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Accessing the role of tourism, renewable energy, and green finance in shaping the sustainable future

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Worldwide efforts to achieve ecological sustainability include addressing the impact of carbon dioxide (CO_2) emissions. Additionally, the issue of lowering CO_2 emissions in developed and industrialised nations, such as China, remains unsolved. Therefore, this study assesses the impacts of tourism, renewable energy, climate disasters, and financial development on carbon emissions in China for the period 1990–2022 by using Fourier Cointegration analysis under both triangular hypotheses using the ARDL approach and bivariate causality tests with a frequency domain structure. The study found that tourism seems to increase climate change by driving energy use, whereas renewable energy counters it. Climate-related disasters perpetuate climate change, while financial growth supports and hinders it, based on where it is geared. However, the work does show that sustainable tourism practices, coupled with even higher levels of renewables investments and green finance efforts to help meet climate change commitments in China, are crucial. The avenues for further research and limitations are also discussed.

Keywords Tourism, Energy transition, Climate change, Fourier ARDL, China

Climate change is a global issue affecting ecosystems, human health, and global economies. It causes a greater frequency and intensity of weather events that disrupt infrastructure and threaten food security by reducing agricultural productivity[1]. Moreover, it issues health problems due to worsening air pollution and expansion of vector-borne diseases (WHO 2018)[2]. Economically, the costs of climate-related disasters can amount to trillions of dollars in damage and lost productivity[3]. In September 2015, the United Nations member states unanimously adopted "Transforming the World: The 2030 Agenda for Sustainable Development", a universal action plan for the global cooperation and mitigation of climate change from 2015 to 2030. The 2030 Agenda defines a set of 17 interconnected goals (and 169 targets), which 193 UN member countries have endorsed and are intended to achieve worldwide by 2030. These 17 SDGs serve to encourage all countries—poor, rich, and middle-income—to work together to improve the lives of people while protecting the planet we all live on. They recognise that all countries need to cooperate to follow socioeconomic development paths that enable economic growth while meeting multiple social demands—education, health, social protection, and employment prospects—together with combating climate change and delivering environmental protection by 2030. China is the second largest economy in the world, with a central role in defining the global sustainability agenda[4]. Over the past few years, with the rise of tourism, renewable energy, and green finance, sustainability has been embedded in China's national policies. Each of these three sectors is increasingly recognised as a key engine for sustainable development in its own right, wherein economic growth can be sustained while minimising environmental damage and enhancing social welfare.

The over consumption of resources and adverse environmental results are worldwide distress that all suffer from the impacts and vengeance of climate change and global warming[5]. In the tourism industry, host destinations and natural resources of host communities face the risk of over-exploitation or exploitation [6]. Responsible and sustainable tourism can be an important part of solving these problems[7]. Tourism and entities of irresponsible behaviour by various actors in the tourism industry have negative effects on the social and environmental dimensions of society[8]. As mass tourism has become a concern for host destinations and local communities[9], criticism of the old growth strategy has accelerated. Responsible and sustainable tourism is another emerging philosophy within the tourism sector, aiming primarily at tackling the problem of mass tourism and stressing the

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problematic action behaviour of the tourism industry[10]. Clear and planned tourism is relevant and will appear in any presentation associated with ecological tourism[11] and it is: the very problem of mass tourism is the existence of various kinds of the tourism friendly to the atmosphere answers (responsible tourism of sustainable and responsible tourism, responsible and ecotourism[12]. The key sector of the national economy in China is tourism in terms of its roles in GDP and employment. But the 'scramble' for tourism has raised environmental issues related to over-consumption of natural resources, pollution and habitat loss. Sustainable tourism focuses on a responsible use of resources, ensuring cultural and natural heritage are protected, providing a solution to the negative impacts while still benefiting from economic growth in this sector. China is in a unique position to provide this model for the world through eco-tourism, cultural tourism, and other forms of sustainable tourism.

Furthermore, renewable energy is also among the pillars of China's sustainability efforts, a crucial part of the efforts to wean the country off fossil fuels and combat climate change. As the world's largest energy consumer, China is under huge pressure to shift to cleaner energy sources without sacrificing economic growth[13]. Over the last decade, China has become a leader in renewable energy, pouring money into its wind, solar, and hydropower projects. These efforts not only cut carbon emissions but also helped clean the air, thereby tackling a major public health issue. This was a mistake; renewable energy also has economic advantages, such as job creation, technological innovations, and energy security. China provides an example to other countries that growth does not have to come at the cost of environmental quality simply by massively deploying many renewables[14]. The cross-sectoral integration between renewable energy and sectors such as tourism also has an amplifying effect, creating synergies that contribute to the overall sustainability chain.

Similar to renewable energy, green finance facilitates capital mobilisation for sustainable development and creates opportunities for financing projects that provide environmental and social benefits. Green finance has become an emerging trend in China in recent years, spurred by the efforts of government policies, market demand, and cooperation with other countries[15]. Currently, the country is the world's biggest source of green bonds, with Chinese issuers responsible for 346% of the total issuance. Green finance encompasses everything, from renewable energy projects to energy-efficient buildings for sustainable agriculture. By mobilising funds for sustainable projects, green finance promotes the transition to a low-carbon economy and provides financial returns to investors. The double dividends of green finance thus render it a vital facilitator of sustainable development, both locally and globally[16]. Green finance has also spurred the adoption of sustainable practices in the tourism industry, as it supplies the capital required for environmentally friendly infrastructure and technologies.

Moreover, environmental disasters, including floods, earthquakes, and typhoons, constitute a major challenge for sustainable development in China. These disasters are not just immediate causes of human suffering and economic loss but also have long-term consequences for environmental sustainability and economic stability[17]. In recent years, China has faced more frequent and severe environmental disasters owing to the impacts of climate change and environmental degradation. Tackling these issues calls for a holistic approach that combines disaster risk reduction and sustainable development strategies[18]. Renewable energy, green finance, and sustainable tourism are vital for strengthening resilience to environmental disasters, minimising vulnerability, and accelerating recovery. One such example is renewable energy infrastructure that can ensure reliable power in disaster-affected areas, or green finance to finance disaster-resilient infrastructure and recovery efforts[19]. The inclusion of these aspects in China's sustainability agenda is crucial in creating a resilient and sustainable future.

Another important area is financial development index (which measures the depth, access, and efficiency of financial systems), which plays a significant role in sustainable development. Thus, a developed financial system can promote the collection of resources into sustainable initiatives, support innovation, and increase the stability of the economy[20]. Recent Reforms And Technological Improvements In China Have Drastically Increased Its Financial Development Index Such propelled inclusive access to green finance, facilitating an economy-wide transition to low-carbon. However, there is still room for improvement in areas such as transparency, regulatory frameworks, and risk-management practices. Tackling these hurdles is paramount to ensuring that financial development provides a shot in the arm for sustainability[21]. This underscores the need for a comprehensive view of sustainable development given how financial development interacts with green finance and other drivers of sustainability.

Finally, the key piece of China's sustainability puzzle is trade, which brings opportunities for economic growth at home as well as the abstraction of technological know-how and close international ties[22]. As the world's largest trading country, China is a key player in global supply chains, driving sustainability practices worldwide. Some sustainable trade trends, such as the use of green standards or more eco-friendly products[23], will facilitate environmental sustainability and economic prosperity. However, trade brings challenges as well as the risk of environmental degradation and resource depletion. Such issues can be addressed only through holistic and integrated trade policies and practices that promote sustainability. Sustainable trade can be promoted through renewable energy, green finance, and sustainable tourism, thereby establishing synergies that improve overall sustainability[24]. These elements must now be integrated into China's trade strategy if the country aims to achieve development goals.

This work is motivated by the imperative of addressing climate change, against a backdrop where rapid economic development in China has come at a considerable environmental cost. The research explores the intricate pathways of tourism, renewable energy, climate-related disasters, financial development, and open trade regimes in influencing the cross-sectional environment through a mix-type econometric technique such as Fourier cointegration or Fourier ARDL to reveal long-run and short-run determinants of weather change. This study is important because it provides scientists with a good empirical basis for how these factors impact climate change and provides essential information that policymakers should follow to balance economic growth with environmental sustainability. The main research task consists of revisiting these dynamics in China and assessing their immediate and future impact, with the aim of producing policy recommendations that can support sustainable development while also combating climate change, thereby contributing, broadly speaking, to a better understanding of both economic and environmental challenges faced by newly industrialised countries.

Review of literature

Previous research has thoroughly investigated the relationship between tourism and environmental studies, specifically by employing Environmental Kuznets curves as a theoretical framework. Nevertheless, technology is crucial for facilitating this framework. The intricate framework is also influenced by several socioeconomic aspects, including Foreign Direct Investment (FDI), Financial Development (FD), and trade openness (TO). Therefore, the literature was methodically partitioned into subsequent subsections.

Tourism and carbon emission

Many countries depend on tourism-led growth because they allow for the accumulation of capital through the advantages of economies of scale. Majumdar[25] suggested that the introduction of a regulatory framework specifically targeting environmental concerns can alleviate the adverse impacts of economic growth on the environment. Current research indicates an intricate correlation between economic expansion and emissions, with the analysis grounded in Environmental Kuznets Curve (EKC) theory. The EKC hypothesis suggests that there is a curvilinear relationship between economic expansion and pollution, specifically, an inverted U-shaped relationship. This concept has received empirical support from various studies, including that undertaken by Caglar[26]. This is because the environment is classified as a normal good, which implies that once income exceeds a specific level, demand for it is expected to rise. The results indicate that nations with greater prosperity are more likely to support the implementation of environmentally sustainable measures in the tourism sector. These activities include promoting energy-efficient housing, obtaining eco-certification, and developing eco-friendly infrastructure for transportation such as hybrid and electric cars[27]. As nations advance economically, there is a discernible inclination towards placing greater significance on environmental preservation and implementing strategies to reduce their ecological footprint. Studies suggest that countries might operate under the threshold range of the EKC, resulting in environmental degradation[28]. This notion has been refuted for the G7 nations, both in the immediate and extended periods. Including a quadratic term to measure nonlinearity is statistically insufficient, as it fails to consider the changing effect over time and address potential endogeneity. Consequently, current studies prioritise co-integration, FMOLS, and ARDL techniques. Moreover, this research suggests a unidirectional correlation and reciprocal connection between tourism revenue and CO_2 emissions. Most investigations have been constrained inside a predetermined panel structure. Although a proven dynamic relationship may be found, the methodology used to determine the strengths of integrated variables in estimations is vulnerable to potential biases[29].

Liu[30] investigated the relationship between tourism and carbon emissions in the United States for the period of 1996 to 2015. The data indicated that tourism is a significant determinant of the emission of carbon. Furthermore, it has been established that there is a one-way correlation in which tourism impacts carbon emissions. Li[31] conducted a comprehensive analysis of the energy efficiency of the tourism industry in all 30 regions of China from 2005 to 2013. It has been shown that the energy efficiency of the tourism sector is lower in comparison to that of the industry. Multiple studies have investigated the correlation between tourism and carbon emissions by evaluating panel data from various country groupings. Agyeman[32] conducted a study to investigate the enduring connections among real GDP, GDP, energy consumption, trade openness, and tourism in OECD states from 1995 to 2010. Research findings suggest that tourism has a negative impact on environmental quality since it contributes to the rise in carbon. The findings of the causality test showed that there is a one-way causal relationship from tourism to carbon. Rahaman[33] undertook a study to investigate the relationships between economic growth, tourism, and CO_2 emissions in certain Asia-Pacific countries from 1995 to 2013. According to their statement, tourist arrivals have a positive long-term effect on carbon emissions. A study conducted by Juwita[34] investigated the correlation between tourism activities and carbon dioxide emissions in Malaysia, Thailand, and Singapore. Based on their research, tourism has a positive impact on carbon emissions in Malaysia, but a negative impact on carbon emissions in Thailand and Singapore.

Renewable energy and carbon emission

There has been much research into what drives CO_2 emissions, with many studies showing that the growth of renewables lowers emissions and reduces reliance on fossil fuel sources[35]. According to a study conducted by Caglar[36] using the STIRPAT model and OECD data (1980–2011), the results revealed a positive correlation between non-renewable energy consumption and CO_2 emissions and a negative correlation between the impact of renewable energy consumption and emissions. Additionally, Kutlu[37] highlighted that the upgrading and optimization of the industrial structure could effectively reduce CO_2 emissions, based on panel data covering China from 1995 to 2009. The relevance of transitioning to renewable energy sources (as opposed to fossil fuel dependency) and focusing on energy efficiency in order to be carbon neutral by 2050 has been reiterated by other studies[38].

Xu[39] emphasise the importance of green energy and high-tech exports in lowering China's carbon footprint, and Zhan[40] argue that energy efficiency programs must take multiple factors into account, including the potential pitfalls if only high-tech exports are relied upon to curb emissions. Data until October 2023 highlight the need for a holistic approach towards reforming and finding a solution for the challenges related to CO_2 emissions due to globalised nations' interlinked carbon footprints, coal combustion, real income, and FDI. For a similar study, see the work of Chen[24] shows that has a strong and positive correlation with economic growth and sustainable environment. Overall, previous studies have mainly focused on the important role of green energy in reducing CO_2 emissions[41], calling for more ambitious policies to incorporate renewable energy sources.

As of October 2023, studies from other BRICS countries have yielded pertinent outcomes involving natural and environmental conditions related to renewable energy. In particular, Arslan[42] and Bekun[43] found evidence of EKC in respective countries, but for renewable energy. This essentially implies that, as renewable energy deployment increases, urban degradation can keep ramping up beyond a certain threshold, well before we start seeing a significant reduction in carbon pollution. Simply stated, the adoption of renewable energy initially harms the environment, but eventually improves it. These discoveries highlight the significant potential role renewable energy can have on the environment, both positively in BRICS countries over time. However, some scholars have shown that the effect of renewable energy on CO_2 emissions is limited globally[44] and in ASEAN countries[45], indicating the necessity of a more large-scale and close study on the relationship between renewable energy and CO_2.

Climate related disasters and carbon emission

There is scientific evidence linking increasing carbon emissions to the persistence and severity of climate disasters. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), higher amounts of greenhouse gases (GHGs, mainly from burning fossil fuels and deforestation) have worsened global warming and have been associated with an increase in extreme weather events, such as hurricanes, wildfires, and floods[46]. Higher rates of CO_2 are linked to sea-level rise and ocean acidification, both of which intensify coastal flooding and affect ecosystems[47]. According to empirical evidence, places with larger carbon footprints have been shown to experience more severe climate impacts, supporting the need for urgent emission reductions to reduce disaster risks[48,49].

The price tag of climate devastation — stoked by carbon emissions — is staggering in both social and economic terms. According to the World Bank (2020), climate disasters could force more than 100 million people into poverty by 2030 (caused by agricultural losses, damage to infrastructure, and health crises). Developing countries, while contributing to a lesser extent to global emissions, pay the price for these disasters out of proportion because they have very low adaptive capacity[50]. Furthermore, carbon-oriented sectors have increasingly faced material costs for disruptions owing to disasters, creating pressures to strengthen climate measures and corporate responsibility[51,52]. More frequent disasters related to these same climate-related factors have resulted in climate mobility, with millions being displaced every year, further affecting global resources and increasing geopolitical tensions[53,54].

Research gap

Economic activities significantly impact climate change, yet many datasets reveal only partial environmental implications. This model contributes to research examining multi-faceted interrelationships over different temporal scales, addressing limitations in studies focusing on single factors. Past research typically uses standard econometric models, overlooking sophisticated methods like Fourier Cointegration and Fourier ARDL that effectively calibrate long-run vs. cyclical behavior in data generation. The literature inadequately discerns whether financial development acts purely as an economic growth engine, potentially causing environmental degradation, or involves separate phenomena. Additionally, the endogeneity problem concerning financial development and climate change remains underexplored, while international policy frameworks like the Paris Agreement are often ignored in regional analyses. This paper addresses these gaps by examining complex drivers of climate change in China using sophisticated methodologies and provides detailed policy suggestions for future and immediate challenges.

Materials and methods

Theoretical framework

According to the EKC Hypothesis, there is an inverted U-curve relationship that describes how environmental degradation increases in tandem with economic development. The EKC posits that during economic expansion, environmental degradation risen initially but after a certain level of per capita income flows out, further increase in growth may lead to reduction in the overall pollutant levels as economies can afford cleaner technologies and stricter regulations[55].

The EKC theory can be more circulated if it takes out external tourism[56], renewable energy, disaster climate-associated, financial development, FDI, and carbon emissions. An example would be that international tourism, because of an increase in local economic activity it leads to more emissions coming from business activities, however over time countries through further financial development could switch to sustainable forms of the same and lessen their carbon emission[57]. Additionally, renewable energy consumption implies a substitution of cleaner for dirtier forms of energy and reflects environment-friendly technology that is characteristic to the further stages in the EKC where economic growth fosters environmental betterment[58]. When interpreted in view of the development trajectory, climate-related disasters become external shocks which could either compound emissions during recovery or accelerate a transition towards sustainable practices. Financial development is important to enable the investments required for this transition, which corresponds with the turning point in EKC hypothesis environmental quality starts deteriorating[59]. Production quality and production process can either increase or decrease the emission level on their own because international trade acts to reduce of raise emissions through scale itself, type is composition.

$$CC_i = \alpha_0 + \alpha_1 \mathrm{Y_i} + \alpha_2 \mathrm{Y}_i^2 + \eta_\mathrm{i} \tag{1}$$

Whereas CC stand for climate change, $\alpha_0, \alpha_1, \alpha_2$detect the coefficients andηdefines the error term. The EKC proposes a curvilinear association between environmental deterioration and economic growth, characterized by an inverted U-shaped pattern. The mathematical Eq. (1) of EKC were further extended to include international tourism, renewable energy consumption time series data together with climate related disasters incidents and lastly financial development indices over the scope of trade as well as foreign direct investment in equation form by adding four extra parameters.

$$CC_i = \alpha_0 + \alpha_1 \mathrm{Y_i} + \alpha_2 \mathrm{Y}_i^2 + \beta_1 TOR_i + \beta_2 ET_i + \beta_3 CRD_i + \beta_4 FD_i + \beta_5 TRD_i + \eta_\mathrm{i} \tag{2}$$

Whereas TOR_i stands for international tourism arrivals for country "i", ET_i energy transition for country "i". CRD_i shows frequency of climate-related disasters for country "i". FD_i describes the financial Development Index for country "i". TRD_i denotes the trade as a percentage of GDP for country "i". FRD_i illustrates the foreign direct investment, net inflows as a percentage of GDP for country "i". $\beta_1, \beta_2, \beta_{3,} \beta_4 and \beta_5$ detects the coefficients.

α1−a > 0 & α2 < 0: These coefficients imply the traditional EKC relation, i.e. prices for α1 do not change sign while those of α^2 are negative reflecting an inverted U-shaped relationship between income per capita and CO_2 emissions; β1\beta_1β1: The international tourism coefficient is expected to be positive (where β 0 > 0)(≍2.63), that implies the increase in tourist arrivals will lead towards CO emission thus it converts a non-pollutant sector into carbon pollutant revenues. The coefficient of renewable energy consumption is a priori expected to have negative sign (β2 < 0\beta_2 < 0β2<0), since an increased participation in the provision by sources environmentally cleaner tends to diminish emissions. Climate-related disasters: The coefficient may be positive or negative, reflecting the fact that emission during recovery from a disaster are higher than during normal operations which might lead to more sustainable practices. βi < 0\beta_i < 0 β i<0 only for financial development since it is assumed that F captures the investments in cleaner technologies. γ1\gamma_1 and γ2\gamma_2: the sign on the coefficients for trade (and FDI) could go either way depending on what these things are like in practice how they affected scale/nature of economic activities. While considering the above discussion, the suggested model can be reported as below in Fig. 1.

Data

Climate change and excessive fossil fuel burning, and tourism have contributed in the destruction of our environment which is a direct action response towards climate related disasters that disrupt global security[60]. These threats manifest in forms such as food insecurity, natural catastrophes, energy poverty, economic crises and the dearth of resources that may ultimately result in conflicts and displacement. The details of parameters are reported in Table 1.

Method

$$St = \sum_{i=1}^{t} \widehat{\mu}_i \tag{3}$$

$$KPSS = \frac{1}{T^2} \sum_{t=1}^{T} S_t^2 / \widehat{\sigma}^2 \tag{4}$$

T is time while $\widehat{\sigma}^2$ long run variance of $\widehat{\mu}_i$, which is estimated as.

Fig. 1. The proposed model (Drwan by authors).

Symbol	Description	Source
CC	Carbon emissions (metric tons per capita)	WDI
TOR	International tourism, number of arrivals	WDI
ET	Renewable energy consumption (% of total final energy consumption)	WDI
CRD	Climate related disasters frequency, number of disasters: total	IMF
FD	Financial Development Index	IMF
TRD	Trade (% of GDP)	WDI
FRD	Foreign direct investment, net inflows (% of GDP)	WDI

Table 1. Summary of parameters.

$$\widehat{\sigma}^2 = \frac{1}{T}\sum_{t=1}^{T}\widehat{\mu}^2_i + 2\sum_{l=1}^{L} wl(\frac{1}{T}\sum_{t=l+1}^{T}\widehat{\mu}_i\widehat{\mu}_{i-l}) \quad (5)$$

Non Stationary means unit root bootstrap is a statistical test Indicates of the presence factort and stationary which are fitted in time series. The bootstrap part means the use of resampling techniques to improve test accuracy and reliability, arguing in favor especially when doing it with a small sample or having heteroskedasticity or serial correlation of their own data. Rather than a standard example root test that uses the asymptotic distribution, unit boot lock examples generate a wide range of samples from an original data series and build empirical dispersion for testing statistics. This approach gives more appropriate critical values and values making the test robust to misspecifications due, for example, to structural breaks or non-linearities. Thus, bootstrap unit root tests are considered as a better approach for testing stationarity in time series analysis which is a very useful tool within the field of econometrics.

$$y^*_t = \widehat{\alpha} + \widehat{\beta}t + \gamma y^*_{t-1} + \sum_{i=1}^{p}\widehat{\phi}\Delta_i y^*_{t-1} + \varepsilon^*_t \quad (6)$$

The Fourier Augmented Dickey-Fuller (Fourier ADF) test is an extension to the standard Dickey-Fuller test that better accounts for structural breaks in time series data. It also improves the ability to detect unit roots while allowing more flexibility in modelling complex trend structures and seasonal effects by including equivalent Fourier series terms. This improvement weakens the value of the Fourier ADF test to perform statistical analysis in real-world time series, more notable perhaps within financial/economic applications where trends and seasonal patterns are often very complex, if not evolving, as reported in Eq.

$$\Delta \mathrm{X_t} = \alpha + \beta \mathrm{X_{t-1}} + \sum\sum_{i=t}^{p} p\phi_{\mathrm{i}}\Delta \mathrm{X_{t-i}} + \sum_{k=1}^{n}[\gamma_{\mathrm{k}}\sin(\frac{2\pi \mathrm{kt}}{\mathrm{T}}) + \delta_{\mathrm{k}}\cos(\frac{2\pi \mathrm{kt}}{\mathrm{T}})] + \epsilon t \quad (7)$$

Where Xt = CCt, TORt, ETt, CRDt, FDt, TRDt, and FRDt, X_{t-1} is the first difference of series of Xt, $f(t) = \sum\sum_{i=t}^{p} p\phi_{\mathrm{i}}\Delta \mathrm{X_{t-i}} + \sum_{k=1}^{n}[\gamma_{\mathrm{k}}\sin(\frac{2\pi \mathrm{kt}}{\mathrm{T}}) + \delta_{\mathrm{k}}\cos(\frac{2\pi \mathrm{kt}}{\mathrm{T}})]$ is the Fourier function

Fourier cointegration is a novel econometric methodology, which improves traditional cointegration analysis by considering both nonlinear relationships and structural breaks that are commonplace in economic data. Since economic variables often change significantly and exhibit nonlinear dynamics, as also can be affected by policy regime shifts or external shocks Fourier cointegration is able to capture these aspects effectively to provide a superior analysis. It also provides a method of dealing with structural breaks (e.g., sudden economic crises or market events) by employing Fourier functions that allow for modeling both gradual and abrupt shifts in the data series. This method opens econometric models, helps to better match data and achieve more accurate estimates as well as improved forecasts — which are essential components for policy analysis, financial modeling or economic planning. Fourier cointegration is widely applicable in economics and finance, providing a new and unique way to extract meaningful relationships from high dimension data that can be considered complementary or at least substitute for the traditional methods of other equilibrium relations on long-run basics.

$$X_{1t} = \alpha + \beta X_{2t} + F(t) + \eta_t \quad (8)$$

$$\widehat{\eta}_t = X_{1t} - \alpha - \beta X_{2t} + F(t) \quad (9)$$

$$\Delta\widehat{\eta}_t = \rho\widehat{\eta}_{t-1} + \sum_{i=1}^{p}\phi\Delta\widehat{\eta}_{t-i} + \varepsilon_t \quad (10)$$

Fourier ARDL is a more sophisticated econometric method than the basic ARDL models by utilizing Fourier functions to capture any nonlinear nature and/or structural breaks within data. This is important because economic and financial time series are generally non-linear and suffer structural breaks because of policy changes, or external shocks. As opposed to traditional ARDL methods which consider linear relationships and non-ability of dealing with structural breaks, Fourier ARDL can capture these complexities in a more proper way. It also performs better compared to bootstrap ARDL that reduces small-sample bias but still assumes linearity, and dynamic simulated ARDL by accounting for dynamics relationships which may disregard nonlinearities and structural breaks. The improvement it allows in model fitting and the considerable reduction of parameter estimates — among some other advantages like more accurate forecasts makes Fourier ARDL a very useful tool for analyzing complex economic relationships, thereby making it an essential component of any researcher or policy maker's toolkit.

$$\Delta y_{\mathrm{t}} = \alpha + \sum_{i=t}^{p} \beta_i \mathrm{y}_{\mathrm{t}-i} + \sum_{j=0}^{q} [\gamma_{\mathrm{k}} x_{t-j} + \delta_1 \sin(\frac{2\pi \mathrm{kt}}{\mathrm{T}}) + \delta_2 \cos(\frac{2\pi \mathrm{kt}}{\mathrm{T}})] + \epsilon \mathrm{t} \quad (11)$$

$$\Delta y_{\mathrm{t}} = \alpha + \phi(y_{t-1} - \theta x_{t-1}) + \sum_{i=t}^{p} \beta_i \mathrm{y}_{\mathrm{t}-i} + \sum_{j=0}^{q} [\gamma_{\mathrm{k}} x_{t-j} + \delta_1 \sin(\frac{2\pi \mathrm{kt}}{\mathrm{T}}) + \delta_2 \cos(\frac{2\pi \mathrm{kt}}{\mathrm{T}})] + \epsilon \mathrm{t} \quad (12)$$

Conducting frequency domain causality tests post estimation of Fourier ARDL serves as a suitable robustness check along time-domain analysis in terms of understanding how relationships may change at different frequencies.

Results and discussion

Figure 2 shows climate change and tourism from 1990 to 2030 in the study area. The x-axis represents climate change and the y-axis shows the years. The color scale denotes the tourism levels (low = blue, high = red). The visualization illustrates the complex relationship between climate change and tourism. Climate change generally increases, whereas tourism vacillates. Three areas showed high climate change and large tourism potential around 2000, suggesting that some activities might benefit from climate change. However, some periods, such as 2015, show decreased tourism alongside climate change, implying possible negative outcomes. The impact of climate change on tourism is nuanced and context specific. Figure 2 shows the climate and energy transition changes from 1990 to 2030. The red area shows climate change, which increased until 2010 and then flattened. In bright blue, energy transition began slowly but accelerated post-2010, overtaking climate change by the 2030s. This indicates that despite the climate change threats, energy transition momentum is building. A scatterplot shows the correlation between climate change and climate-induced disasters from 1990 to 2030. The number of data points increased over time, suggesting an upward trend. However, this relationship is not strictly linear; some years show disaster intensity dips even as climate change rises. Data clusters during certain periods indicate increased exposure to climate-related disasters. Although visual effects suggest a correlation, more research is needed to link climate change to specific types of damage. Figure 2 shows the x-axis representing climate change, from decreasing to increasing left-to-right, and the y-axis showing years. Financial development index scale (low-blue; high-red) color scheme on the right. The visualization revealed a nonlinear relationship between the variables that will be challenging over time. Higher climate change levels are generally associated with lower financial development, but there is variation: areas where investments finance economic production/exchange do well despite facing environmental stress. The impact of climate change on economic development differs across decades. The relationship with climate change is complex, and the channels affecting financial development likely depend on other factors that vary in time and space.

The Table 2 discloses that values are located vary close to mean line while skewness exposes a moderate negative skewness. Kurtosis illustrates a positive tailed data, along with the normal distribution. Consequently, it reports that central tendency, deviation from mean and spread of the data is in the favor of the study.

Figure 3 shows a matrix of numbers, which could be the correlations or coefficients between variables. It has a value of about − 0.98 to 0.92 in each cell. These values might say something about the strength and direction of relationships that these variables represented by all given row-column pairs have with each other. Positive numbers show a positive correlation, and negative values show the opposite. The value provides the strength of relationship between variables. We cannot give a more concrete interpretation without knowing what these variables represent.

The information in Fig. 3 exposes that the medium and strong correlation which seems to be problematic and may leads towards multicollinearity. However, the VIF values (see Fig. 4) indicate that there is no problem of multicollinearity in the series because the coefficient values are within the threshold values range (± 5, ± 10).

It is mandatory to confirm the stationery before estimation, because is it the pre- requisite to detect the stationery in the series. Therefore, we employed traditional ADF, GKPSS and for structural break applied LSLM unit root, which is reported in Table 3.

Based on the ADF, GKPSS and LSLM unit root tests results for CC, TOR, ET CRD FD TO & FDT as explanatory variables they are all or at least most of them are non-stationary in level form. This means that the values of these variables are non-stationary and therefore they have a mean, variance or autocorrelation which changes over time. Yet all three tests suggest the first-difference of these factors [i.e., (change from one period to next)] is stationary. This means that the factors themselves trend or cycle, but after differencing (removing a period lag) these trends in changes cancel. The LSLM test further allows us to investigate potential structural breaks in the estimate of factors across time.

Table 4 shows the results of bootstrap unit root test of variables. It confirms if all the variables are stationary or not which means they have statistical properties and order of differencing is fixed for analysis. The t-statistic

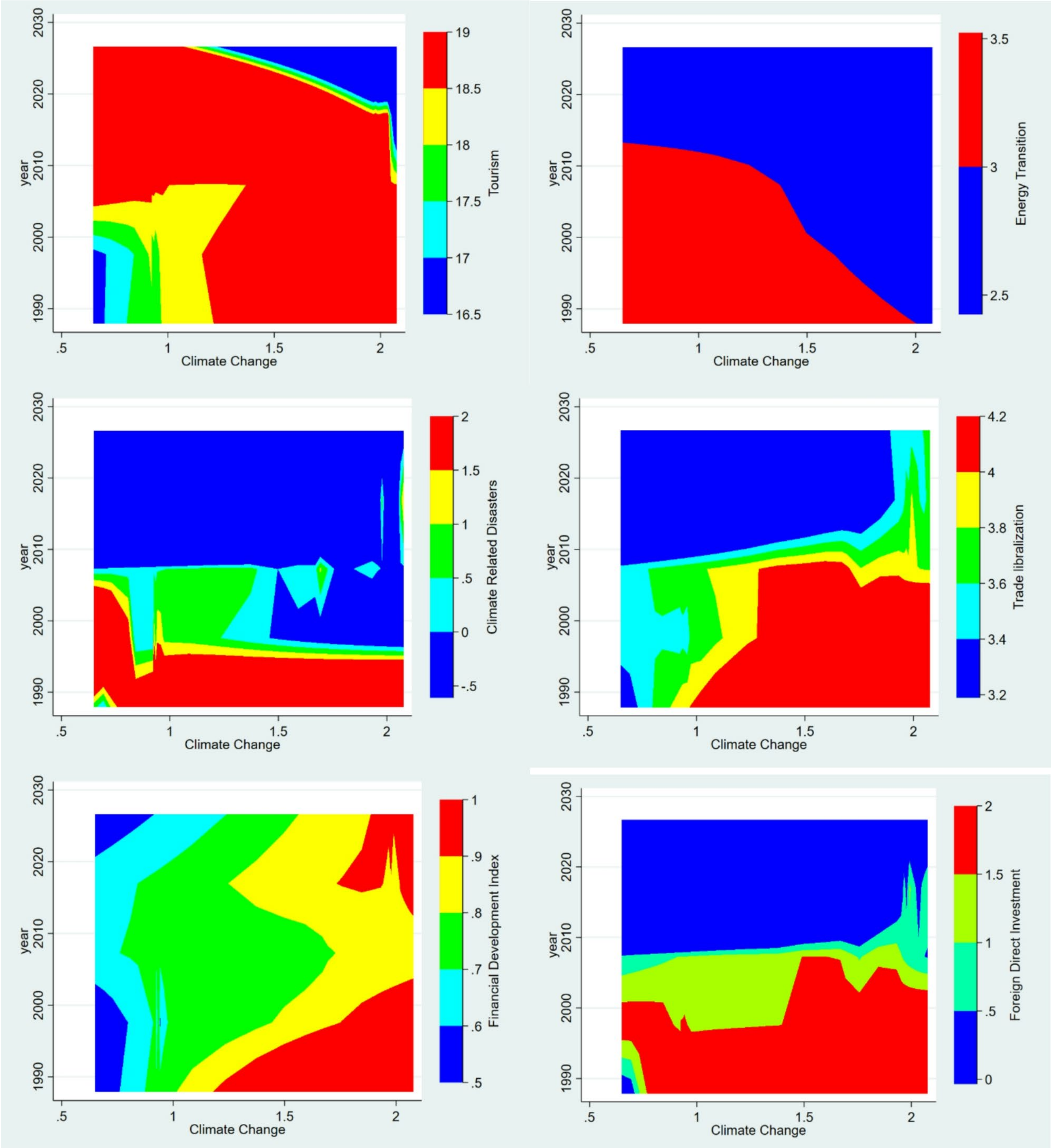

Fig. 2. Response of predictors with respect to climate change.

of each individual variable is compared to a bootstrap critical value, creating a p-value. According to the results obtained, all the variables but ITA (p-value = 0.0560) are stationary at lower than %5 significance level. It means there is strong evidence against a presence unit root in these series. It indicates that there are no increasing or decreasing movements and it is relatively stable amid the time behavior of these factors.

Table 5 shows the results of the Fourier Augmented Dickey-Fuller (ADF) test testing stationarity hypothesis for these factors. Generally, the factors are stationary in nature as per the results. Moreover, the attempts for unit root test indicates that CC, TOR, RNC CRD and FD are stationary at 1% significance which is strong evidence against such non-stationarity. TRD and FRD are not stationary at a 10% level of significance which shows that their statistical evidence is weaker however points towards stationarity. In general, the table reveals that for most of these variables there is a large degree in stable-time behavior (in other words it presents no trend or mean reverting stochastic fluctuation).

Parameters	Mean	Min	Max	SD	Skewness	Kurtosis	JB
CC	1.459	0.649	2.077	0.514	-0.187	1.371	3.840
TOR	12.222	16.656	18.906	0.638	-0.950	2.697	4.781
ET	2.956	2.425	3.523	0.408	0.142	1.303	4.070
FD	0.760	0.508	0.959	0.124	-0.311	2.338	1.134
CRD	0.399	-0.610	1.946	0.639	0.425	2.473	1.378
TRD	3.707	3.189	4.166	0.245	0.186	2.554	0.463
FRD	1.046	-0.034	1.822	0.522	-0.626	2.302	2.826

Table 2. Summary statistics.

Fig. 3. Correlation matrix.

Table 6 shows the results of Augmented Engle-Granger cointegration test results. The test seeks to ascertain if there's a long-run relationship among the variables TOR, RNC, CRD FD, TRD and FRDF with the null hypothesis of cointegration.

From the Z(t) statistic of -7.523 this cross section mean test is significant at all levels and suggests strong evidence in favor of cointegration between these variables. This means these variables have a common trend and they move together in the long run. Moving to the multivariate cointegration regression coefficients, TOR, RNC TRD and FD (but not CRD nor FRD) all exhibit significant effects on the dependent variable. FD (positive coefficient) has positive relationship and TOR, RNC, TRD having negative coefficients with climate change. The results indicate some variables have significant influence on the dependent variable at a later stage, and that there is an equilibrium relationship among them given enough time as well.

Table 7 shows the results of Fourier cointegration results which suggest that the data may be related by a long-term equilibrium relationship. The model includes cyclic patterns as evidenced by the sine and cosine terms. Though 1 retards residual suggests some degree of short-term dynamic, the main components in driving

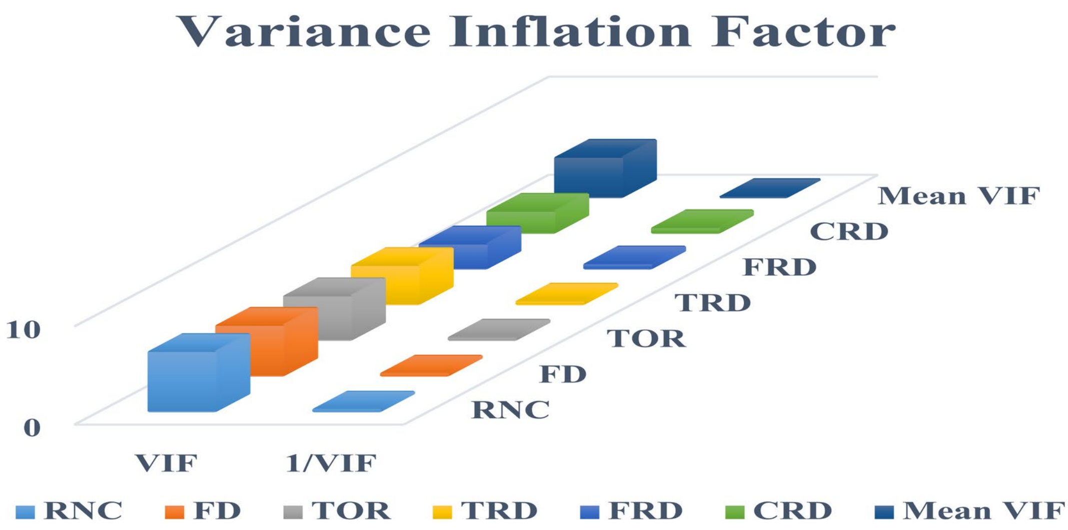

Fig. 4. VIF values.

	AD-Fuller		GKPSS		
Factors	Level	Difference	Level	Difference	
CC	− 0.643	− 5.862***	0.171*	0.179***	
TOR	1.732	− 4.633***	0.012	0.251***	
ET	1.945	− 4.638***	0.229**	0.189***	
CRD	0.842	− 3.667**	0.183**	0.173***	
FD	0.342	− 3.799***	0.139	0.177***	
TO	0.592	− 4.938***	0.212**	0.189***	
FDT	0.472	− 4.215**	0.070	0.189***	
LSLM					
Factors	Minimum test statistic	Break point	1% level	5% level	10% level
CO	− 3.836	2015	− 4.073	− 3.563	− 3.296
TOR	− 5.396	2016	− 7.1960	− 6.3120	− 5.8930
ET	− 6.512	2020	− 7.004	− 6.1850	− 5.8280
CRD	− 6.636	2017	− 6.6910	− 6.1520	− 5.7980
FD	− 7.452	2018	− 6.7500	− 6.1080	− 5.7790
TO	− 6.735	2019	− 6.9780	− 6.2880	− 5.9980
FDT	− 6.863	2020	− 6.9780	− 6.2880	− 5.9980

Table 3. ADF, GKPSS and LSLM unit root tests. ***, **, and * denote 1%, 5%, and 10% significance levels, respectively.

Variable	t stat	Bootstrap value	Prob.
CO	− 3.1802**	− 2.439	0.0100
TOR	− 3.6936**	− 2.0761	0.0560
RNC	− 3.7071**	− 3.581	0.0320
CRD	− 3.5911**	− 2.036	0.0120
FD	− 4.5914**	− 3.137	0.0480
TRD	− 4.3371**	− 3.254	0.0440
FRD	− 4.9342**	− 3.9451	0.0491

Table 4. Bootstrap unit root. ***, **, and * denote 1%, 5%, and 10% significance levels, respectively.

Factors	K	F(k)	Prob > F
CC	1	7.02***	0.0146
TOR	1	18.39***	0.0003
RNC	1	9.564***	0.012
CRD	1	6.5434**	0.0434
FD	1	8.42***	0.0078
TRD	1	3.08*	0.0945
FRD	1	3.59*	0.0703

Table 5. Fourier ADF. ***, ** and * dotes the 1%, 5% and 10% respectively.

Augmented Engle-Granger test for cointegration					*N* (1st step) = 31	
Number of lags = 2					N (test) = 28	
Test statistics	1% critical values		5% critical values		10% critical values	
Z(t) − 7.523	− 6.569		− 5661		− 5.226	
Factors	Coeffi.	Sd. err	t	P > t	[95% conf. interval]	
TOR	− 0.369	0.168	− 2.2	0.038	− 0.715	− 0.023
RNC	− 4.299	0.298	− 14.42	0.000	− 4.914	− 3.683
CRD	0.053	0.05	1.05	0.306	− 0.051	0.156
FD	6.398	0.972	6.58	0.000	4.392	8.403
TRD	− 0.984	0.413	− 2.38	0.026	− 1.836	− 0.131
FRD	− 0.25	0.171	− 1.46	0.157	− 0.604	0.103
_cons	23.185	3.123	7.42	0.000	16.739	29.631
Engle-Granger test regression						
L1	− 1.192	0.264	− 4.52	0.000	− 1.735	− 0.65
LD	0.641	0.211	3.04	0.006	0.206	1.076
L2D	0.371	0.201	1.84	0.077	− 0.043	0.784

Table 6. Augmented Engle-Granger cointegration test.

Source	SS	df	MS	
Model	0.569	3	0.0189	
Residual	2.917	22	0.1325	
	Coefficient	**St. err.**	**t**	***P*>|t|**
Resid L1	0.1981	0.1015	1.956	0.078
sin-term	0.869	0.3105	2.801	0.010
cos-term	0.9357	0.4586	2.040	0.069

Table 7. Fourier cointegration.

cointegration relationship are quite obviously to do with cyclical parts. Since the variables move in tandem over time reflecting repeated patterns back and forth, these results indicate one state is a common cause of another.

The Fourier ARDL model shows that (D. co) is both in long run and short run with all the incorporated independent variables. Co shows have a strong negative effect on D.co in the long run, while TOR proves to be significant. Both RNC and CRD similarly had a negative impact, with the latter showing somewhat more decline in D.co. FD has a positive but marginally insignificant effect, indicating some kind of hint at its return if the relationship is true with appropriate strength. Compared with the results, TRD has a positive and significant impact on D.co; contrastingly FRD had a significantly negative effect. There are moderately strong relationships in the short run, with TOR showing a truly negative effect but other variables like RNC, CRD, FD, and TRD having no significant impacts on each other's. FRD demonstrates a slightly positive short-term effect. The Fourier terms indicate potentially cyclic patterns, where the cosine term is statistically significant in each case and remains such with Φ sill. These variations can be time-dependent or by a period of evolution which have an impact on carbon that will change D.co over different scales for similar events (see Table 8).

The Frequency Domain Causality can be used to identify which factors may cause climate change in different frequency bands. The tourism (+), renewable energy (-) as well as the climate-related disasters (+) and financial development variables have negative signs (+), while trade liberalization variable is positive (+) in respect to

D.co	Coefficient	Std. err.	t	*P*>|t|
Co	− 0.8709	0.2169	− 4.01	0.001
LR				
TOR	1.8501	0.6042	3.06	0.007
RNC	− 0.3031	0.09765	− 3.1	0.005
CRD	0.3892	0.143	− 2.68	0.014
FD	2.692	1.4849	1.81	0.084
TRD	0.0568	0.0267	2.12	0.043
FRD	− 0.875	0.4496	− 1.95	0.006
SR				
TOR	− 1.7392	0.5627	− 3.09	0.006
RNC	− 0.2371	0.2259	− 1.05	0.308
CRD	0.3677	0.295	1.25	0.226
FD	0.1669	0.25712	0.65	0.523
TRD	− 0.1532	1.015	− 0.15	0.881
FRD	0.3547	0.1777	2	0.066
sin_term	0.257	0.147	1.75	0.098
cos_term	0.5949	0.2217	2.68	0.014

Table 8. Fourier ARDL.

	$\lambda_1 = 0.05$	$\lambda_2 = 1.5$	$\lambda_3 = 2.5$
Tourism → climate change	5.669	5.184	5.257
	0.0483**	0.038**	0.0391**
Renewable energy → climate change	6.639***	6.686**	5.446**
	0.0028	0.0435	0.0595
Climate related disaster → climate change	6.675***	7.113***	7.792***
	0.007	0.0015	0.0073
Financial development → climate change	7.592***	8.407***	8.428***
	0.003	0.001	0.001
Trade liberalization → climate change	9.713***	8.412***	7.225**
	0.0075	0.002	0.041
Foreign direct investment → climate change	7.3539	6.013**	8.516***
	0.003	0.042	0.006

Table 9. Frequency domain causality.

climate change. Renewable energy also has pervasive effect but modest, partly offset by climate-related disasters on inter-regional transactions. The impact of financial development, trade liberalization and foreign direct investment on climate change remain pronounced at a wide range of frequency bands. These findings illustrate better the complex drivers of climate change and argue for assessing time horizons as additional relevant variables (see Table 9).

This study provides strong evidence on climate change determinants through Fourier ARDL and Frequency Domain Causality analysis. Results show that the Fourier ARDL model identifies long-run relationships and cyclical effects between climate change and variables like tourism, renewable energy, and financial development. The Frequency Domain Causality analysis supports these findings over different time horizons, endorsing the robustness of effects in both short-term and long-run. This analysis showcases that climate change drivers are important across different frequencies, reinforcing their roles as leading factors of climate evolution.

Discussion

Climate change and tourism in China are interconnected. Chinese tourism demand is negatively affected by climate conditions, as established in studies[61]. The tourism industry contributes to energy consumption and carbon emissions, accounting for 0.51% of China's total energy consumption and 0.86% to14% of carbon emissions[62]. Climate change impacts tourism resources, market structure, tourist patterns, and consumer behavior[63], bringing economic benefits to specific locations. Chinese tourists' attitudes on climate change significantly predict their mitigation behaviors for energy saving and carbon reduction during travel[64]. To promote sustainable tourism development, adaptive measures are necessary to address climate change impacts. These results show complex interconnections between tourism and climate change in China, indicating new research areas to efficiently solve this problem. Findings reveal that a 1% increase in Chinese tourism increases climate change by 1.85%, as increased tourism activities escalate transportation, emitting significant carbon levels. The work of[65–67] and[68] are in the favor of the study.

Recent studies such as[69,70] also have examined whether China's investment in renewable energy does lead to climate change mitigation or not. Hu[71] suggested that renewable energy generation and utilization are inversely correlated with pollution created from greenhouse gas emissions In particular, the latest work by[72] finds that renewable energy technology innovation helps significantly mitigate climate risk - especially in provinces with a higher level of government fiscal expenditure and upper quantiles regions experiencing more severe exposure to elevated physical risks due to global warming. According to the[73,74], enhancing renewable energy development levels would lead to a decrease in carbon emission of 0.084–0.149%, per 1% generation increase fossil-fuel share. Unfortunately, the inhibitory effect is reduced by electricity capture and less comprehensive change in energy consumption structure. Also, renewable energy development has a greater effect on reducing carbon intensity in regions with low (or high) than intermediate levels of CI[75,76]. The empirical investigation denoted that a 1% increase in energy transition will decelerate climate change by 0.303%. Simply, it is indicating that in Chian upsurges the installation of renewable energy will improve the environmental quality. The work of[24,38] and[74] are in the line of findings.

Worldwide, the number of climate related disasters is growing and may be linked to anthropogenic climate change[77]. While disaster impact is driven by factors like population growth and vulnerability, climate change may enhance these events[78]. Studies have identified heat waves and droughts as disasters with countrywide climate anomalies, showing significant impacts on agriculture worldwide and increasing the likelihood of crop failures due to higher mean temperatures[79]. Climate-related disasters inhibit economic growth, and while a positive relation is hypothesized between natural disasters and armed civil conflict, research suggests the former does not directly entail later risk of one, even accounting for economic impacts[80]. As climate change is expected to increase extreme climatic events' severity and frequency, understanding their societal impact remains pertinent for effective mitigation. The investigation declares that a 1% increase in climate related disaster will increase climate changes by 0.389%.This study results are consistent with the results of[81–83] and[84].

Financial development can help in reducing the negative effects of climate change while in the long term, it will also impact positively. Economic growth can directly cause the carbon emission and energy consumption to increase[85,86]. Nevertheless, it can lead to reduction of emissions indirectly through fostering technological innovation and energy efficiency[85]. Factors like population, economic growth and trade openness are the policy variables which determine the association between financial development and climate change[86]. While financial development can lead to income redistribution and higher living standards[87], which in turn puts pressure on the environment. Monetary improvement might oppositely affect these individuals; albeit the advantages may initially be concentrated among just a couple of until later spreading to most others[88]. These results underscore the importance of policies that strike a balance between economic development and environmental conservation while promoting green technologies[89]. The results indicates that a 1% increase in the financial development will increase the climate change by 2.692%, Because the emerging economies are focusing to expand their industrial sector to bridge supply demand gap and for sustainability in the long term. The work of[90,91] and[92] are in the favor of the study.

Conclusion and policy implications

Climate change has been a global crisis described by permanent changes in the temperature and weather of our world. This is largely due to heightened levels of greenhouse gases that are emitted by burning fossil fuel, climate related disasters and development. The Fourier ARDL and frequency domain causality indicated that the predictors such as tourism, renewable energy, climate related disasters, financial development, trade liberalization and foreign direct investment are significantly participating remarkably in climate change in the perspective of China. The finding exposes that tourism significantly but negatively integrated with climate change, as tourism increases the chances of climate change upsurges in China. Renewable energy exposes that an escalation in adoption and installation of renewable energy and energy transition will lowers the threat of climate change and emit zero carbon. While the climate related disasters, on contrary, will promotes the climate change, because natural disasters significantly impact the climate change. However, financial development has both positive and negative affiliation with climate change, because if investment is made in clean energy projects or green projects will promotes environmental quality, but if invested in production or industry sector will escalate the climate change.

Policy implications

There are some ways to implement policies which could reduce the negative impact of tourism toward climate change. Other measures proposed are long term sustainable tourism campaign, investment in green transportations and carbon offsets programs for tourists. Other important factors/distinctions such as promoting renewable energy in tourism, raising the environmental awareness of tourists and their effects on host communities/destinations or enforcing that new ones are developed sustainably. Combined, these initiatives will mitigate the carbon emissions associated with tourism and further contribute to China's work against climate change.

China should step up its investments in renewables and must do so especially where there are greater risks associated with the changing climate. To advance the development of renewable energy technologies, subsidies should made available by government and are matched on a dollar-for dollar basis. Building up the energy infrastructure to more effectively incorporate renewable sources, adapting regional energy policies for specific challenges and promoting public-private partnerships is also critical. Increased public awareness of renewable energy advantages will push for more extensive adoption thus lessening carbon emissions and enhancing environmental standards.

The key policies must be enforced so that financial development in China is kept at such a level as it supports economic growth and environmental sustainability. To promote green finance initiatives, such as investment in greener technologies and projects; integrate environmental standards into financial regulation; support technological innovation so that cleaner methods of production become more mainstream. In addition, we should stimulate public-private partnerships that help us to fund 'the big levers' in green infrastructure philanthropy, finance policies like tax incentives for greener practices. Such an alignment of climate action with the financial growth requires improving financial literacy around environmental impact as well as reconciliation economic and environmental objectives. In doing so, China can harness financial development to underpin sustainable economic growth with a dual approach that tackles climate change and builds a more resilient economy over the long term.

Limitations and future study directions

Although the findings of this study contribute to advancement in tourism, renewable energy, climate-related disaster financial development, and trade liberalization aspect for addressing another challenge on Climate change issue within China; however there are some limitations. It is specific to Developing Countries and Emerging Economies, therefore its application may be restricted. The use of aggregated data can obscure sectoral impacts, and Fourier ARDL/Frequency Domain Causality may fail to encompass the intricate interrelations among variables. Moreover, the endogeneity problem between financial development and climate change is unexplored or partially accounted for; international policy initiatives such as the Paris Agreement are limited. The time frame may also not take in to consider long-term trends or new renewable energy breakthroughs. Considering these limitations, future research should complement the coverage and quality (i.e., disaggregation) of data used herein with more detailed analyses using DGSE models or theoretical setups that parameterize economy-climate dynamics explicitly to better capture the synergistic impacts reported here.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Xinyu CAI: Conceptualization, Data curation, Methodology, Writing - original draft, Visualization, Ali ALJOFAN: Supervision, editing, Writing - review & editing, and software.

Declarations

Competing interests

The authors declare no competing interests.

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