



Research article

Ecological footprints and sustainable environmental management: A critical view of China's economy

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ABSTRACT

Global economies have recently been concerned about sustainable environmental management by reducing emissions and tackling ecological footprints. The rapid economic expansion and investment in traditional manufacturing further raises environmental degradation. China surpasses other emerging economies in the economic growth race yet has remained the top pollution-emitting economy for the last few decades, necessitating scholarly attention. This study examines the influencing factors of ecological footprints in China from the perspective of COP27. Using the extended dataset from 1988 to 2021, this study uses several time series diagnostic tests and verifies the existence of the long-run association between the study variables. Consequently, the non-linear scattered data leads to non-parametric (method of moment quantile regression) adoption. The empirical results indicate that only economic growth is a significant factor in environmental quality degradation in China. However, improving renewable energy usage, research and development, and foreign direct investment reduces the country's ecological footprint. Hence, the latter variables substantially lead to environmental sustainability. The robustness of the results is confirmed via a robust non-parametric estimator and causality test. Based on the empirical results, this study recommends increased investment in research and development, renewable production, and foreign direct investment enhancement.

1. Introduction

The ecological footprint (ECFP) is a physical indicator measuring human actions' environmental influence. The Global Footprint report describes that most economies are on the verge of ending their ecosystems and are suffering from an ecological deficit. (Doytch, 2020). The increasing demand for production has caused an overwhelming influence on the atmosphere to recuperate ecosystems' sustainability. However, energy is a necessary component for achieving economic development. But as the country grows, the energy demand alongside industrialization increases due to augmented economic activities (Murshed et al., 2022). This directly influences the environment because the economies are predominantly based on non-renewable consumption, aggravating environmental pollution and ECFP (Khan et al., 2020).

It is a known fact that the growing human activities have intensified ecological deterioration since the industrial revolution. Meanwhile, the economic activities in China, a prominent emerging economy, have significantly contributed to environmental degradation. According to a CNN report, China is one of the biggest emitters of emissions, reaching 3 tons (billions) due to economic reflection (He, 2023). Therefore, this piqued the interest to inspect the factors of ECFP in the Chinese economy. The graphical depiction of the ECFP in China in Fig. 1 from 1990 to 2020 indicates a positive trend in the study economy. The higher footprint in the economy can be explained by the increasing economic growth (GDP), industrialization, energy demand, and urbanization, which led the country to an upsurge in the ECFP levels. The rising population demands more resources to fulfill requirements, increasing urbanization and industrialization. Hence, energy for human activities

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escalates, significantly enhancing ECFP and disrupting environmental management (Majeed et al., 2021; Usman and Hammar, 2021). From the graphical analysis in Fig. 2, it can be observed that renewable consumption decreased till the year 2020 because the economy was primarily focused on fossil energy for economic production. Additionally, in retrospect, the impact of R&D spending has been negligible, but the increasing carbon emissions and environmental deterioration have increased the R&D expenses recently for attaining ecological sustainability (Khan et al., 2021).

The Conference of Parties (COP) was established in 1995 to combat climate change (United Nations, 2017). Since then, renewable production has sparked the interest of scholars and policy enthusiasts in limiting emissions. Fig. 3 depicts the production of electricity from environmentally friendly resources in China. Over the years, the country has been promoting renewable electricity for climate stability. Due to its significant importance, the study examines the influence of environmentally friendly depletion on the ECFP of China. Besides, the role of foreign direct investment and R&D are analyzed in the ECFP in China from 1988 to 2021. The study incorporates GDP, renewable consumption (REC), research and development (REDEV), and foreign direct investment (FDI) as explanatory factors, while ECFP is the dependent factor for the research. Due to the asymmetry and non-linearity of data, the study uses Quantile regressions and pairwise causality analysis to obtain reliable and efficient estimates. The increasing environmental issues and economic sustainability crises have motivated the authors to inspect the novel link between economic development, renewable ingesting, research and development, foreign direct investment, and ECFP in China. China has huge growth potential, but in terms of the environment, the country lacks significant regulations to limit environmental deterioration. The meaningful effect of the economy on environmental governance worldwide inspired the authors to determine the ECFP determinants in China. From the viewpoint of COP-27, the country is facing substantial ecological concerns that make it difficult to achieve the target of lowering greenhouse gases and global warming. Therefore, the present study is motivated to analyze the eco-footprint determinants for environmental sustainability to address these issues.

The chosen area, i.e., China, offers significant opportunities for studying the intricate relationship between GDP, sustainable energy deployment, research and development expenditure, foreign direct investment, and ECFP. China's remarkable GDP and successful shift towards renewable energy sources have profound global implications for promoting sustainable development. Examining how these factors interrelate within the Chinese context provides valuable insights into the region-specific determinants of ECFP. It facilitates the identification of policy interventions that are likely to be effective. This research acknowledges the unique characteristics of China's economic structure, investment patterns, and energy landscape, which allows for a comprehensive and detailed analysis. By considering these context-specific elements, the research aims to augment the precision and

significance of the findings, thereby providing valuable insights into the progress of customized strategies to encourage ecological sustainability in China (Khan et al., 2022).

The study corroborates the literature in the following ways. First, the prior studies have provided ambiguous results with outdated data periods (Kızılgöl and Öndes, 2022); Ikram et al. (2021); Sahoo and Sethi (2021); Usman and Hammar, 2021; Murshed et al. (2022a); Xu et al. (2022); Alvarado et al. (2021); Aydin et al. (2023). The present research adds to the literature by examining the innovative determinants of ECFP in China in the context of environmental management. This is useful in providing new evidence with reliable estimates for refurbishing sustainable environmental management policies. Besides, this research extends the ongoing debate on environmental sustainability and the efforts of China in this regard. Second, COP27 was fruitful for vulnerable economies because the developed economies finally agreed to pay for loss and damage. Besides, China made other positive contributions to combating the global climate crisis in the 'Side Events'. Therefore, due to the increasing importance of COP27, the present research discusses the factors of ECFP in the context of COP27. Third, studies on the link between R&D and ECFP are scarce. Thus, the present research explicitly examines this nexus in the Chinese economy, providing additional evidence to the empirical literature. Lastly, the research uses an extensive data timeframe from the year 1988 to the year 2021, which covers the maximum period for an extensive view of the node in the country. This is also a substantial and innovative addition to the empirical literature.

The rest of the document is ordered in the following ways. Section 2 pertains to the research literature on study variables. Section 3 pertains to the data and methodology segment of the research. Section 4 explains the predicted findings and their economic interpretations. Finally, in the end, the research documents the conclusion and policy implications.

2. Literature review

The literature on variables under consideration is documented here, clarifying their associations for research interpretation.

2.1. Nexus between GDP and ECFP

Economic activities are exclusively responsible for increasing environmental degradation, as GDP is vital in observing ECFP. For instance, Hassan et al. (2019) assessed the connection between GDP and ECFP from the period between 1971 and 2014. The ARDL technique approximations demonstrated that the increase in GDP encourages ECFP in the economy and disrupts environmental quality. In a panel data analysis, Ahmad et al. (2020) examined the connection between economic development and ECFP between 1984 and 2016 using panel estimation analysis (CS-ARDL, AMG). The empirical results depicted that economic development significantly escalates the ECFP of the environment and causes environmental deterioration. Likewise, using non-linear analysis,

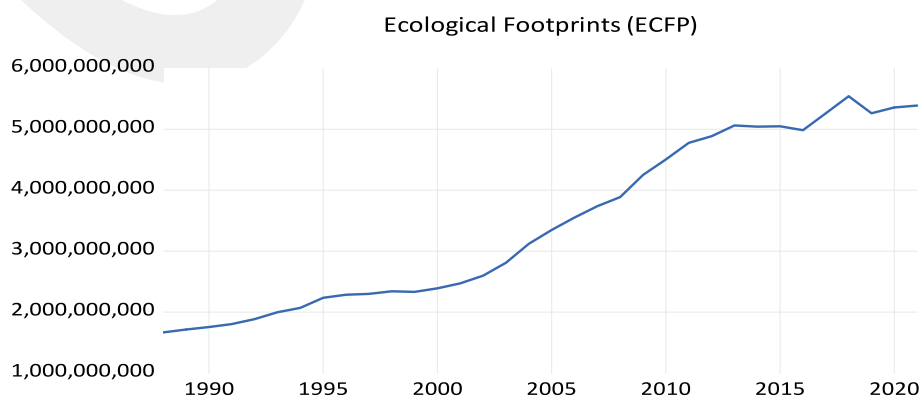


Fig. 1. Ecological footprint in China.

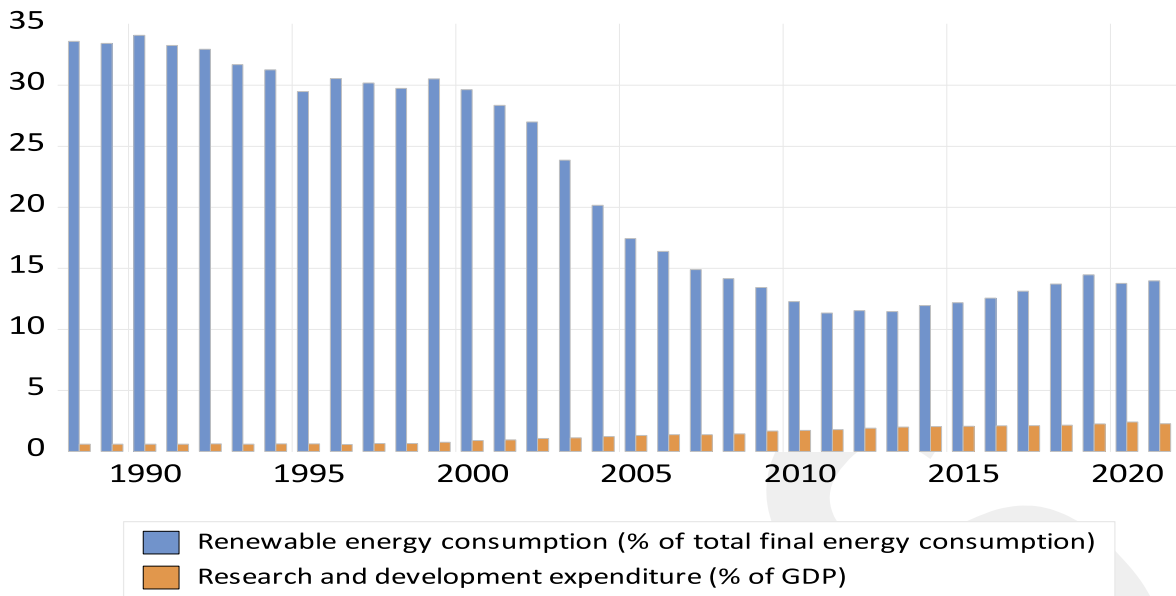


Fig. 2. Renewable energy and R&D expenses in the Chinese economy.

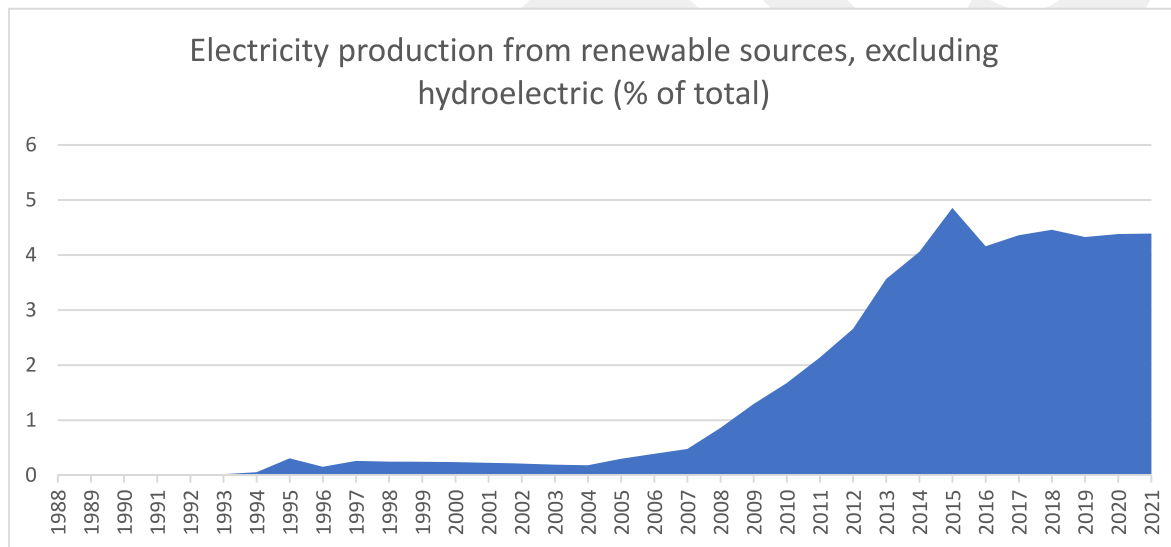


Fig. 3. Electricity production from renewable sources.

Baz et al. (2020) inspected the connection between GDP and ECFP in Pakistan. The estimates depicted that from 1971 to 2014, economic development was asymmetrically linked with the ECFP. Besides, the outcomes depicted a strong influence of economic development on the ECFP. Similarly, Kızılgöl and Öndes (2022) examined the effect of GDP on the ECFP in OECD economies from 1995 to the year 2017. The empirics from panel estimations demonstrated that economic development is a statistically significant determinant of ECFP. The findings depicted that GDP is positive and bidirectionally related to escalating ECFP. It is suggested to revamp environmental policies for a sustainable environment. Ahmed et al. (2020) investigated the impact of GDP on ECFP in China. The estimates from the econometric analysis depicted that GDP substantially contributes to ECFP in the economy, leading to environmental deterioration with statistical evidence from 1970 (1.05) to 2016 (3.7). In another research, Ikram et al. (2021) explored the nexus in Japan between the period 1965Q1 and 2017Q4 using ARDL analysis. The result demonstrates that GDP is positively and asymmetrically related to ECFP with a bidirectional causal relationship. Kihombo et al.

(2021) assessed the nexus using the STIRPAT model during 1990–2017 in the WAME regions. The results depicted that GDP is a significant component in determining ECFP. The more economic development, the more ecological deterioration, causing high levels of EF. Additionally, the recent research of Ali et al. (2021), Jie et al. (2023), Saqib et al. (2023), Bashir et al. (2023), and Gu et al. (2023) investigated the influence of GDP on ECFP in different income economies. The statistical outcomes depicted that GDP substantially aggravates the ECFP in all studied panels with a bidirectional and positive impact of GDP on ECFP (Khan et al., 2023).

2.2. Nexus between REC, FDI, RDEV, and ECFP

Energy consumption is one of the significant sources of rising ECFP (Li et al., 2022a,b,c). While renewables are the efficient solutions to combat the climate crisis and lessen ECFP [Pata (2021); Wang et al. (2023)]. Several studies have investigated this nexus in different economies. Such as Kızılgöl and Öndes (2022) assessed the association of

REC with ECFP in OECD nations. The results from the econometric analysis depicted that renewables consumption lowered the ECFP with a unidirectional association from REC to ECFP. Besides, a reducing impact of renewables on ECFP is observed in low and high-income economies. The panel data study depicted that REC lowers the ECFP in all studied panels. In G7 economies, [Aydin et al. \(2023\)](#) inspected the association between REC and ECFP during the period between 1990 and 2018. The empirical estimates validated that renewables reduce ECFP and enhance environmental sustainability by limiting harmful emissions. Another study on a similar nexus assessed the REC and ECFP in European countries between 1990 and 2020. The empirics discovered that REC harms ECFP with a unidirectional causality ([Saqib et al., 2023](#)). Likewise, [Xu et al. \(2022\)](#) assessed the empirical relation between REC and ECFP in China. The empirics depicted that REC reduces the ECFP (ECFP), especially in the long run. Also, [Sahoo and Sethi \(2021\)](#) explored the nexus from 1990 to 2016 in developing economies. The findings using FMOLS and DOLS depicted that renewable consumption limits the ECFP in those nations and helps enhance the environment. Similarly, [Usman and Hammar \(2021\)](#) inspected the link between REC and ECFP between 1990 and 2017. The outcomes demonstrated that REC substantially reduces ECFP and improves the quality of the environment from 0.09% to 0.4%. [Li et al. \(2022a,b,c\)](#) showed that REC has a weak negative influence on the ECFP, which gets strings over time in 120 economies. [Nathaniel et al. \(2021\)](#) observed the nexus of MENA economies. The estimates obtained from DOLS and FMOLS demonstrate that REC significantly limits the ECFP. The same outcomes were observed in oil-exporting/producing economies [[Adekoya et al. \(2022\)](#); [Çakmak and Acar \(2022\)](#)], denoting REC helps in improving environmental quality.

Foreign Direct Investment is another important element that has a meaningful effect on ECFP because the extant studies suggest that investments are prominent factors in escalating environmental emissions ([Chancel, 2022](#)). In the context of South Asian nations, [Murshed et al. \(2022\)](#) examined the FDI influence on ECFP. The empirical analysis depicted that FDI significantly diminishes the negative influence of ECFP and enhances the environment with the negative effect of FDI. Likewise, [Zafar et al. \(2019\)](#) examined the connection in the USA using ARDL analysis. The empirical estimates FDI lowers the ECFP and improves environmental sustainability. In contrasting literature, [Xu et al. \(2022\)](#) examined the impact of FDI on ECFP in China between 1990 and 2017. The results depicted that FDI has a positive relationship with ECFP. Their significant increase deteriorates the environment and then increases the ECFP. [Murshed et al. \(2022a\)](#) investigated the impact of FDI on ECFP in Bangladesh from 1972 to 2015. The analysis shows that FDI directly deteriorates the environment by raising ECFP, but the interaction of renewable energy indirectly reduces the ECFP. In research on Africa, [Arogundade et al. \(2022\)](#) inspected the influence of FDI on ECFP. The study depicted that FDI limits the ECFP in the economy, but after a critical level, it worsens the environmental condition and increases the ECFP. Similarly, in Pakistan, [Liu et al. \(2022\)](#) examined the same relationship using Toda-Yamamoto and ARDL analysis. The study depicted that FDI increases ECFP by deteriorating the environment, describing the investments causing emissions that worsen the ECFP. Another study assessed the FDI influence on ECFP in different-level economies. The outcomes described that FDI has an optimistic effect on ECFP, whether production-related or consumption-related ecological influence in the economies ([Doytch, 2020](#)). From 2001 to 2016, [Chowdhury et al. \(2021\)](#) analyzed the effect of FDI on ECFP in 92 economies. The empirics depicted that FDI has a significant association with ECFP with an optimistic effect on ECFP. In contrast, [Udemba \(2020\)](#) examined the relationship between FDI and ECFP in India. The findings asserted a negative effect of FDI on ECFP, denoting that increasing investments lower footprint. Despite the mixed influence of FDI, developing the country's financial system and financial inclusion substantially reduces environmental hazards ([Qin et al., 2021a, 2021b](#)).

Scientific evidence on the correlation between R&D and ECFP in the

present literature is scarce. But, the subsequent studies might be brief on the direction of the association. For instance, [Zhang et al. \(2022\)](#) assessed the influence of REDEV on ECFP in E5 countries using GMM and FMOLS. The empirical findings between the span of 1990–2019 demonstrated that R&D increases the ECFP by degrading the environment by 0.07% and 0.08%. Moreover, research and development increase the ECFP. While [Alvarado et al. \(2021\)](#) depicted that REDEV and ECFP have a bidirectional causal but asymmetric association with each other in panel countries from 1996 to 2016. The predicted estimates established that the impact depends on the economic structure of the economies. In contrast, [Adedoyin et al. \(2020\)](#) examined EU countries' REDEV and ECFP relationship. The empirical estimates described a negative association between REDEV and ECFP. [Génesis-Carolina et al. \(2021\)](#) scrutinized the impact of REDEV on ECFP. The outcomes depicted that REDEV is negatively related to ECFP in South America. Besides, the empirical literature asserted that enhancement in environmental R&D and investment in renewable sources could significantly reduce emissions levels and promote environmental sustainability ([Luan et al., 2022](#); [Jiang et al., 2022](#); [Shahzad et al., 2021](#); [Cai et al., 2022](#)).

3. Data and methods

3.1. Theoretical framework

The relationship between economic development and ecological footprints has received considerable attention in the field of sustainability studies. The pursuit of economic expansion, often used as an indicator of societal well-being, frequently requires higher levels of resource use, possibly amplifying the impact on ecological footprints. Nevertheless, recent hypotheses argue that a more complex and interconnected relationship exists. According to Solow's seminal model proposed in 1956, the relationship between economic development and technical breakthroughs suggests that the latter might enhance resource efficiency, potentially reducing ecological footprints ([Solow, 1956](#)). This highlights the complex nature of the influence of economic development on ecological footprints, whereby trade-offs between resource use and innovation may exist. Since China is the leading natural resources consumption economy for higher economic growth and development. Therefore, this study assumes the positive influence of economic growth (GDP) on the ecological footprint (ECFP), given as: $\delta_1 = \frac{\partial ECFP_t}{\partial GDP_t} > 0..$

The use of renewable energy sources establishes an additional conceptual connection with ecological footprints. According to neoclassical theory, the use of renewable energy sources has the potential to separate economic development from the negative impacts on the environment. This concept has gained prominence via the Environmental Kuznets Curve (EKC) hypothesis, as proposed by [Grossman and Krueger \(1995\)](#). The idea posits that there exists an initial positive correlation between economic expansion and environmental deterioration, which subsequently diminishes as a result of technical improvements and legislative interventions. Hence, it may be postulated that an escalation in the use of renewable energy sources has the potential to reduce ecological footprints, harmonizing with the EKC concept. Since China has increased its investment level in generating energy and electricity from renewable sources, which could substantially influence environmental sustainability. Therefore, this study assumes that renewable energy consumption (REC) is harmful to environmental deterioration, such as: $\delta_2 = \frac{\partial ECFP_t}{\partial REC_t} < 0..$

Theoretical discourse also includes the examination of research and development (R&D) investment and its influence on ecological footprints. [Schumpeter's \(1942\)](#) theory of innovation emphasizes the role of research and development (R&D) in stimulating economic growth while also acknowledging its potential for generating positive spill-over effects on sustainability endeavors. An escalation in R&D investment has the potential to foster significant technological advancements, therefore exerting a positive influence on sustainable practices and mitigating

ecological footprints. As discussed earlier, China increased its substantial budget level towards attaining R&D and technological advancement. Therefore, this study assumes the negative role of R&D expenditure (RDEV) in the ECFP: expressed as: $\delta_3 = \frac{\partial ECFP_t}{\partial RDEV_t} < 0$.

Similarly, the impact of foreign direct investment (FDI) on ecological footprints may be seen in several channels. According to Dunning's (1988) institutional theory, FDI has the potential to facilitate the transfer of innovative technology and management methods, hence fostering the adoption of environmentally friendly manufacturing processes. On the other hand, the pollution haven theory posits that FDI may lead to an increase in ecological footprints inside host nations with lax environmental regulations (Cole et al., 2005). With reference to China, the level of FDI is rapidly increasing, yet technological innovation and management systems are further strengthening during the last few decades. Therefore, this research assumes that FDI could improve environmental quality by reducing the level of carbon-intensive products and services, given as: $\delta_4 = \frac{\partial ECFP_t}{\partial FDI_t} < 0$.

3.2. Model development

In times of rapid industrialization, the pollution emissions level is rapidly growing, attracting international organizations' attention to restrict nations from extensive pollution emissions. Since China is an emerging nation, which uses energy extensive resources to production of goods and services. Due to the lack of significant determinants of environmental quality, this study uses ECFPs (ECFP: including grazing land, cropland, forest land, fishing grounds, and built-up land) as the primary proxy of environmental quality. Following the objectives, this study uses economic growth (GDP: constant US\$ 2015), research and development expenditure (RDEV: % of GDP), renewable energy consumption (REC: % of total energy used), and foreign direct investment (FDI: % of GDP) are used as explanatory factors of the environmental quality. After the empirical work of Baz et al. (2020), the constructed model of this study is given as:

$$ECFP_t = \alpha_1 + \delta_1 GDP_t + \delta_2 REC_t + \delta_3 RDEV_t + \delta_4 FDI_t + \varepsilon_t \quad (1)$$

In the preceding model, it could be distinguished that the slopes, intercept, and random error terms are represented by δ_s , α , and ε , respectively. Further, the time span is represented via t (1988–2021) in case of China's economy. Data for ECFP is obtained via Global Footprint Network (2022),¹ and GDP, REC, RDEV, and FDI are extracted from the World Bank.²

3.3. Estimation approach

The present investigation employed an analysis of data utilizing summary statistics and assessed the assumption of parameter normality. The present research investigates the statistical properties of the time series data. Specifically, the study calculates each variable's averages, median, and range within the time series. The analysis aims to provide insights into the highest and lowest values observed in the data. The study examines the time series instability by analyzing the fluctuating standard deviation influenced by range statistics. This research's data normality assessment is conducted using skewness and kurtosis. The normalcy test developed by Jarque and Bera (1987) is also employed in this study. This test is designed to maintain excess kurtosis and skewness at zero. The equation for the normality statistic is a mathematical expression used in statistical analysis to assess the normality of a data set. It is commonly denoted as:

¹ For ECFP data, visit: <https://data.footprintnetwork.org/#/>

² For variables data, visit: <https://databank.worldbank.org/source/world-development-indicators#>.

$$JB = \frac{N}{6} \left(S^2 + \frac{(K-3)^2}{4} \right), \quad (2)$$

The present study aims to investigate the presence of unit roots in each variable, following an assessment of parameter irregularity. The Augmented Dickey-Fuller unit root test, a commonly used method in time-series examination, is utilized in this study. In recent years, significant progress has been made in developing more advanced statistical methods. In their seminal work, Elliott et al. (1992) contributed significantly to the field by introducing an enhanced version of the Dickey-Fuller (DF) statistical test. This revised statistic incorporated a generalized least squares (GLS) framework, which provided a more effective and robust testing procedure. By incorporating GLS, the authors improved the test's accuracy and reliability, enhancing its usefulness in empirical research. This advancement in the DF test has since been widely adopted and has greatly contributed to econometrics. The researchers present their findings, showcasing their test's enhanced characteristics compared to the DF analysis. Specifically, they highlight their approach's larger sample size and increased factual validity (Elliott et al., 1992).

This research used the Bayer-Hanck (BH) combined cointegration assessment, which integrates methods from Johansen (1991), Boswijk (1994), Banerjee et al. (1998), and Engle and Granger (1987). These approaches are well-known in econometrics for identifying and assessing the variables' long-run connection. This thorough technique offers a rigorous prediction of the variables under research. Shahbaz et al. (2018) found that the cointegration test's dependability coefficient might mislead projections if the previous techniques are done separately. To avoid misleading or unclear results, Bayer and Hanck (2013) integrative cointegration assessment techniques were used. This research uses a wide variety of Fisher's F-statistics-based cointegration techniques to provide accurate and dependable results, as Shahbaz et al. (2018) described. I(1) integration sequence is needed for assessment in this test. This test suggests no cointegration for the factors under examination. Fisher's calculation for BH cointegration is as follows:

$$EG - J = -2[\ln(P_{EG}) + \ln(P_J)], \quad (3)$$

$$EG - J - Ba - Bo = -2[\ln(P_{EG}) + \ln(P_J) + \ln(P_{Ba}) + \ln(P_{Bo})], \quad (4)$$

where the probabilities are P_J (Johansen, 1991; P_{EG} Engle and Granger, 1987; P_{Ba} Banerjee et al., 1998; P_{Bo} Boswijk, 1994 $P_{EG}P_{Ba}P_{Bo}$). In addition to the cointegration, this research also utilizes Johansen (1991) test of cointegration test for further authenticating the cointegration status of the variables.

Given that the considered variables exhibited stationarity, a prerequisite for determining long-run coefficients, it becomes possible to compute the long-run elasticity. Furthermore, it is worth noting that the variables under consideration exhibit features indicative of long-term connections. Therefore, it is feasible to ascertain the long-term elasticity through a highly effective approach. The present study utilizes the Method of Moment Quantile Regression (MMQR) estimation approach developed by Sarkodie and Strezov (2018). The equation presented in this context characterizes the location-scale variance $Q_y(\tau|R)$ given specific conditions.

$$Y_{it} = \alpha_i + \beta R_{it} + (\gamma_i + \rho \dot{Z}_{it}) \mu_{it}, \quad (5)$$

in the aforementioned expression, the likelihood equation $p(\gamma_i + \rho \dot{Z}_{it} > 0)$ bears resemblance to a well-known equation commonly used in research. The parameters α , β , γ , and ρ correspond to the anticipated collection of coefficients that are being investigated in this research. In this study, the subscript i is used to denote the fixed effect, that the specifications can describe α_i and γ_i . These variables are constrained to $i = 1, 2, \dots, n$. The distinguishing characteristic of R , as Z outlines, is the k -vector, whereas the " vector demonstrates its lack of

stability.

$$Z_i = Z_i(R), i = 1, 2, \dots, k, \tag{6}$$

in the study conducted by Machado and Silva (2019), it was observed that the variable R_{it} exhibits a dispersed symmetrical and distinct pattern over time (t). Additionally, it was found that the variable i remains orthogonal and fixed to both t and i . As a result, both the external influences and the reserve remain unaffected. Based on the aforementioned justification, it is deemed necessary to reframe the overall framework of the research study, denoted as Eq. (1), in the following manner:

$$Q_y(\tau|R_{it}) = (\alpha_i + \gamma_i q(\tau)) + \beta R_{it} + \rho Z_{it} q(\tau), \tag{7}$$

where FDI , GDP , $RDEV$, and REC are regressors in the current research model, as signified by R_{it} . This study transforms the parameters selected using the natural logarithm function. This conversion results in the parameters becoming unitless, which allows for the utilization of percentages in subsequent analyses. Moreover, the analysis emphasizes the dispersion of the regressing agents, denoted as R_{it} , and its impact on the dependent variable Y_{it} . Specifically, the focus is on the quantile location of ECFP, as reported by Y_{it} . Furthermore, the equation $-\alpha_i(\tau) \equiv \alpha_i + \gamma_i q(\tau)$ can be used to determine the specific vector component that is responsible for the constant impact of quantiles on i . The results indicate that the intercept remained constant across the different quantiles analyzed. The presence of fundamental dependence among variables leads to a diverse range of results. In the context of this study, $q(\tau)$ represents the τ -th sample's quantile. This sample includes the values $Q^{0.25}$, $Q^{0.50}$, $Q^{0.75}$, and $Q^{0.90}$. The equation for quantile utilized in this study is presented as follows.

$$\min_q \sum_i \sum_t \theta_\tau(R_{it} - (\gamma_i + \rho Z_{it})q) \tag{8}$$

where $\theta_\tau(A) = (\tau - 1)AI\{A \leq 0\} + TAI\{A > 0\}$ is the formula for assessing performance.

Following a comprehensive analysis of the aforementioned factors, this study further investigated the authenticity of the model. The present investigation utilizes the non-parametric technique of robustness known as bootstrap quantile regression (BSQR). The adoption of such estimator in this context can be attributed to the presence of a non-linear distribution of data. In addition, this study also uses robust least square estimators with structural breaks considering "what if" analysis to strengthen the empirical estimates of the model further. The limitations of these estimations lie in their inability to accurately capture the causality connection between the elements under consideration. Hence, the pairwise Granger causality assessment is employed to examine the causal connection among the variables within the scope of this study.

4. Results and discussions

4.1. Results

Estimated results are documented and interpreted in this section. First, the overview of descriptive statistics demonstrates that the data is asymmetrical. The numerical presentation of the pre-estimation diagnostics of all study variables is offered in Table 1. The data asymmetry can be explained by the difference between the mean and median values of the variables that show the information is non-balanced. Then, the skewness and Kurtosis statistics validate the existence of irregularity of data and distribution. The variables ECFP, GDP, REC, FDI, and RDEV are positively skewed, having values of 0.187092, 0.687394, 0.141102, 0.137751, and 0.225626, respectively. At the same time, the kurtosis statistics show a non-normal tail of the distribution with variable values as 1.413947, 2.120498, 1.235993, 2.164792, and 1.511000, respectively. The J-B test confirms the irregular distribution with the displayed

Table 1
Descriptive statistics.

	ECFP	GDP	REC	FDI	RDEV
Mean	3.46E+09	5.96E+12	21.71295	3.132762	1.310777
Median	3.23E+09	4.19E+12	18.80500	3.479362	1.261450
Maximum	5.54E+09	1.58E+13	34.08361	6.186882	2.400930
Minimum	1.67E+09	9.49E+11	11.34000	0.966308	0.563240
Std. Dev.	1.38E+09	4.68E+12	8.847061	1.450674	0.640545
Skew.	0.187092	0.687394	0.141102	0.137751	0.225626
Kurt.	1.413947	2.120498	1.235993	2.164792	1.511000
Jarque-Bera	3.762068	3.773384	4.521094	1.095754	3.429398
Probability	0.152432	0.151572	0.104293	0.578176	0.180018

probability distribution. Lastly, each variable's range is displayed with the minimum and maximum statistics shown in the table.

Second, after the confirmation of unequal distribution, unit root assessments are employed for examining the stationary characteristics of data. Table 2 displays the unit root statistics outcomes from ADF and DF-GLS tests. The summary describes that in both tests, the data is stationary I(0). At I(1), all variables have shown significant outcomes with negative coefficients denoting the stationarity of variables at first difference. Then, a structural break test is performed to examine the significance of breakpoints. These structural breakpoints present major changes in government policy or some sudden economic/financial or war event that affects the information. At this level, FDI showed structural breaks in 1991, while the remaining variables showed significant structural breaks in different years for each variable. The breakpoint of ECFP and GDP occurred in 2002, RDEV in 1996, and REC showed a significant structural breakpoint in 2011.

Table 3 depicts the test results from the cointegration. Different types of tests are applied for assessing cointegration analysis. The outcomes show that the variables have a substantial presence of unit roots. The following tests are applied: EG, J, Ba, Bo (discussed in the methodology section), EG-J, EG-J-Ba-Bo, and Unrestricted Cointegration Rank (Trace) Tests displayed in the table. The results from Johansen, Boswijk, EG-J, and EG-J-Ba-Bo-show noteworthy coefficients at 1% and 5% levels of significance, depicting that the parameters have a significant presence of long-run associations. The outcomes of trace statistics show that two of four have significant findings with a significance level of 10% and 1%. The overall results demonstrate that GDP, REC, FDI, and RDEV are significantly and meaningfully associated in the longer run with the ECFP. The existence of a long term relationship indicates moves toward the estimation process to evaluate the determinants of ECFP.

Table 4 shows the results from Quantile regressions. From the estimated outcomes, it is proved that GDP aggravates the ECFP in the country. While the other three factors, such as REC, research and development, and FDI are significant in improving environmental sustainability by decreasing the ECFP. All variable quantiles have significant coefficients at the 1% level. According to the quantile results, GDP has an optimistic impact on ECFP, indicating that increasing economic activities leads to a significant increase in the ECFP of an economy. The impact of REC, research, development, and FDI has an inverse relationship with ECFP, demonstrating that improving these factors will significantly enhance environmental sustainability by reducing the ECFP in the economy. The MMQR estimates show consistent estimates for assessing the determinants of ECFP. But then again, robustness examination is employed to examine the consistency of results presented in Table 5 below.

The robustness check from BSQR has shown significant outcomes. The coefficient signs of all variables have shown similar results to MMQR regressions, i.e., GDP escalates ECFP while REC, RDEV, and FDI decrease ECFP in the country significantly. GDP and REC have shown significant results in all quantiles, while REDEV and FDI have shown significant and insignificant results. The graphical analysis of the variable quantiles from BSQR is presented in Fig. 4 below. The figure displays the estimated results pictorially for all variables.

Table 2
Results of unit root test.

Variable	ADF		DF-GLS	
	I(0)	I(1)	I(0)	I(1)
ECFP	-1.118056	-3.519540*	-1.517967	-3.603325**
FDI	-2.242177	-4.337212***	-1.705430	-4.374238***
GDP	-1.964145	-3.286951*	-2.698927	-4.634580***
RDEV	-1.529185	-4.307881***	-1.344234	-4.434992***
REC	-1.420266	-5.534267***	-2.604363	-5.581509***

ADF Test with Structural Breaks				
Variables	I(0)	Breakpoint I(0)	I(1)	Breakpoint I(1)
ECFP	-3.198956	2018	-5.232486**	2002
FDI	-5.865917***	1991	-	-
GDP	-3.695814	2017	-6.734761***	2002
RDEV	-3.329288	1999	-7.959360***	1996
REC	-4.096213	2006	-5.380899***	2011

Note: 1%, 5%, and 10% levels of significance reported via ***, **, and *, respectively.

Table 3
Cointegration tests.

Test	EG	J	Ba	Bo
Test Stats.	-3.3476	127.7361***	-3.1709	59.7831***
EG-J-		EG-J-Ba-Bo-		
57.153,481**		115.36884**		

Unrestricted Cointegration Rank Test (Trace)					
Hyp. CE (s) number	Eigenvalue	Trace Statistic	Prob. **	Max-Eigen Statistic	Prob. **
None *	0.679401	79.87493***	0.0063	36.40208**	0.0244
At most 1	0.490961	43.47285	0.1215	21.60740	0.2412
At most 2	0.384606	21.86544	0.3060	15.53575	0.2531
At most 3	0.096086	6.329,691	0.6566	3.232,685	0.9300
At most 4	0.092246	3.097006*	0.0784	3.097006*	0.0784

Note: 1%, 5%, and 10% levels of significance reported via ***, **, and *, respectively.

Now, Least square with structural breaks and robustness least square tests are applied. In Table 6, GDP shows a positive association with ECFP; both tests denote that increasing economic production increases ECFP. Whereas, renewable energy, research and development, and foreign investment show a negative association with ECFP. Besides, with non-breaking variables, the relationship between REC, FDI, and REDEV is negative, depicting that these factors are resourceful in lowering the ECFP of the economy.

Table 7 denotes the role of additional variables. The table shows that ELREC and REO have a noteworthy and negative relation with the ECFP. Whereas, the role of FD and GCF are positively connected with the ECFP. This signifies that Renewable output and electricity are beneficial in reducing the ECFP, whereas financial development and Gross capital formation are intensifying the ECFP in the economy. The overall analysis denotes that investments increase economic production, contributing to ecological deterioration. However, the use of green energy helps in controlling ECFP.

Table 4
Estimates of quantile regression MMQR.

Variable	Loc.	Scal.	Quantiles			Q _{0.90}
			Q _{0.25}	Q _{0.50}	Q _{0.75}	
GDP	0.365*** [0.021]	0.018 [0.014]	0.353*** [0.028]	0.369*** [0.021]	0.377*** [0.020]	0.391*** [0.020]
REC	-0.389*** [0.026]	-0.009 [0.017]	-0.383*** [0.032]	-0.391*** [0.024]	-0.395*** [0.024]	-0.402*** [0.024]
RDEV	-0.140*** [0.044]	-0.035 [0.030]	-0.117** [0.057]	-0.148*** [0.043]	-0.163*** [0.042]	-0.189*** [0.042]
FDI	-0.021*** [0.006]	-0.003 [0.004]	-0.020** [0.008]	-0.022*** [0.006]	-0.023*** [0.006]	-0.025*** [0.006]
Cons.	5.419*** [0.260]	-0.212 [0.175]	5.561*** [0.338]	5.369*** [0.255]	5.280*** [0.246]	5.120*** [0.246]

Note: 1%, 5%, and 10% levels of significance reported via ***, **, and *, respectively. Where the dependent variable is ECFP.

Now, moving towards causality analysis of the model for assessing the cause and effect between ECFP and explanatory variables. The study uses pairwise causality analysis, whose results are presented in Table 8 below. The possible pairs between dependent and independent variables are presented as follows GDP ≠ ECFP, ECFP ≠ GDP, REC ≠ ECFP, ECFP ≠ REC, RDEV ≠ ECFP, ECFP ≠ RDEV, FDI ≠ ECFP, and ECFP ≠ FDI. All the mentioned pairs neglected the null assumption of no causality except for ECFP ≠ REC at significant levels (1%, 5%, and 10%). The results depict that all pairs have bidirectional associations except between REC and ECFP, which is unidirectional, running from renewable energy to ECFP.

4.2. Discussion

The study thoroughly examines the complex correlation between economic growth, the use of renewable energy, investment in research and development, foreign direct investment, and the ecological footprint of China spanning the years 1988–2021. This work enhances the empirical knowledge of these processes and addresses established ideas and ethical concerns, representing a significant progression in the academic literature. The confirmation of non-normal distribution via normalcy tests and the verification of stationarity utilizing the stationarity testing methods are under designated statistical methodologies,

Table 5
Robustness results BSQR.

Variable	Quantiles			Q _{0.90}
	Q _{0.25}	Q _{0.50}	Q _{0.75}	
GDP	0.328***	0.364***	0.364***	0.374***
REC	-0.425***	-0.405***	-0.398***	-0.423***
RDEV	-0.109	-0.146***	-0.148**	-0.182**
FDI	-0.012	-0.023**	-0.022	-0.020
Constant	5.919***	5.458***	5.452***	5.355***

Note: 1%, 5%, and 10% levels of significance reported via ***, **, and *, respectively. Where the dependent variable is ECFP.

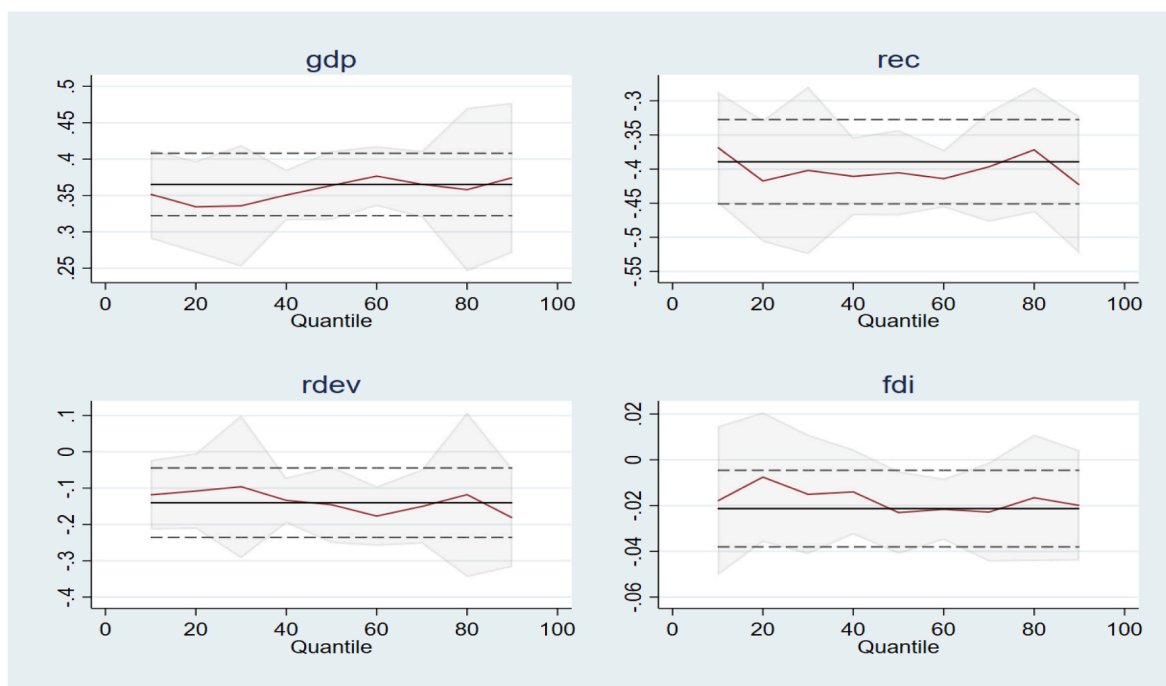


Fig. 4. Quantiles representation of all variables.

Table 6
Least square with breaks and robust least square.

Study Model		Mixed Variables		Robust Least Square	
Var.	Coef.	Var.	Coef.	Variable	Coef.
1988–1995–8 obs.		1988–1992–5 obs		GDP	0.355,285***
GDP	0.781,090***	GDP	0.789,178***	REC	-0.409,596***
1996–2014–19 obs.		1993–2015–23 obs		RDEV	-0.140,351***
GDP	0.775,699***	GDP	0.784,086***	FDI	-0.017961**
2015–2021–7 obs.		2016–2021–6 obs		C	5.568,174***
GDP	0.768,566***	GDP	0.781,199***		
Non-Breaking Variables					
REC	-0.163,361**	ELREC	-0.051754***		
RDEV	-0.474,323***	RDEV	-0.492,749***		
FDI	-0.094667***	REC	-0.296,830***		

Note: 1%, 5%, and 10% levels of significance reported via ***, **, and *, respectively. Where the dependent variable is ECFP.

Table 7
The role of additional variables.

ELREC		FD		REO		GFCE, IDVAD, EXPR	
Var.	Coef.	Var.	Coef.	Var.	Coef.	Var.	Coef.
1988–1997–10 obs		1988–2004–17 obs		1988–2003–16 obs		1988–1992–5 obs	
GDP	0.756,325***	FD	4.542,268***	GDP	0.352,584***	GCF	2.191,194***
1998–2015–18 obs		2005–2014–10 obs		2004–2008–5 obs		1993–2014–22 obs	
GDP	0.750,718***	FD	4.803,167***	GDP	0.358,235***	GCF	2.031729***
2016–2021–6 obs		2015–2021–7 obs		2009–2021–13 obs		2015–2021–7 obs	
GDP	0.745,143	FD	4.671,241***	GDP	0.362,682***	GDF	2.265,771***
Non-Breaking Variables							
ELREC	-0.063546***	ELREC	-0.076719	REO	-0.126,635**	IDVAD	2.265,771***
RDEV	-0.071758	RDEV	-1.637,121***	RDEV	-0.054080	EXPR	2.265,771

Note: 1%, 5%, and 10% levels of significance reported via ***, **, and *, respectively. Where the dependent variable is ECFP.

confirming the dependability of the study’s underlying framework. The detection of substantial cointegration using the combined cointegration test highlights the interdependence of these variables, confirming the need to study them as a whole. The use of the technique of moment quantile regression offers a novel perspective for examining the impact of economic development and sustainability variables on China’s

ecological footprint. The study contradicts current ideas by demonstrating that economic expansion contributes to the worsening of ecological footprints, while the use of renewable energy, investment in research and development, and foreign direct investment help to reduce them. This innovative discovery makes a noteworthy scholarly contribution by enhancing the discussion on sustainable development, beyond

Table 8
Causality.

Pairwise Granger Causality Tests		
H ⁰ :	F-Statistic	Prob.
GDP ≠ ECFP	6.30647***	0.0000
ECFP ≠ GDP	4.23400**	0.0155
REC ≠ ECFP	2.47000*	0.0863
ECFP ≠ REC	0.89232	0.4593
RDEV ≠ ECFP	3.39442**	0.0342
ECFP ≠ RDEV	2.66948*	0.0704
FDI ≠ ECFP	6.51254***	0.0000
ECFP ≠ FDI	3.65442**	0.0266

Note: 1%, 5%, and 10% levels of significance reported via ***, **, and *, respectively.

the limited viewpoint that economic expansion and environmental stewardship are incompatible.

The findings are consistent with the prevailing literature. Firstly, the impact of GDP is observed on ECFP, a positive and bidirectional causal association. This indicates that increasing growth activities directly impacts the environment quality because it increases the ECFP and adversely affects the sustainability of the environment. The same results are claimed in the research study of (Kızılgöl and Öndes, 2022; Ikram et al., 2021). Second, the influence of REC is examined on ECFP and MMQR, providing a negative association between them. This implies that renewables generally have lower ECFP than non-renewables and limit the use of fossil fuels. This lowers the deterioration and damage to the environment, making human activities sustainable. The relationship is in line with the findings of the following extant studies (Aydin et al., 2023; Saqib et al., 2023; Kızılgöl and Öndes, 2022). Third, the influence of REDEV on ECFP is also negative, indicating that it significantly lowers ECFP from the economy. This implies that research and development are significant in enhancing green innovational technologies that are cost and energy-efficient and substantially lower emissions because they have a lesser impact on ecological sustainability as the ECFP is low. The results are similar to the predicted estimates of studies in the literature (Sahoo and Sethi, 2021; Nathaniel et al., 2021). Fourth, the influence of FDI on ECFP is negative, indicating that FDI in the Chinese economy significantly lowers emissions. This implies that FDI is used in technological practices with less impact on environmental deterioration. This ultimately emits fewer emissions and has a lower ECFP, signifying that foreign economies are investing in innovational and management practices that bring environmental sustainability. The result is consistent with the following results (Zafar et al., 2019; Murshed et al., 2022).

Due to industrialization and globalization, the Chinese economy is projected to experience continuous growth. But, this relentless GDP raises significant concerns about the country's environmental sustainability. One of the major impacts of this rising growth is carbon emissions escalation. This is primarily attributed to the enhancement of various economic indicators. For instance, the role of foreign investments and financial development. Additionally, improvements in net international liquidity and exchange rate stability are also some contributing factors. These economic developments result in the expansion of economic progression, leading to a surge in energy usage from non-renewable energy and causing escalating CO₂ emissions. The measures taken to efficiently and effectively manage financial resources are essential in controlling environmental sustainability. Further, adopting renewable energy for electricity generation is essential in mitigating carbon pollution. China has witnessed a notable increase in the proportion of renewable energy sources utilized in electricity production, which helps reduce emissions. This shift towards renewable energy offers a promising solution for enhancing energy security and environmental sustainability. Besides, relying more on renewable energy sources effectively limits the release of harmful emissions into the atmosphere.

Furthermore, the methodological strength of this study is shown by

the use of bootstrap quantile regression and least squares with breaks, which contributes to its overall credibility and adherence to the established standards of empirical research. Confirming bidirectional causal relationships between the variables enhances the sophisticated comprehension of their interaction. Significantly, this study is in line with and expands upon the existing body of knowledge, since the anticipated outcomes are consistent with the findings of other researchers. This study enhances theoretical frameworks by offering a detailed analysis of the intersection between economic development and sustainability considerations. The ethical significance of this contribution resides in its disclosure that implementing sustainable practices does not always impede economic achievement. This concept has substantial policy implications. Overall, the research contributes to the advancement of both theoretical and ethical aspects, establishing a foundation for more comprehensive approaches to development that emphasize the responsible management of the environment while simultaneously promoting economic progress.

5. Conclusion and policy implications

The study inspects the impact of GDP, REC, research and development, and foreign direct investment on the ECFP in China in an updated and extensive data period (1988–2021). The increasing attention toward sustainability goals and climate change has led scholars to study ECFP and sustainable management. China is an emerging global economy with higher economic development levels. The intensifying industrialization in the economy has caused several adverse environmental effects, making the economy a large contributor to harmful emissions worldwide. Limited efforts have been made in the past years to improve the environment. With the increasing prominence of COP27 in this regard, the authors intended to explore the factors that impact the ECFP for sustainable management. The study uses Quantile regressions and pairwise causality analysis for estimating significant and reliable estimates. The regression outcomes depicted comparable findings with the following (Kızılgöl and Öndes, 2022; Ikram et al., 2021; Aydin et al., 2023; Saqib et al., 2023; Sahoo and Sethi, 2021; Nathaniel et al., 2021; Zafar et al., 2019; Murshed et al., 2022). The estimated results show that GDP significantly contributes to the increasing ECFP in China, while the remaining explanatory factors tend to lower the ECFP. It can be argued that the spending and investments in renewable innovation and energy-efficient technologies help lower the ECFP because these have limited to no impact on increasing environmental deterioration.

However, grounded on the estimated outcomes, the following suggestions are recommended for sustainable management of the environment and mitigation of ECFP from the COP-27 standpoint. First, the loss and damage fund initiation and China's contribution are fruitful in lessening the ECFP. However, to meet its carbon neutrality targets and lower ECFP, China must prioritize promoting and adopting efficient and sustainable technologies. The increasing industrialization has increased GDP, which escalated increased emissions. Therefore, the country needs to promote sustainable R&D and FDI by implementing regulations so that in the future, they may not have a harmful impact on the environment. Besides, the economy must invest in forestation activities because the more greenery, the lesser the environmental emissions and ECFP. Second, China should promote financial development that aligns with its goals. In this way, the country achieves a sustainable environment alongside growth. The government must focus on increasing and implementing carbon prices and taxes to lower non-renewable energy usage and is fruitful for environmental sustainability.

The study is limited to the economy of China. The study can be replicated in other high carbon-emitting economies for a more comprehensive and detailed analysis for overhauling environmental policies for sustainable development and mitigation of climate change. Moreover, different ECFP indicators can be used to thoroughly analyze the ECFP and the world.

Author statement

Menghan Li: Idea, Writeup, Estimations and Final Review, **Ramez Abubakr Badeeb:** Methodology and Data Collection, **Eyup Dogan:** Results and Discussion Part with theoretical underpinning, **Xiao Gu:** Review; proofreading, **Hong Zhang*:** Supervision; revised version.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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