macro-variables in the context of economic globalization, such as urbanization, population, government assistance, inflation rate, and industrialization.

5.2 Future study

The study recommends that researchers scrutinize the same determinates for the top ten carbon emissions countries. Moreover, the present study measures the single proxy as kt of CO_2 equivalent for the sustainable environment of Pakistan; however, future studies can use different proxies like ecological footprints, N_2O, and SO_2. Furthermore, cross-sectional studies may also be informative.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

SUQ: conceptualization. ANN: Data Analysis and Interpretation and Results SR: methodology and interpreted results. LB: software, formal analysis, investigation resources, and visualization. SUQ, SR, AA, MSA, LB, ANN, and XS: validation, and writing—original draft preparation and review and editing. SUQ, ANN, and XS: data curation. XS and MSA: project administration. All authors have read and agreed to the published version of the manuscript. LB: Finally Review the Manuscript and SUQ: Final Complete and Review Draft.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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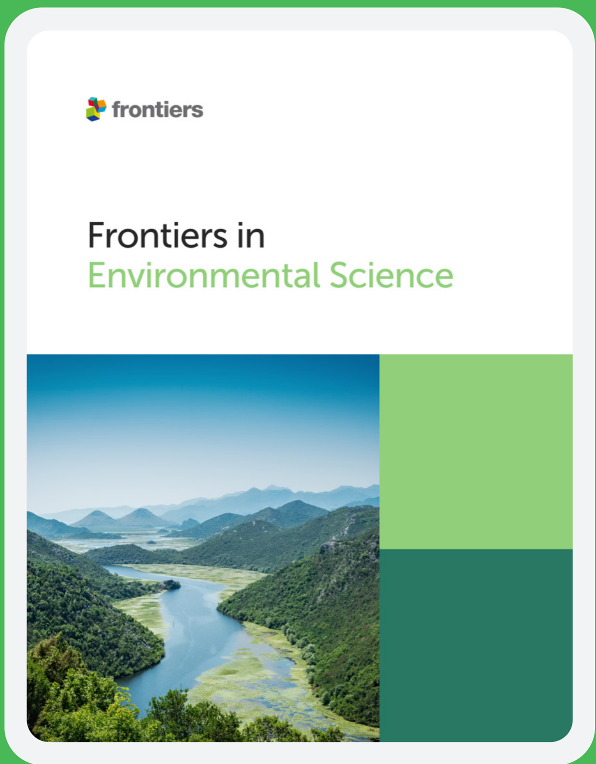

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