Journal of Cleaner Production 498 (2025) 144987

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

On China's sustainable future: How do eco-technological innovations and financial development moderate the tourism-environmental pollution nexus?

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ARTICLE INFO

Handling Editor: Giovanni Baiocchi

Keywords:
Technological innovations
Tourism
Financial development
Environmental pollution
China

ABSTRACT

The global anthropogenic activities among nations are largely behind the growing environmental concerns of our modern time. The rise of China on the frontiers of all economic activities with rapidly booming industries including the tourism industry has raised valid concern about the country's future sustainability. Past studies have largely focused on CO_2 perhaps because of the long-lasting environmental damages from the atmospheric accumulation of this greenhouse gas (GHG) relative to other gases like methane (CH_4) and nitrous oxide emissions N_2O. However, there is a need to examine other greenhouse gases given that their immediate warming impacts could be much more pronounced over a relatively shorter period. As such, China's sustainability future was assessed via direct & indirect environmental aspects of the booming tourism industry while exploring the moderating roles of eco-technological innovations and financial development. The robust empirical simulation capitalizes on the Dynamic Autoregressive Distributed Lag (DARDL) framework. We obtained the long-run evidence of the aggravating pollution impacts of tourism and financial development as revealed by the exacerbation of methane (CH_4) and nitrous oxide (N_2O) emissions. Additionally, isolating eco-technological innovations also revealed a short-run detrimental environmental impact. However, the environmental damages from both tourism expansion and financialization were significantly curtailed when interacting these factors with the overall eco-technological progress. The outcomes highlight to policymakers as well as authorities, the necessity of specifically prioritizing eco-related technologies in any policy framework for China's sustainable future.

1. Introduction

Greenhouse gas (GHG) emissions stemming from human activities contribute to climate change and global warming (Umar and Safi, 2023). The environmental externalities of emissions necessitated the establishment of the 2015 Paris agreement to come out with comprehensive response strategies to avert this menace (Prempeh, 2024). According to the pact, global warming should be limited to 2 °C over pre-industrial levels, with additional steps to restrict it to 1.5 °C. The rise in emissions not only demands immediate action but also casts doubt about the feasibility of achieving the net-zero emission goal. In China, this trend is even more pronounced, with a staggering 584.159% increase in CO_2 emissions from 1990 to 2020 (Textor, 2023), highlighting the nation's critical environmental challenges and placing its anthropogenic

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https://doi.org/10.1016/j.jclepro.2025.144987
Received 12 August 2024; Received in revised form 13 January 2025; Accepted 7 February 2025
Available online 7 February 2025
0959-6526/

activities at the center of discussions on sustainable futures (Shen et al., 2024).

While CO_2 emissions dominate discussions of greenhouse gases, we believe that methane (CH_4) and nitrous oxide (N_2O) warrant greater attention due to their distinct characteristics and implications. Methane, for example, has a global warming potential approximately 28–34 times higher than CO_2 over a 100-year period, despite its shorter atmospheric lifetime of around 12 years (Balcombe et al., 2018). Similarly, nitrous oxide, though less abundant, plays a dual role as a potent greenhouse gas and a contributor to ozone layer depletion, thereby compounding environmental risks (Ussiri and Lal, 2012). Both gases are deeply intertwined with sectors pivotal to China's economy, such as agriculture, energy, and waste management for CH_4, and nitrogen-based fertilizer use in agriculture for N_2O (Kumar et al., 2024). Thus, tackling CH_4 and N_2O emissions is critical, not only for mitigating climate change but also for aligning with sustainable development goals (SDGs) and supporting long-term economic resilience. Their inclusion in China's sustainability discourse highlights the complex interplay between ecological health and socioeconomic progress, setting the stage for broader considerations of systemic impacts on the environment.

Among the various factors influencing environmental quality, tourism has emerged as a significant driver due to its pronounced impact on ecological dynamics (Avci et al. (2024)). The notion is that tourism, as an agent of economic growth and resource use, has an impact on ecological dynamics. This phenomenon is vividly illustrated by the global tourism rise from 1.08 billion foreign arrivals in 1995 to 2.40 billion in 2019 (World Bank Group, 2021). As reported by the World Travel and Tourism Council (2020), domestic and foreign tourism contributed to 10.3% of the global gross domestic product (GDP), and 330 million direct and indirect employment opportunities were created by domestic and foreign tourism. As the fact reveals, China's tourism industry, a key agent of its economic development, has witnessed a remarkable increase (Irfan et al., 2023). According to a report by the National Bureau of Statistics, China generated 6.64 trillion Yuan from 65.72 million foreign investors in 2019. Also, the tourism industry contributed 10.94 trillion Yuan, or 11.05 percent to the GDP of the nation. Besides, 28.26 million people representing 10.26 percent of the nation's working population directly worked in the tourism sector while 79.91 million individuals had direct or indirect involvement in the sector. With respect to total tourism revenue, tourism shopping accounted for 1311600 million Yuan in 2020, making it the highest sector (National Bureau of Statistics, 2021), followed by traveling (1060000 million Yuan), tourism-related catering (553600 million Yuan), sightseeing (209100 million Yuan), and entertainment (172900 million Yuan) in that order (National Bureau of Statistics, 2021). These benefits among others, have made tourism one of China's most important economic drivers.

While the rise in tourism propels economic growth and innovation, it concurrently accelerates environmental issues due to its connection with the utilization of polluting energies. Besides, tourism can put undue pressure on the ecosystem, leading to soil erosion, habitat damage, waste buildup, and overutilization of natural resources, resulting in environmental damage (Yu, 2023). In contrast to these challenges, tourism also holds the potential for positive environmental impact. It follows that transitioning from heavy pollution to more sustainable practices in the tourism industry could help improve environmental sustainability. Thus, higher reliance on eco-technologies, green energy, and energy efficiency in the tourism sector enhances environmental quality by reducing pollution in society.

Indeed, theories amplify the tourism effect in the sustainability discourse; however, the dynamics of its influence are multilayered, extending beyond direct impact to include other factors. Key among these factors relates to financial development and eco-technologies. According to the United Nations Sustainable Development Goals (SDGs), development in the financial sector has been a major influencing factor in environmental sustainability, albeit with a dual role. Financial sector development can stimulate environmental degradation by supporting energy-dependent industrial activities (Shobande and Ogbeifun, 2022) but also has the potential to mitigate pollution through investments in clean energies (SDG 7) and innovative technologies (SDG 9) (Tamazian et al., 2009). Moreover, robust financial systems promote energy efficiency (SDG 7), and investments in research and development initiatives (SDG 9) that are friendly to the environment.

Eco-technologies have also emerged as drivers of economic activity and potential solutions to environmental challenges (Dauda et al., 2021). They are often associated with decreased pollution as they drive clean energy initiatives and emission mitigation efforts (Yu et al., 2022). Due to the gains associated with green technologies, scholars have advocated for more resources to be channeled into their investments to help promote environmental quality in economies.

Despite the critical interplay between tourism, financial development, eco-technologies, and environmental quality, existing literature reveals a series of gaps that need to be addressed. In the first place, extant studies predominantly focus on the direct effects of tourism, financial development, and eco-technologies on environmental quality, overlooking the indirect effects of financial development and eco-technologies on environmental sustainability through tourism. Moreover, nitrous oxide (N_2O) and methane (CH_4), which are deeply connected to economic sectors such as agriculture, energy, and waste management, have not received as much attention as CO_2 despite their critical environmental and socioeconomic impacts. These issues leave a crucial aspect of the relationship underexamined. In terms of methodology, existing studies present a compounded problem, limiting the depth of insight into the counterfactual influences of tourism, financial development, and eco-technologies on environmental quality. This limitation is further deepened by a prevalent oversight in examining the causal relationships between these variables, which is crucial for formulating effective policy solutions. Furthermore, a significant number of these studies fail to adequately address statistical complexities such as structural breaks, serial correlation, and heteroscedasticity among others, leading to potentially biased regression estimates and thus unreliable conclusions.

Considering the identified knowledge gaps and the implied research problems, this study primarily examines the dynamic relationship between tourism, financial development, eco-technologies, and environmental pollution in China. In specifics, it investigates the direct connectedness, while also estimating the interactive effects of financial development and eco-technologies in the link between tourism and environmental pollution. To this end, the present study employs the Dynamic Autoregressive Distributed Lag (DARDL) technique to offer a deeper understanding of these relationships and enhance policy formulation for sustainable ecological management.

This study uniquely contributes to existing literature in five main folds. Firstly, unlike prior explorations that used CO_2 emissions to measure environmental quality in China, this study employs nitrous oxide emissions (N_2O) as the measure of the nation's environmental quality. Secondly, this study bridges a notable gap in the existing literature by exploring the indirect effects of financial development and eco-technologies on environmental pollution. This is achieved through a detailed examination of how financial development and eco-technologies influence environmental pollution through tourism. Such an inquiry provides a more nuanced understanding of the interplay between the variables.

Thirdly, this study stands out by employing the DARDL technique for parameter estimation. Specifically, dynamic ARDL in relation to the standard ARDL highlights the model's ability to capture dynamic adjustment processes within the data employed. This emphasizes the model's capability to not only estimate the long-run equilibrium relationships but also the short-term dynamics and the speed of adjustment toward the equilibrium. More importantly, the dynamic aspect of the ARDL is crucial for understanding how shocks to the system propagate over time and how quickly variables return to equilibrium after disturbance. Comparatively, the dynamic nature of the ARDL allows for better modeling of complex interactions among variables, making it more suitable for multifaceted economic, environmental, and financial analysis. This choice marks a departure from conventional approaches in existing studies on China, providing a deeper and more comprehensive understanding of the counterfactual influences of regressors on the response variable.

Moreover, rather than employing other times series elasticity estimation approaches to check the robustness of the results obtained as observed in numerous research in the same field of study, this study performs a dual-phase sensitivity analyses to ensure that the results have policy-relevant effects. That is, the main response variable nitrous oxide emissions (N_2O) is replaced with methane emissions (CH_4) to determine the consistency of the results across models. This approach makes our study novel and distinct from prior environmental studies on China. Hitherto, the second phase replaces population with urbanization as a control variable to further examine how the explanatory variables will predict environmental pollution in the country. The adoption of population and urbanization as control variables in the models is strategic, aiming to minimize the consequences of variable specification bias thereby ensuring the accuracy and reliability of the regression coefficients.

Finally, the study goes beyond mere exploration of the elasticities of the predictors. It rigorously investigates the causal relationships between the variables via causality analysis. This dual approach is crucial for developing powerful policy options, aimed at advancing China's agenda towards environmental sustainability. Each of the contributions collectively signifies a considerable leap forward in the quest to understand and address the intricate environmental challenges facing China today.

The significance of this study cannot be understated. To begin with, the comprehensive insights provided by this study can aid policymakers in pinpointing particular areas that need proper attention. Equipped with this knowledge, they can allocate resources more effectively, prioritize challenges, and formulate policies that can propel China toward a greener future. Understanding the consequences of environmental pollution may encourage individuals and businesses to engage in eco-friendly activities and take advantage of opportunities in the green field. Moreover, businesses in the tourism industry may experience an increase in the demand for their services when they shift towards green practices. Embracing sustainable practices could be a competitive selling tool that could draw in partners and customers who care about the environment. Besides, the study offers knowledge that could help individuals to make eco-friendly choices. It also serves as the foundation for future investigations into the nexus between tourism, financial development, eco-technologies, and environmental pollution in different geographical settings. Lastly, our work contributes to scholarly conversation and provides concrete methods and results that academics in the future might build upon.

The paper is structured to include a detailed introduction, literature review, methodology, and results and discussion sections. It ends with the presentation of conclusions and policy implications alongside limitations and future research directions. This structure draws together insights for policy development in the realm of China's environmental sustainability.

2. Literature review

This section presents a comprehensive review of related studies, systematically profiled into four main strands. Each strand carefully details the relationship between environmental quality and the key variables of interest: tourism, financial development, and eco-technologies. The review highlights how each of these variables uniquely contributes to environmental quality, providing a deeper understanding of their individual and collective impacts.

2.1. Nexus between tourism and environmental quality

The nexus between tourism and environmental quality has been a subject of extensive research, yielding a spectrum of findings that often appear contradictory. For instance, Raihan (2024) focused on Brazil and reported that tourist arrivals harmed the nation's environmental quality. The study advocated for the promotion of sustainable tourism practices to help improve environmental quality in the country, a sentiment echoed in similar studies by Adebayo et al. (2023), Irfan et al. (2023), and Nwaeze et al. (2023). Wang et al. (2024) explored this relationship in the One Belt One Road economies, finding that tourism adversely affected the nations' ecological quality. This finding supports Voit and Rhoden (2024) study on Europe which confirmed tourism-related expenditure and tourism arrivals as damaging to environmental quality. Contrastingly, Avci et al. (2024) affirmed tourism as eco-friendly in the 15 most visited countries aligning Wei and Lihua (2023) investigation on the Association of Southeast Asian Nations (ASEAN) economies. According to Zhao et al. (2024), tourism development boosted carbon emission efficiency in 31 Chinese tourist cities. In Sun et al.'s (2022) systematic review of 81 tourism-published studies from 2013 to 2021, the nexus between tourism and emissions was contradictory across income levels, regions, and the sector's economic importance. Based on the conflicting findings from the tourism-environmental quality connection, we hypothesize that.

H1. Tourism has a positive or negative effect on environmental quality.

2.2. Nexus between financial development and environmental quality

Numerous studies across diverse geographical environments have yielded mixed findings regarding the relationship between financial development and environmental quality. Dada et al. (2024) explored this relationship by examining 28 African economies, concluding that financial development harmed environmental quality in the nations. Besides, financial development positively moderated the association between energy poverty and environmental pollution in the economies. While the study offers valuable insights, its applicability is limited to the selected economies and may not be generalizable across Africa or globally. In New Zealand, Solaymani and Montes (2024) found that financial development had a beneficial effect on the country's environmental quality. This finding contrasts the study of Saboori et al. (2024) for Oman and Fakher and Ahmed (2023) for 25 economies. Li et al. (2024) researched China's Belt and Road Initiative (BRI), revealing that development in the financial sector has significantly promoted the SDG ambitions of the related economies. Prempeh (2024) explored this relationship in 10 Economic Community of West African States (ECOWAS) from 1990 to 2019. From the panel quantile regression estimates, financial development harmed environmental quality in high-emitter countries, but neutrally explained environmental quality in medium-emitter economies. The Driscoll-Kraay regression approach however confirmed that an increase in financial development was associated with lower levels of environmental pollution. Based on the conflicting outcomes of the financial development-environmental quality connection, we hypothesized that.

H2. Financial development has a positive or negative effect on environmental quality.

2.3. Nexus between eco-technologies and environmental quality

Eco-technologies, often hailed as pivotal solutions for environmental sustainability, have garnered mixed empirical evidence regarding their actual impact on environmental quality. While studies suggest that these technologies improve environmental quality by reducing carbon emissions and enhancing resource efficiency, others argue that their implementation can inadvertently exacerbate environmental degradation through mechanisms such as the rebound effect and resource-intensive production (Gillingham et al., 2013). Based on this, the relationship between eco-technologies and environmental quality has been extensively studies, yet the findings remain inconclusive. In terms of studies that have highlighted the benefits of eco-technologies in mitigating environmental challenges, Ali et al. (2024) and He et al. (2024). Highlight the potential of eco-technology to significantly improve environmental quality, demonstrating reductions in ecological footprints and enhancements in energy efficiency. Similarly, Aydin et al. (2024) reported that eco-technologies promoted environmental quality in Austria by raising the nation's load capacity factor, while Traoré and Asongu (2024) found that reductions in carbon emissions amplified green technology adoption in Sub-Saharan Africa. These findings underscore the role of eco-technology in advancing sustainable agendas, particularly when coupled with adequate financial and regulatory support.

Conversely, other researches warn of the unintended negative impacts of eco-technologies. For instance, Liu et al. (2022), Adebayo et al. (2022), and Rahman and Alam (2022) argue that innovative technologies can worsen environmental quality by promoting economic activities and energy consumption, leading to higher missions. Furthermore, the extraction of rare earth metals for green technologies, such as wind turbines and electric vehicles, can have adverse environmental consequences, including habitat destruction and pollution. The duality in findings underscores the complex relationship between eco-technologies and environmental quality. While eco-technology can significantly improve environmental outcomes, their impacts are not universally positive. Contextual factors, such as the scale of implementation, maturity of technology, and regional socio-economic conditions, often mediate these effects. This complexity forms the basis of Hypothesis 3. Theoretical frameworks such as the socio-technological transition theory support this dual perspective. Specifically, the socio-technological transition theory highlights the systematic challenges and rebound effects of adopting innovative technologies, offering insights into why eco-technologies might not always deliver positive outcomes.

H3. Eco-technologies influence environmental quality, with their impact being either positive or negative.

2.4. Interactive effects

Moreover, financial development and eco-technologies may indirectly influence environmental quality through tourism, as the adoption of green technologies in the tourism industry could lessen the negative environmental externalities of tourism. Also, a well-developed financial sector may help firms to obtain enough funds to promote eco-friendly practices in the tourism sector. However, most prior explorations on China only examined the direct effects of tourism, financial development, and eco-technologies on environmental quality without investigating how financial development and eco-technologies moderated the relationship between tourism and environmental quality in the nation. For instance, Zhuang (2023), Yang et al. (2023), and He et al. (2024) respectively examined the direct impacts of tourism, financial development, and eco-technologies on environmental quality in China, ignoring the indirect effects. However, since financial development and eco-technologies could significantly influence activities in the tourism sector, the interaction between the variables and tourism could substantially impact the nation's environmental quality. Hence, we explore the moderating role of financial development and eco-technologies in the link between tourism and environmental quality in China. In attaining this objective, we propose the following hypothesis for testing.

H4. Financial development and eco-technologies significantly moderate the relationship between tourism and EQ.

Relying on the developed hypotheses which are supported by literature, the following conceptual framework is proposed with references to the relationships among variables to be established (see Fig. 1).

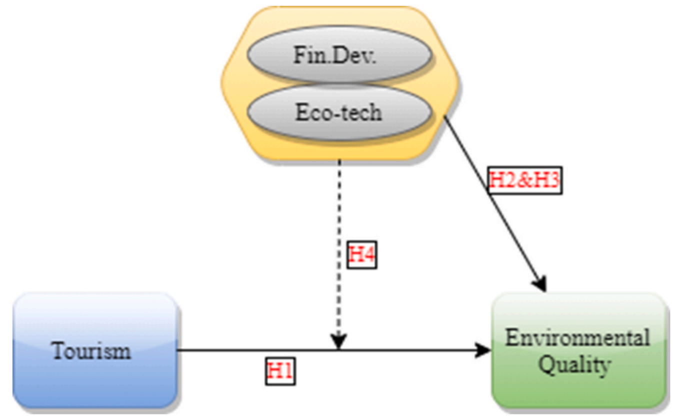

Fig. 1. Conceptual framework based on the interactions between tourism, financial development, eco-technology, and environmental quality.

2.5. Literature gaps

Literature on the nexus between tourism, financial development, eco-technologies, and environmental quality has been expansively explored with varying outcomes. The variations in findings might be due to the differences in geographical locations, econometric methods employed, time dimensions, and variable selection among others. While the studies offer valuable insights, their applicability is limited to the selected economies and may not be generalizable across all nations. Hence, studying the connection amidst the series in the context of China is deemed appropriate. Also, previous studies that attempted to investigate the tourism, financial development, eco-technologies, and environmental quality nexus in China primarily looked at the direct environmental impacts of tourism, financial development, and eco-technologies. Ignoring the indirect effects of financial development and eco-technologies on environmental quality through the channel of tourism has been a common ground among the relevant extant studies. As such, this study fills that void by examining the moderating effects of financial development and eco-technologies in the link between tourism and environmental quality.

3. Methodology

3.1. Data source and variables description

In this study, data for the period 1995 to 2020 is used for the analysis. Though the variables which include tourism, financial development, population, and eco-technologies contained data spanning for larger number of years, the study had to stick to the mention time span (1995–2020) due to the availability of the data pertaining to the main response variables nitrous oxide (N_2O) and its substitute methane emissions CH4. This aided in avoiding the use of unbalanced time series data (or data with numerous missing data for some variables). Based on this information, the period 1995–2020 is appropriate for the study because substantial data on the series can be obtained within this timeframe.

In this study, environmental pollution is the dependent variable proxied by N_2O. Though numerous related research in China use carbon dioxide emissions as the best gauge for environmental pollution, this extant study utilized nitrous oxide instead. Notably, N_2O compared to CO_2 is a significant pollutant with direct adverse effects on human health. High levels of N_2O can cause respiratory problems, exacerbate asthma, and decrease lung function. The health impact of N_2O is more immediate compared to CO_2. While CO_2 is primarily a concern for its role in long-term climate change, N_2O levels can quickly translate into acute health issues for the population, especially in urban areas with high traffic and industrial activities. This approach aligns with the study of Biu et al. (2024) for Vietnam but deviates from Shen et al. (2024) and Zhou and Zhang (2024) who measured environmental pollution in China by only carbon dioxide emissions (CO_2). To test the consistency of the results across models, CH4 is engaged as an alternative measure of environmental degradation. Besides, tourism proxied by the number of tourist arrivals, financial development proxied by domestic credit to the private sector as a percentage of GDP, and eco-technologies proxied by environmentally related technologies as a percentage of all technologies are the main explanatory variables while the annual percentage of population growth is used as a control variable to help minimize the consequences of model misspecification.

Tourism is used as a determinant of environmental degradation in line with the study of Wang et al. (2024) and Avci et al. (2024) while Dada et al. (2024) and Prempeh (2024) support our choice of financial development as a predictor of environmental pollution. Moreover, Ali et al. (2024) and He et al. (2024) corroborate our choice of eco-technology as a determinant of environmental pollution while population growth is engaged as a predictor of environmental deterioration in line with the study of Gershon et al. (2024). Apart from eco-technologies whose data is sourced from OECD (2024), the data corresponding to the other variables which include nitrous oxide, tourism, financial development, population growth, and methane emissions are also sourced from World Bank Development Indicators (WDI, 2024). SDG 13 and its allied counterparts like SDG 9, SDG 7, SDG 16, SDG 12, SDG 14, SDG 11, SDG 3, SDG 15, and SDG 8, among others, inform our choice of the studied variables. A summary of variables descriptions together with their respective sources of data are outlined in Table 1.

As outlined in Table 1, "Thousand metric tons of CO2 equivalent" is used as a proxy for nitrous oxide because it captures the broader climate change of N2O by converting it into a comparable metric with other greenhouse gasses. This approach highlights the N2O's significant contribution to global warming relative to its lower atmospheric concentration, emphasizing its importance in environmental assessment. Additionally, this metric aligns with the international reporting standards, making it easier to integrate into policy discussions. By focusing on CO2 equivalents, this study ensures a comprehensive and globally relevant representation of nitrous oxide's environmental impact within China's broader greenhouse gas profile.

Notably, domestic credit to the private sector (%GDP) is employed as a proxy for financial development because it directly reflects the extent to which financial institutions provide credit to the private sector, a key driver of investment, economic activity, and growth. This measure offers a clear indication of businesses and households, supporting productive economic activities. Other proxies, such as stock market capitalization or bank deposits, are excluded as they focus on specific financial markets or segments that may not be relevant in all contexts. Additionally, proxies like financial inclusion or bank concentration might not directly affect the broader role of financial intermediation, while measures like interest rate spreads can suffer from data inconsistencies. Thus, domestic credit to the private sector offers a more robust, consistent, and widely comparable measure for assessing financial development.

Table 1
Data description and measurement units.

Variable	Symbol	Measurement	Source
Nitrous oxide emissions	N_2O	Thousand metric tons of CO_2 equivalent	WDI (2024)
Tourism	TR	International tourism, number of arrivals	WDI (2024)
Financial development	FD	Domestic credit to private sector (% of GDP)	WDI (2024)
Eco-technologies	ECO	Development of environmental-related technologies (Percentage of all technologies)	OECD (2024)
Population growth	POP	Annual percentage	WDI (2024)
Methane emissions	CH_4	Kt of CO_2 equivalent	WDI (2024)

On the other hand, "international tourism, number of arrivals" is used as a proxy to measure tourism with the reason being that, it directly reflects the volume of international visitors to the country, which is a key indicator of tourism activity. Specifically, the number of arrivals captures the inflow of foreign tourists, which drives tourism-related income, employment, and economic growth. It serves as a reliable and easily accessible measure of tourism demand across countries. Other proxies of tourism which include tourism receipts or expenditure may offer insight into the economic impact of tourism, nonetheless, they can be influenced by factors like exchange rates or inflation, making them less consistent. Similarly, measures like tourism employment may not fully capture the broader tourism activity, particularly in regions with diverse tourism sectors. Therefore, the number of international arrivals provides a more straightforward and consistent measure across different contexts.

Moreover, using the "percentage of all technologies" as a proxy for eco-technologies in this study stems from the fact that, it provides a broad view of the adoption of environmentally sustainable technologies relative to the total technology landscape. This measure captures the share of eco-friendly innovations, helping to assess the country's progression in integrating environmental considerations into technological development. It offers a clear, quantifiable way to track the diffusion of eco-technologies within the broader tech sector. Comparably, proxies such as total investments in technologies are not utilized because they may not fully reflect the actual adoption or impact of these technologies. Investment figures can be influenced by external factors, like government subsidies, and total technological patents may overstate innovation without considering the practical aspects of green deployment. Thus, environmental-related technology as a "percentage of all technologies" is more comprehensive, providing a direct indication of eco-technologies' relative importance and penetration in China's technological eco-system.

Furthermore, methane (Kt of CO2 equivalent) is used as a proxy to measure methane emissions due to its standardized expression of CO2 equivalence, which facilitates cross-comparison and analysis of greenhouse gases' climate impacts. Methane is a significant greenhouse gas with a high global warming potential and expressing it in CO2 equivalence provides a clear measure of its contribution to climate change. The use of "Kt of CO2 equivalent" ensures a consistent and quantifiable approach aligned with global environmental reporting standards, making it suitable for analyzing China's methane emissions within the broader context of environmental sustainability goals.

Moreso, taking into account the variable population growth, the annual percentage is used as a measurement indicator because it reflects the year-on-year growth rate of the population, providing a clear and consistent indicator of demographic changes. This metric captures both natural population increases (birth rates) and net migration, making it comprehensive and easily comparable. For China, this proxy is particularly relevant given the rapid urbanization and shifts in demographic trends that can influence environmental dynamics. Precisely, proxies such as total population size or urban population, are not considered since they do not account for the growth rate over time. Using total population size would only reflect the absolute number of people without providing insights into the speed of population change. Similarly, focusing on urban population growth would miss rural demographic shifts, which are crucial for understanding the broader impacts of environmental factors like pollution and resource consumption. Therefore "annual percentage" offers the most suitable measure for capturing population growth dynamics in the context of this study.

3.2. Model design and theoretical underpinning

Against the backdrop of China's adherence to the Paris Agreement's emission reduction goals, this study is essential, integrating key theories to cohesively explain how the interplay of tourism, financial development, and eco-technologies shape environmental quality in China. This integration provides pivotal insights, guiding the development of sustainable environmental policies.

Theoretically, the tourism led-growth hypothesis posits that tourism promotes the growth of economies (Shahzad et al., 2017). However, economic growth is associated with high energy consumption, consequently harming environmental quality. According to Qiao and Gao (2017), tourism considerably contributes to climate change, because it encourages the utilization of energies from polluting sources. Besides, tourism is primarily reliant on the natural habitat (Robaina-Alves et al., 2013). As a result, excessive utilization of the natural environment could lead to its damage. In contrast, managing tourism effectively through the adoption of eco-technologies could reduce the rate of pollution it causes. Ecological quality is improved by the industry's use of clean energy and energy-efficient technologies. This suggests that sustainable tourism practices are essential to nations' pollution reduction goals.

Besides, theory suggests financial development has a multifaceted impact on the environment. This includes the technique effect, where financial sector development facilitates the transfer of green technologies, improving environmental quality by lowering emissions (Peng et al., 2022). The scale effect describes how financial development, through economic liberalization, enables industries to acquire large-scale machinery and other equipment, increasing energy consumption and pollution (Zhang et al., 2018). The composition effect posits that financial development aids the transition from agricultural to industrial economies, enhancing ecological safety through economies of scale and production expertise (Peng et al., 2020).

Finally, ecological modernization theory focuses on the mitigation of climate change (Kais and Islam, 2023). According to Baer (2012), a large portion of anthropogenic climate change is thought to be caused by technological advancements based on fossil fuels and expanding capitalist patterns of production and consumption. Because this theory is primarily focused on mitigation interventions (Glover, 2011), it eventually becomes the primary means of tackling climate change because it emphasizes environmentally friendly technological improvements (Spaargaren and Mol, 2010).

The above theoretical foundation serves as the basis for examining the nexus between tourism and environmental quality in China, accounting for the moderating roles of financial development and eco-technologies. Following the theories, we specify the following model for estimation:

$$ln\,N_2O_t = \psi_0 + \varpi_1 lnTR_t + \varpi_2 lnFD_t + \varpi_3 lnECO_t + \varpi_4 (lnFD^* lnTR)_t + \varpi_5 (lnECO^* lnTR)_t + \varpi_6 lnPOP_t + u_t \quad (1)$$

where N_2O is the output variable representing environmental pollution while tourism (TR), financial development (FD), and eco-technologies (ECO) are the main regressors. To curtail the consequences of omitted variable bias, population growth (POP) is introduced into the model as a control variable. Besides, $\varpi_1 \ldots \varpi_6$ are the parameters of the predictors, ψ is the constant term, i denotes the studied nation, t is the time frame, and μ is the stochastic error term. Log transformations are taken on both sides of the model to help minimize heteroscedasticity issues.

The coefficient of tourism could be positive $\left(\varpi_1 = \frac{\partial ln\,N_2O_t}{\partial lnTR_t} > 0\right)$ because most activities undertaken in the tourism industry are associated with the consumption of polluting energies that end up degrading the environment. However, if eco-friendly practices are embraced by firms and individuals in the tourism sector, the parameter of the variable could be negative $\left(\varpi_1 = \frac{\partial ln\,N_2O_t}{\partial lnTR_t} < 0\right)$.

Besides, the coefficient of financial development could be positive $\left(\varpi_2 = \frac{\partial ln\,N_2O_t}{\partial lnFD_t} > 0\right)$ because development in the financial sector makes it easy for entities to access low-cost funding facilities to acquire more equipment to expand their operations. This escalates the consumption of energy thereby worsening environmental quality due to more pollutant emissions. In contrast, the parameter of financial development could be negative $\left(\varpi_2 = \frac{\partial ln\,N_2O_t}{\partial lnFD_t} < 0\right)$ because a well-developed financial sector promotes investments in green energy generation, energy efficiency, green technological innovations, and research and development projects that are friendly to the environment.

Moreover, the sign of ϖ_3 could be negative $\left(\varpi_3 = \frac{\partial ln\,N_2O_t}{\partial lnECO_t} < 0\right)$ because eco-technologies promote energy efficiency, minimize the consumption of polluting energies, and optimize the utilization of green energies thereby improving environmental quality. In contrast, the sign of ϖ_3 could be positive $\left(\varpi_3 = \frac{\partial ln\,N_2O_t}{\partial lnECO_t} > 0\right)$ because eco-technologies boost economic growth escalating the consumption of polluting energies, consequently worsening environmental safety.

Furthermore, the parameter of the population could be positive $\left(\varpi_6 = \frac{\partial ln\,N_2O_t}{\partial lnPOP_t} > 0\right)$ because the rise in population leads to the rise in energy-consuming activities escalating the rate of pollution in the environment. Contrastingly, the consumption of green energy and other eco-friendly products may rise as the rate of population increases thereby improving environmental quality $\left(\varpi_6 = \frac{\partial ln\,N_2O_t}{\partial lnPOP_t} < 0\right)$.

Besides, growth in the financial sector can help tourism-related businesses obtain adequate funding to expand their undertakings. The adoption of eco-technologies can also help to advance the operations of firms in the tourism industry. If the above assertions hold, then the interactions between tourism, financial development, and eco-technologies could have an influence on environmental quality. To test whether this assumption holds for China, the interactive terms between financial development and tourism (FD*TR), and between eco-technologies and tourism (ECO*TR) are incorporated into the model. The marginal effects of the interactive terms could better explain how financial development and eco-technologies influence the tourism-environmental pollution linkage in the nation. Differentiating Eq. (1) with respect to tourism, the marginal effects could be computed as;

$$\frac{\partial ln\,N_2O_t}{\partial lnTR_t} = \varpi_1 + \varpi_4 lnFD_t \quad (2a)$$

$$\frac{\partial ln\,N_2O_t}{\partial lnTR_t} = \varpi_1 + \varpi_5 lnECO_t \quad (2b)$$

The signs and significance of $\varpi_1, \varpi_4,$ and ϖ_5 will determine the moderating effects of financial development and eco-technologies in the connection between tourism and environmental pollution in China. Notably, in assessing the moderating effect of financial development and eco-technology on tourism-environment nexus, the respective parameter estimates ($\varpi_1, \varpi_4,$ and ϖ_5) can be positive or negative or a mixture of bother in different instances. Specifically, if tourism enhances environmental degradation as a result of the reinforced moderating effect of financial development and eco-technology then ϖ_1 together to with ϖ_4, ϖ_5 are expected to be greater than zero ($\varpi_1 > 0$ and $\varpi_4, \varpi_5 > 0$). On the other hand, if tourism enhances the quality of the environment as a result of reinforced impact from financial development and eco-technology then ϖ_1 , ϖ_4, ϖ_5 are all hypothesized to be less than 0 ($\varpi_1 < 0$ and $\varpi_4, \varpi_5 < 0$). Nonetheless, if tourism increases environmental deterioration, and the impact is mitigated by financial development and eco-technologies then $\varpi_1 > 0$ and $\varpi_4, \varpi_5 < 0$. However, if tourism promotes environmental quality, and the effect is increased by financial development and eco-technologies then $\varpi_1 < 0$ and ϖ_4, $\varpi_5 > 0$.

3.3. Econometric procedure

3.3.1. Unit root tests

The DARDL technique can only be applied after the series has satisfied all the requirements pertaining to their integration order. Specifically, the response variable must be integrated of order I(1), but the predictors could possess an I(1) or I(0) integration order but must not exceed order I(1). Based on these requirements, the study engages the augmented Dickey-Fuller (ADF) and the Phillips and Perron (1988) (hereafter PP) unit root tests to examine the variables' integration order. The ADF test is widely recognized as a robust method for testing the stationarity of time series data. Unlike the Dickey-Fuller test, the ADF test accounts for higher-order serial correlation in the data by incorporating lagged differences in the response variable. This adjustment makes the ADF test particularly useful in ensuring reliable results when the residuals of the time series are autocorrelated. In the context of this study and as already indicated, the ADF test is used to determine whether the variables are stationary at their levels or require differencing, a critical step for selecting the appropriate econometric models, such as the Dynamic ARDL framework. The flexibility of the ADF test to include options for a constant, trend, or both further enhances its applicability to diverse datasets with varying characteristics. The ADF tests the null hypothesis that a time series sample has a unit root against the alternative hypothesis of usually stationary or trend stationary. The ADF test follows the Dickey-Fuller test procedure applied to the following model.

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \delta_1 \Delta y_{t-1} + \ldots.. + \delta_{p-1} \Delta y_{t-p+1} + \varepsilon_t \tag{2}$$

where the lag order of the autoregressive process is denoted by p, the coefficient on a time trend is represented by β and α denotes the constant term. Under this technique, a random walk is modeled if $\alpha = 0$ and $\beta = 0$ are imposed as constraints. However, if $\beta = 0$ is used as a constraint, a random walk with a shift is modeled. Once the test statistic value $DF_T = \widetilde{\gamma}/\text{SE}(\widetilde{\gamma})$ is computed, it is then compared with the critical values of the Dickey-Fuller test to determine whether the null hypothesis $\gamma = 0$ will be rejected for the alternative hypothesis $\gamma < 0$ or otherwise.

The PP-test on the other hand is chosen to complement the ADF test because it addresses potential weaknesses in the ADF approach, such as sensitivity to lag length selection. The PP-test corrects the heteroscedasticity and serial correlations in the error terms without requiring lagged differences of the dependent variable, making it less prone to overfitting or underfitting the model. This is particularly useful in cases where the time series exhibits irregular patterns, as it provides more robust estimates under such conditions. The PP test on the other hand builds on the ADF test and predicts the null hypothesis that a time series has an integration order 1. Unlike the ADF test that addresses endogeneity by incorporating the lags of Δy_t into the test model as an additional predictor, the PP test handles this issue by making non-parametric modifications to the t-test statistic. In the disturbance process of the test's equation, this test yields robust outcomes in the context of unspecified heteroscedasticity and autocorrelation. In this study, the PP-test offers an additional layer of validation for the stationarity results, ensuring that the integration order of the variables is accurately determined and that the econometric analysis is robust. While the PP-test builds on the theoretical framework of the ADF test, it incorporates additional corrections to improve robustness, particularly in cases where the residuals are not white noise. By employing both ADF and PP-tests, the study ensures the reliability of its unit root testing, as the two methods complement each other and help to cross-check the stationarity results for consistency. This dual approach minimizes the risk of incorrect inference about the data's properties.

3.3.2. Cointegration tests

Since cointegration is a requirement for estimating the elasticities of predictors, we further perform the bound test of Pesaran et al. (2001) to determine the cointegration attributes of the series. Unlike traditional cointegration tests, such as Johansen or the test by Park (1990) and Shin (1994), the bound test as proposed by Pesaran et al. (2001), does not require all variables to be integrated of the same order, making it ideal for this study, where the variables exhibit varying levels of stationarity. Additionally, the Pesaran et al. (2001) bound test is well suited to small to medium-sized samples, which aligns with the dataset in this study covering the period of 1995–2020. This ensures reliable results without relying heavily on asymptotic properties. The bound test integrates seamlessly within the DARDL framework employed in the study, allowing for simultaneous estimation of short-run dynamics and long-run relationships. It confirms the existence of cointegration among the variables before proceeding to analyze the long-run elasticities, ensuring methodological robustness. Moreover, the test accommodates deterministic components such as intercepts and trends, which are often present in real-world data, ensuring that the model specification aligns with the characteristics of the variables. Another significant advantage of the Pesaran et al. (2001)-bound test is its robustness to potential endogeneity. By incorporating lagged levels and differences of the variables, the DARDL framework and the bound test help mitigate reverse causality concerns, which are particularly relevant in examining complex interdependencies like those between tourism, financial development, eco-technologies, and environmental pollution. According to Pesaran et al. (2001), the asymptotic distributions of the test statistics under this method are non-standard under the null hypothesis of no cointegration amidst the underlying series. The bound test developed to test cointegration in this study is expressed as;

$$\begin{aligned}\Delta ln\, N_2O_t = {} & \psi_0 + \varpi_0 ln\, N_2O_{t-1} + \varpi_1 lnTR_{t-1} + \varpi_2 lnFD_{t-1} + \varpi_3 lnECO_{t-1} \\ & + \varpi_4 (lnFD^{*}lnTR)_{t-1} + \varpi_5 (lnECO^{*}lnTR)_{t-1} + \varpi_6 lnPOP_{t-1} \\ & + \sum_{i=1}^{p} \lambda_i \Delta ln\, N_2O_{t-1} + \sum_{i=1}^{q} \Omega_{1i} \Delta lnTR_{t-1} + \sum_{i=1}^{q} \Omega_{2i} \Delta lnFD_{t-1} \\ & + \sum_{i=1}^{q} \Omega_{3i} \Delta lnECO_{t-1} + \sum_{i=1}^{q} \Omega_{4i} \Delta (lnFD^{*}lnTR)_{t-1} \\ & + \sum_{i=1}^{q} \Omega_{5i} \Delta (lnECO^{*}lnTR)_{t-1} + \sum_{i=1}^{q} \Omega_{6i} \Delta lnPOP_{t-1} + u_t\end{aligned} \tag{3}$$

where ψ is the constant term, Δ is the change operator, and ϖ, λ, and Ω are the coefficients to be assessed. Under this test, the null hypothesis of no cointegration is rejected if the value of the F-statistic is greater than the upper bound value but cannot be rejected if the F-statistic is lesser than the lower bound value. The decision is inconclusive if the value of the F-statistic is between the upper and the lower bound values.

3.3.3. Elasticity analysis

Having met all the requirements of stationarity and cointegration concerning the study variables, the elasticities of the predictors are then explored in the third phase of the analysis using the DARDL technique of Jordan and Philips (2018). The DARDL approach is well suited for this study due to its advanced features, which address several challenges inherent in time series analysis. One key advantage is its ability to simultaneously estimate both short-run dynamics and long-run equilibrium relationships within a unified framework. This dual capability is essential for understating the immediate and sustained impacts of tourism, financial development, and eco-technologies on environmental pollution in China, offering nuanced insights into these relationships. The DARDL technique improves on the conventional ARDL approach by explicitly accounting for dynamic adjustment processes. It captures how shocks to the system propagate over time and estimates the speed at which variables return to equilibrium after disturbances. This feature is critical for this study, as it enables the modeling of complex interactions among variables while acknowledging their temporal interdependencies. Another vital advantage of the DARDL method is its robustness to endogeneity issues. By including lagged levels and differences of both dependent and independent variables, the DARDL technique minimizes the risk of biased estimates caused by reverse causality or omitted variables. This robustness is particularly relevant in a study examining multifaceted relationships like those between financial development, eco-technologies, and tourism's environmental impact. Notably, the DARDL approach as well allows for counterfactual analysis, a unique feature that enables the simulation of positive and negative shocks to explanatory variables. This capability enhances the study's policy relevance by illustrating how changes in tourism, financial development, or eco-technology might affect environmental pollution under different scenarios. This is a novel characteristic that the ARDL technique lacks. By leveraging the strengths of the DARDL approach, this study ensures a rigorous and comprehensive analysis of variables' dynamic relationships, providing robust results that are both methodologically sound and practically valuable to policy formulations in China's sustainability efforts. In line with Jordan and Philips (2018), the ensuing DARDL model is developed to estimate the coefficients of the predictors based on the model specified in Equation (4).

$$\begin{aligned}\Delta ln\ N_2O_{t-1} &= \psi_0 + \varpi_0 ln\ N_2O_{t-1} + \varpi_1 lnTR_{t-1} + \varpi_2 lnFD_{t-1} \\ &+ \varpi_3\ ln\ ECO_{t-1} + \varpi_4 (lnFD^*lnTR)_{t-1} + \varpi_5 (lnECO^*lnTR)_{t-1} \\ &+ \varpi_6 lnPOP_{t-1} + \sum_{i=1}^{q} \lambda_i \Delta ln\ N_2O_{t-1} + \sum_{i=1}^{p} \Omega_{1i} \Delta lnTR_{t-1} + \sum_{i=1}^{p} \Omega_{2i} \Delta lnFD_{t-1} \\ &+ \sum_{i=1}^{p} \Omega_{3i} \Delta lnECO_{t-1} + \sum_{i=1}^{p} \Omega_{4i} \Delta (lnFD^*lnTR)_{t-1} \\ &+ \sum_{i=1}^{p} \Omega_{5i} \Delta (lnECO^*lnTR)_{t-1} + \sum_{i=1}^{p} \Omega_{6i} \Delta lnPOP_{t-1} + u_t\end{aligned} \quad (4)$$

where ψ_0 is the constant term, p and q are the differential lags of the predictors and the response variable, Δ is the change operator, and $t-1$ represents the lags. It is essential to test the validity and reliability of the results. Therefore, the Jarque-Bera test, Ramsey Reset test, ARCH test, Breusch-Pagan-Godfrey test, and the Breusch-Godfrey LM test were performed.

Next, two sensitivity analyses are conducted to check the robustness of the study results. First, methane emissions (CH_4) are used as a response variable to examine the consistency of the results across models. Second, the control variable (population) is replaced with urbanization to also assess how the regressors will explain environmental pollution in the nation.

3.3.4. Causality analysis

To determine the causal paths between the variables, the Engle and Granger (1987) causality test is performed. The choice of the mentioned causality test in this study is grounded in its theoretical foundation, which emphasizes the concept of cointegration and its implication for dynamic relationships between non-stationary time series variables. Engle and Granger established that if two or more variables are cointegrated, they share a long-run equilibrium relationship despite being individually non-stationary. This property implies that any short-term deviations between the variables are temporary and that an adjustment mechanism exists to restore the equilibrium overtime. This theoretical underpinning makes the test particularly relevant in this study which as well aims to explore the causality in the context of the long-term relationship among study variables. Specifically, another rationale for using the Engle and Granger approach is its reliance on a two-step procedure that aligns with the principles of econometric consistency and efficiency. The first step involves testing for cointegration by estimating a static long-run relationship and examining the residuals for stationarity. If cointegration is established, the second step involves specifying the error correction term, which incorporates the residuals. This sequential approach reflects the theoretical premise that causal inference in the presence of non-stationary variables must account for the long-run equilibrium relationship to avoid spurious results. The test also aligns with the Granger causality framework, which defines the causality in terms of predictive content. However, Engle and Granger extend this concept to the cointegration context, recognizing that, variables may exhibit causality if they are bound by a long-term relationship. This theoretical enhancement ensures that the causality test is robust to the peculiarities of non-stationary data, which is a common feature in our study.

According to this approach, a variable y is said to have Granger caused another variable x if the previous values of y helped to predict the future values of x. In contrast, x Granger causes y if the previous values of x statistically enhance the prediction of y. Under this test, at least the stationary error terms from a cointegration regression must exhibit either a unidirectional or bidirectional Granger causation. Specifically, the study investigated the causal effect among the variables of interest which includes nitrous oxide, tourism, financial development, and eco-technology. Thus, relying on the theoretical model of the Engle and Granger causality test, the following cointegrated models are modified by augmenting them with an error correction term as follows;

$$\begin{aligned}\Delta ln\ N_2O_t &= \alpha_{1,0} + \sum_{i=1}^{p-1} \alpha_{1,1i} \Delta N_2O_{t-i} + \sum_{i=1}^{p-1} \alpha_{1,2i} \Delta lnTR_{t-i} + \sum_{i=1}^{p-1} \alpha_{1,3i} \Delta lnFD_{t-i} \\ &+ \sum_{i=1}^{p-1} \alpha_{1,4i} \Delta ECO_{t-i} + \alpha_{1,3} ecm1 + \varepsilon_{1t}\end{aligned} \quad (6a)$$

$$\begin{aligned}\Delta ln\ TR_t &= \alpha_{2,0} + \sum_{i=1}^{p-1} \alpha_{2,1i} \Delta N_2O_{t-i} + \sum_{i=1}^{p-1} \alpha_{2,2i} \Delta lnTR_{t-i} + \sum_{i=1}^{p-1} \alpha_{2,3i} \Delta lnFD_{t-i} \\ &+ \sum_{i=1}^{p-1} \alpha_{2,4i} \Delta lnECO_{t-i} + \alpha_{2,3} ecm1 + \varepsilon_{2t}\end{aligned} \quad (6b)$$

$$\begin{aligned}\Delta ln\ FD_t &= \alpha_{2,0} + \sum_{i=1}^{p-1} \alpha_{3,1i} \Delta N_2O_{t-i} + \sum_{i=1}^{p-1} \alpha_{3,2i} \Delta lnTR_{t-i} + \sum_{i=1}^{p-1} \alpha_{3,3i} \Delta lnFD_{t-i} \\ &+ \sum_{i=1}^{p-1} \alpha_{3,4i} \Delta lnECO_{t-i} + \alpha_{1,3} ecm1 + \varepsilon_{3t}\end{aligned} \quad (6c)$$

$$\begin{aligned}\Delta ln\ ECO_t &= \alpha_{2,0} + \sum_{i=1}^{p-1} \alpha_{4,1i} \Delta N_2O_{t-i} + \sum_{i=1}^{p-1} \alpha_{4,2i} \Delta lnTR_{t-i} + \sum_{i=1}^{p-1} \alpha_{4,3i} \Delta lnFD_{t-i} \\ &+ \sum_{i=1}^{p-1} \alpha_{4,4i} \Delta lnECO_{t-i} + \alpha_{1,3} ecm1 + \varepsilon_{4t}\end{aligned} \quad (6d)$$

Where the I(1) series generated by the $p-th$ order VAR model is denoted by x_t and y_t, the stationary error-correction term is represented by ecm_t, and the serially uncorrelated sequences are depicted by $i = 1,2$. The null hypothesis that x does not cause y is expressed as; $H_0 : \alpha_{1,21} = \alpha_{1,22} = \ldots \alpha_{1,2p-1} = 0$ and $\alpha_{1,3} = 0$ (see Fig. 1).

The analytical framework based on the econometric times series methods employed is thus summarized using the path diagram in Fig. 2 as.

4. Results

4.1. Descriptive analysis

We examine the descriptive statistics by analyzing the mean, standard deviations, minimum, and maximum together with correlation among the study variables. It is obvious from Table 2 that, tourism had the highest mean and standard deviation, indicating its high volatility among the variables, while population growth showed the lowest mean

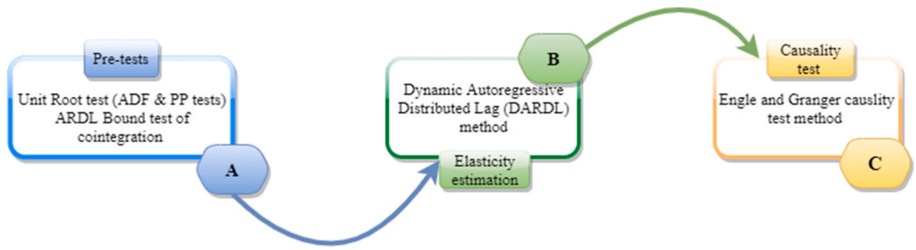

Fig. 2. Analytical roadmap for estimating how technological innovation and financial development moderate tourism-environmental pollution nexus.

Table 2
Descriptive and Correlational analysis.

Descriptive statistics						
Variable	Mean	Std. Dev.	Minimum	Maximum	VIF	Tolerance
N_2O	13.02182	0.1563856	12.7834	13.22073	–	–
TR	18.43238	0.4305066	17.23002	18.90642	1.47	0.679729
FD	4.808584	0.1937216	4.433267	5.208765	2.56	0.391180
ECO	0.7527982	0.257393	0.3624219	1.577256	1.63	0.614047
POP	−0.4821586	0.333006	−1.435313	0.0829699	2.36	0.424287

Correlation Matrix					
Variable	N_2O	TR	FD	ECO	POP
N_2O	1.000				
TR	0.58***	1.000			
FD	0.85***	0.36*	1.000		
ECO	−0.47**	−0.55***	−0.46**	1.000	
POP	−0.71***	−0.28	−0.76***	0.39**	1.000

Note. ***, **, * denote statistical significance at the 1%, 5%, 10% levels respectively.

and standard deviation. Also, the correlation analysis shows that tourism and financial development were positively associated with nitrous oxide (N_2O) emissions, whereas eco-technologies and population growth have a negative relationship with N_2O emissions. Variance inflation Factor (VIF) and tolerance tests further confirm no multicollinearity issues among the variables.

4.2. Unit root and cointegration analyses

Tables 3 and 4 correspondingly outline the summary results from the unit root tests (ADF and pp-tests) and the cointegration test of Pesaran et al. (2001) based on the F-test statistic. Results from Table 3 show a mixed integration order among the variables where at stationary state, N_2O and FD have unit root whereas ECO is stationary at levels with TR and POP being non-stationary at first difference. This thus supports the use of the Dynamic ARDL approach. Moreover, the bound test cointegration analysis in Table 4, confirms the existence of long-run cointegration association among study variables, since the F-statistic is greater than the upper bound value leading to the rejection of the null hypothesis of no cointegration. This thus validates estimating the elasticities among the study's explanatory variables (ECO, TR, FD, POP) with respect to the response variable (N_2O).

Table 3
Unit root test results.

	Augmented Dickey–Fuller (ADF) test		Phillips–Perron (PP) test	
Variable	Levels	First Difference	Levels	First Difference
lnN_2O	−1.04	−6.39***	−1.07	−6.19***
lnTR	−1.75	−0.14	−1.75	−0.14
lnFD	−0.58	−3.94***	−0.62	−3.80***
lnECO	−5.25***	−10.20***	−5.53***	−10.49***
lnPOP	0.05	−1.07	−0.03	−1.07

Note. *** denotes statistical significance at the 1% level.

Table 4
ARDL bound test.

Model F-statistic		
lnN_2O = f(lnTR, lnFD, lnECO, lnFD*lnTR, lnECO*lnTR, lnPOP) 15.58***		
Critical values	Lower bound	Upper bound
10%	2.12	3.23
5%	2.45	3.61
2.5%	2.75	3.99
1%	3.15	4.43

Note. *** denotes statistical significance at the 1% level.

4.3. Regression analysis

4.3.1. Dynamic ARDL simulation results

Table 5 presents the long- and short-run simulation outcomes among the study variables based on the dynamic ARDL approach. Specifically, it is evident that tourism significantly increases environmental pollution by 3.05% in the long-run but has no significant effect in the short-run. This indicates that tourism-related activities harm environmental

Table 5
Dynamic ARDL simulation results.

Dependent variable = Nitrous oxide emissions (N_2O)		
Variables	Short-Run	Long-Run
lnTR	0.84[1.26]	3.05[0.51]***
lnFD	2.21[4.49]	9.91[2.04]***
lnECO	5.60[1.37]***	11.42[1.89]***
lnFD*lnTR	−0.12[0.24]	−0.53[0.11]***
lnECO*lnTR	−0.30[0.08]***	−0.62[0.10]***
lnPOP	−0.03[0.04]	−0.01[0.04]
ECT	−0.23[0.11]*	–
F-statistic	9.44(0.00)***	Adjusted R^2 0.82
R-squared (R^2)	0.92	Root MSE 0.01

Notes: Values in [.] denote standard errors, while those in (.) denote probabilities. ***, **, * denote significance at the 1%, 5% and 10% levels respectively.

quality in the longt-term but their impact diminishes over time. Furthermore, financial development similarly worsens environmental pollution in the long-run by 9.91%, with no significant short-term effects. The long-run impact reflects the financing of activities reliant on carbon-intensive energy. Moreover, eco-technologies had a dual effect, promoting environmental pollution by 11.4% in the long run and 5.60% in the short-run. Despite their potential to mitigate emissions, certain practices, such as the extraction of rare earth metals may contribute to pollution. Considering the assessment of interactive effects, financial development significantly mitigates the environmental impact of tourism in the long-run but is insignificant in the short-run. Nonetheless, eco-technologies reduced the harmful effects of tourism on the environment by 0.30% in the short-run and 0.62% in the longt-run. In addition, population growth employed as a control variable, has an insignificant negative impact on environmental pollution in both the short and long-run. This suggests that advancement in green infrastructure and sustainable practices offset the potential negative effects of population growth. Finally, the estimate of the error correction term (ECT) is statistically significant and negative indicating the convergence from the short-run equilibrium to long-run equilibrium is at the speed of 23%. Precisely, diagnostic tests (Table 6) confirm the model's accuracy following a normal distribution, with no issues of serial correlation, heteroscedasticity, or misspecification. The adjusted R-squared value of 0.82 as well indicates a strong explanatory power of the predictors. A summary of the outcomes from long and short-run elasticities are as well illustrated in Fig. 3.

4.3.2. Counterfactual effects

The counterfactual analysis highlights key dynamics in the relationships between the predictors and environmental pollution. From Figs. 4–6, a 1% positive shock in tourism, financial development, and eco-technologies significantly escalated environmental pollution, whereas a percentage negative shock in these variables reduced pollution. This result emphasizes the direct influence of tourism, financial development, and eco-technologies on environmental quality. Further, positive shocks in the interactions between financial development and tourism or between eco-technologies and tourism improved environmental quality whereas negative shocks in the mentioned interaction harms environmental quality all at 1% (Ref: Figs. 7 and 8 respectively). For instance, the interaction between financial development and tourism mitigates pollution when financial resources are allocated to sustainable tourism practices. Similarly, eco-technologies in tourism enhance environmental sustainability by promoting green innovations and efficient resource management. Moreover, from Fig. 9, the population variable exhibits a positive 1% shock led to the reduction in environmental pollution, suggesting that sustainable urban planning and resource management can offset potential negative impacts of population growth. Conversely, a negative shock worsens pollution, highlighting the need for consistent investment in green infrastructure.

4.3.3. Further discussions

The results demonstrate a complex interplay between tourism, financial development, eco-technologies, and environmental quality. Specifically, tourism and financial development contribute significantly to environmental degradation. This thus implies that tourism and financial development harms environmental quality in China. On the side of tourism, the finding is not amazing since activities undertaken in the tourism industry are dependent on dirty energies like coal, fossil fuels, and natural gas among others. This escalates the rate of pollutant emissions resulting in environmental damage. Besides, most tourists in China move from one location to another, necessitating extensive transportation and consumption of polluting fuels leading to the high discharge rate of pollutant emissions. Moreover, tourist locations promote filth, garbage, and disposal resulting in land, water, and air pollution. This is in tandem with the assertion of Davies and Cahill (2000) that the discharge of solid, liquid, and semi-solid hazardous materials into rivers and oceans due to marine and coastal tourism, poses several potential risks. As indicated by Zhu et al. (2022), sustainable tourism could have a positive influence on the environment, economy, and society, however, unsustainable tourism-related activities could pose a risk to the environment. This finding aligns with the studies of Raihan (2024) and Wang et al. (2024) but contrasts those of Avci et al. (2024) and Wei and Lihua (2023). Considering the case of financial development, the finding is justifiable because financial institutions in the country help businesses to obtain low-cost financial facilities to expand their operations resulting in the consumption of more polluting energies, thereby worsening ecological quality. The financial sector of the nation also helps households access funds to acquire polluting items like automobiles, air conditioners, refrigerators, and other home appliances, consequently damaging environmental safety. Further, robust financial systems stimulate economic activities in the nation. However, most of the economic activities undertaken in the country are driven by carbon-intensive energies, worsening the level of pollution in the environment. The studies of Dada et al. (2024) and Prempeh (2024) support this finding, albeit that of Solaymani and Montes (2024).

In contrast, the short-run effects of tourism and financial development were found to be insignificant. This could reflect the gradual adaptation to sustainable practices or diminishing marginal impact over time. Specifically, the short-run trivial effect of tourism on environmental pollution may suggest that tourism activities in China have no material influence on the nation's environmental quality. This finding deviates from the various studies which include Zhao et al. (2024) in 31 Chinese tourist cities, Wang et al. (2024) in One Belt One Road economies and, Al-Mulali et al. (2014) in European economies. Likewise, the insignificant effect of financial development on environmental pollution also suggests that, in the short run, advancements in the financial sector have no material impact on the nations' environmental sustainability. This finding thus varies from the research of Ren et al. (2023), Wang et al. (2023), and Li et al. (2024) all in China. However, Destek and Sarkodie (2019) and Ozturk and Acaravci (2013) support this study's finding as they discovered an immaterial association between financial development and environmental quality.

The paradoxical role of eco-technologies, which is evidenced to increase environmental pollution in both the long and short-run, highlights the unintended consequences of green innovations. Eco-technologies have been evidenced to improve environmental quality in many contexts (Ali et al., 2024; Onifade and Alola, 2022; He et al., 2024; Onifade et al., 2023). However, in China, certain eco-technologies have absurdly hindered the environmental quality, potentially due to factors such as the carbon intensity production processes or rebound effects that increase overall emissions. Even though green technologies are meant to improve the environment, they may equally have damaging environmental repercussions. For instance, the production of renewable energy technologies such as solar panels and wind turbines requires the extraction of rare wire metals, which is an energy-intensive process with significant environmental costs. A notable example is the Bayan Obo Mining District in China, one of the largest rare earth element mines in the world. This site has been associated with soil erosion, water contamination, and air pollution, which offset the environmental gains from green technologies that it supports. Similarly, the disposal of "e-waste" from outdated or broken eco-technologies, such as

Table 6
Diagnostic tests.

Test	Value	Probability	Conclusion
Breusch-Godfrey LM test	2.13	0.16	No serial correlation
Harvey test	0.28	0.94	No heteroscedasticity
Jarque-Bera test	0.19	0.91	Normal distribution
Reset test	0.55	0.47	The model is accurately specified

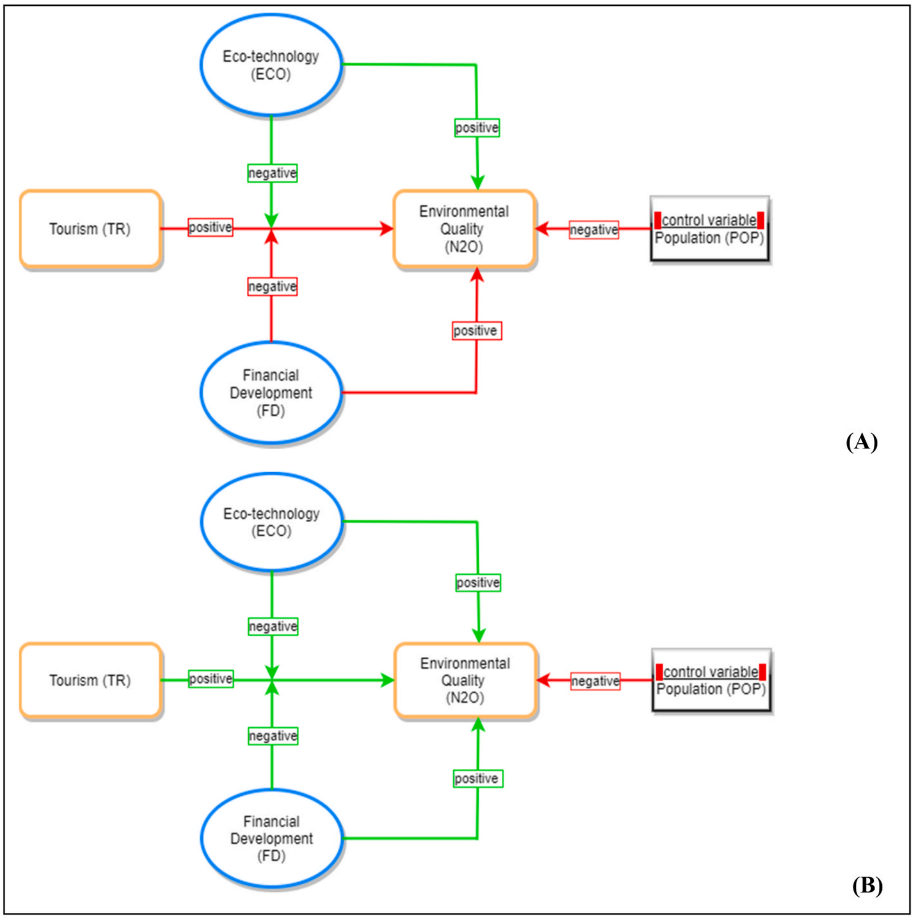

Fig. 3. Path estimation on the inter-relationships amid tourism, eco-technology, financial development, and environmental quality. **Note: A** and **B** represent the Path coefficient chart for short and long-run estimation respectively; red arrows represent insignificant direct effects being positive or negative whereas green arrows mean significant positive effects being positive or negative; Population growth is employed as a control variable. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

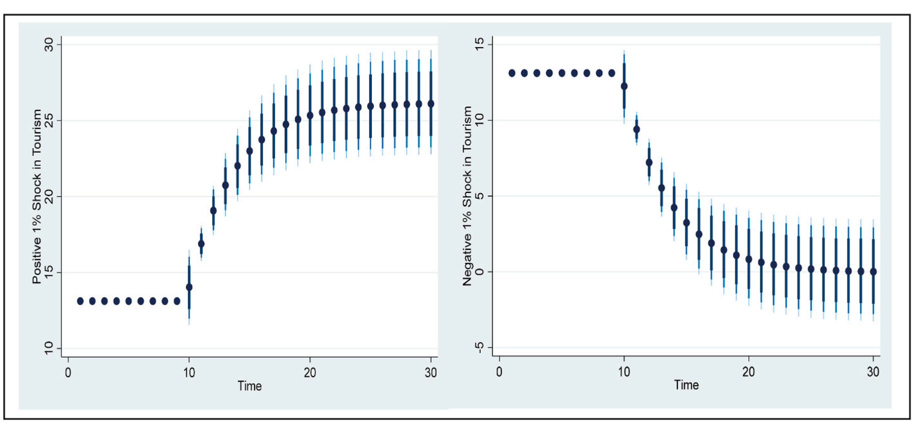

Fig. 4. Counterfactual assessment of shock in tourism. Note: The dots denote average predicted values while the dark blue to light blue lines represent 75%, 90%, and 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

photovoltaic cells and batteries from electric vehicles, poses significant challenges. If not managed properly, this waste can leach hazardous substances into the environment, as has been observed in electronic waste dumping grounds like Guiyu in China. Additionally, eco-technologies promote economic growth in China (Feng et al., 2024). As the economy of the nation grows, activities like manufacturing and construction increase resulting in the consumption of more polluting energies thereby degrading environmental quality. China has hugely invested in green technologies to help drive its carbon neutrality agenda, however, according to this study, the technologies are rather promoting environmental pollution instead of reducing it hindering the attainment of such an ambition. The damaging environmental effects of green technologies discovered in this study contrast with the assertion of Song et al. (2020), Qin et al. (2023), Meng et al. (2023), and He et al. (2024) but in line with the studies of Liu et al. (2022), Adebayo et al. (2022), and Rahman and Alam (2022).

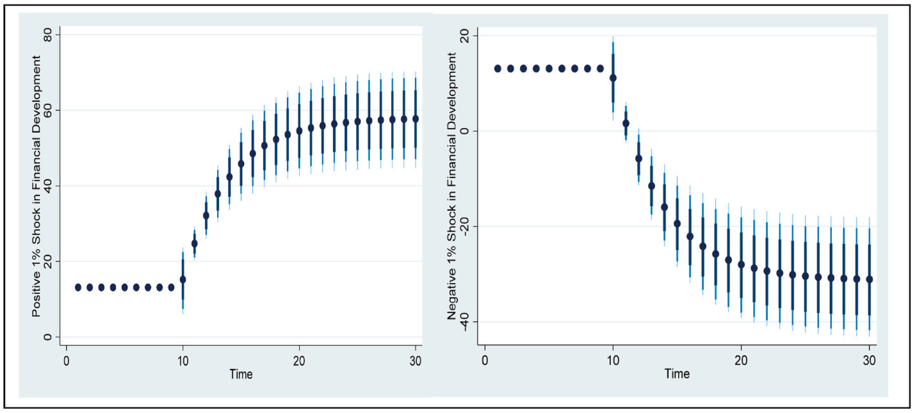

Fig. 5. Counterfactual assessment on shock in financial development. Note: The dots denote average predicted values while the dark blue to light blue lines represent 75%, 90%, and 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

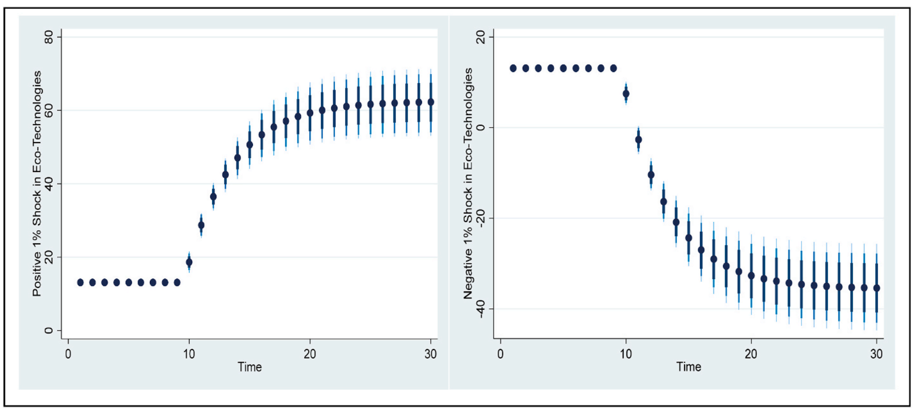

Fig. 6. Counterfactual assessment on shock in eco-technologies. Note: The dots denote average predicted values while the dark blue to light blue lines represent 75%, 90%, and 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

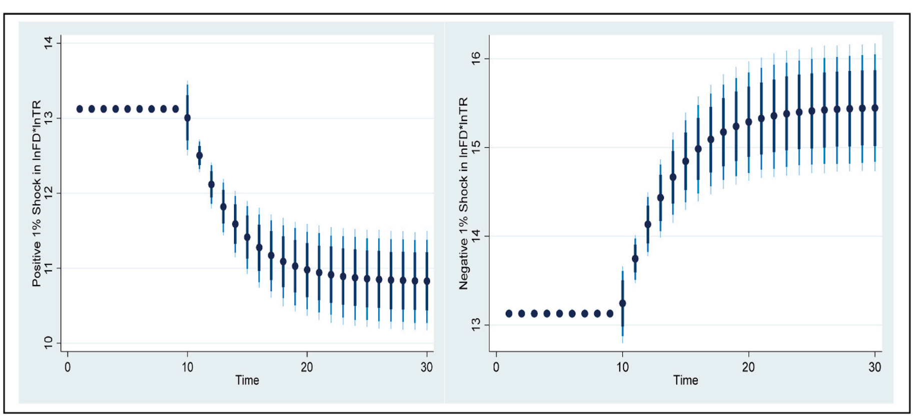

Fig. 7. Counterfactual assessment of shock concerning the interaction between financial development and tourism. Note: The dots denote average predicted values while the dark blue to light blue lines represent 75%, 90%, and 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Further, the moderating effects of financial development and eco-technologies on the tourism-environment nexus are noteworthy both in the long and short-run. Financial development significantly mitigates the environmental impact of tourism in the long-run by promoting investments in green infrastructure and sustainable practices. This means development in the financial sector reduces the damaging environmental effects of tourism in the nation. The finding is justifiable because a well-developed financial sector can help to reduce pollution in the environment by facilitating investments in renewable energies, energy efficiency, and sustainable tourism infrastructure among others. Also, financial development can be used to encourage eco-tourism and responsible travel, two sustainable tourist strategies that lessen environmental damage. The studies of Fakher and Ahmed (2023) and Chiu and Zhang (2023) contrast this finding. Likewise, the interactive effect of eco-technologies in the link between tourism and environmental pollution is significantly negative in both the long and the short run

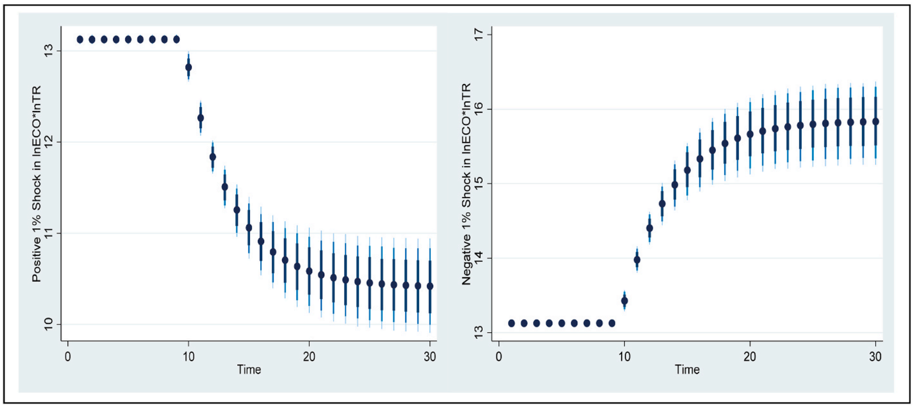

Fig. 8. Counterfactual assessment of shock concerning the interaction between eco-technologies and tourism. Note: The dots denote average predicted values while the dark blue to light blue lines represent 75%, 90%, and 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

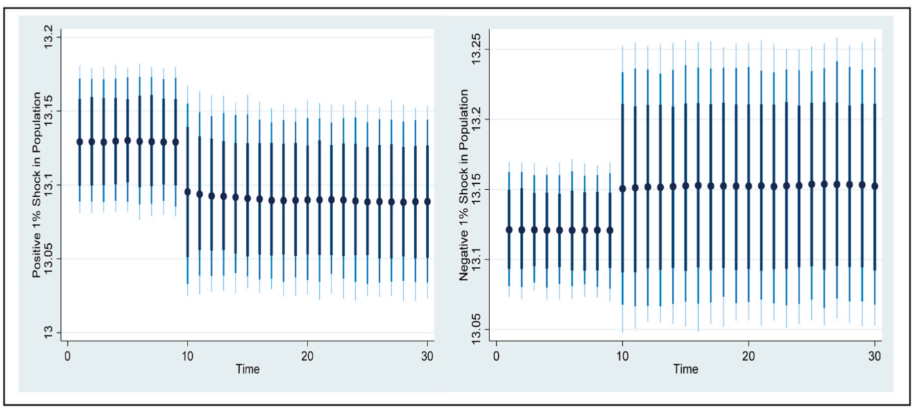

Fig. 9. Counterfactual assessment on shock in population growth. Note: The dots denote average predicted values while the dark blue to light blue lines represent 75%, 90%, and 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

implying that green technologies mitigate the negative environmental externalities of tourism. Eco-technologies like sustainable water management and green energy reduce the damaging effects of tourism on the environment. Also, water and air purification technologies enhance the quality of the environment, drawing tourists to various destinations. Besides, waste management and energy-efficient technologies promote environmental sustainability by minimizing pollution in the tourism industry. Moreover, eco-technologies facilitate the creation of regulations and policies, allowing for efficient administration and governance of the environmental impact of tourism. Furthermore, green technologies encourage innovation in the tourism sector resulting in the development of new sustainable solutions. This discovery varies from the studies of Sharma et al. (2021) for South Asian economies and Zeqiraj et al. (2020) for the European Union.

Moreover, the population employed as a control variable has revealed an insignificant negative effect on environmental pollution in China. Several factors might account for this discovery. For instance, improved efficiency can offset the environmental effects of the population in the country. Also, a shift in lifestyle and consumption patterns can reduce the influence of population growth on the environment. Moreover, the broad implementation of green infrastructure like sustainable transportation and green buildings among others, can reduce the impact of population growth on the environment. Besides, environmental awareness and education can also lead to behavioral changes that could offset the detrimental effects of population on the environment. This outcome thus corroborates with the finding of You et al. (2024) but not in tandem with the assertions of Li et al. (2019), together with Shum et al. (2021) and Pan et al. (2021).

4.3.4. Sensitivity analysis

Two sensitivity analyses are conducted to examine the robustness of the study's outcomes. First, the dependent variable N_2O is replaced with CH_4 while maintaining all explanatory variables to determine whether the results will be consistent across models or not. From the results displayed in Table 7, tourism and financial development have a significantly positive effect on environmental pollution in the long run but an insignificantly positive effect on environmental deterioration in the short run. Also, eco-technologies worsen environmental quality in both the short and the long run. Besides, population and the interaction

Table 7
Dynamic ARDL simulation results.

Dependent variable = Methane emissions (CH_4)		
Variables	Short-Run	Long-Run
lnTR	1.74[1.70]	1.23[0.63]*
lnFD	4.97[6.10]	2.80[2.42]***
lnECO	7.33[1.92]***	11.27[2.73]***
lnFD*lnTR	−0.27[0.33]	−0.15[0.13]
lnECO*lnTR	−0.40[0.11]***	−0.62[0.15]***
lnPOP	−0.09[0.050]*	−0.12[0.05]**
ECT	−0.24[0.10]**	–
F-statistic	3.71(0.02)**	Adjusted R^2 0.60
R-squared (R^2)	0.81	Root MSE 0.02

Notes: Values in [.] denote standard errors while those in (.) denote probabilities. ***, **, * denote significance at the 1%, 5% and 10% levels respectively.

between eco-technologies and tourism promote a sustainable environment in both the long and the short run, but financial development plays an immaterial role in the link between tourism and environmental quality in the nation. Aside from the results on population growth and the interaction between financial development and tourism, all the other results are consistent with those under the N_2O model in terms of signs but slightly different in terms of significance. The inconsistencies in the outcomes might be due to the differences in the measurement units of the response variables. For instance, CH_4 is measured in Kt of CO_2 equivalent while N_2O is measured in thousand metric tons of CO_2 equivalent.

Secondly, N_2O and the core explanatory variables are maintained but control variable population growth (annual percentage) is replaced with urban population as a percentage of the total population to further assess how environmental pollution will be predicted in the country. Based on the estimates shown in Table 8, tourism and financial development significantly positively predict environmental pollution in the long run but trivially predict it in the short run. Also, eco-technologies significantly positively explain environmental pollution in both the short and the long run. Besides, the interaction between financial development and tourism has an insignificantly negative influence in the short run but a significantly negative impact in the long run. Moreover, the interactive effect of eco-technologies and tourism significantly negatively predicts environmental pollution in both the short and the long run. Finally, urbanization has an insignificantly positive effect in the short run but a significantly positive influence in the long run. Except for the results on the interactive effect of financial development and tourism, the results of all the other variables of interest are consistent with those under the principal estimator. This justifies that the study's outcomes are very robust to help offer policy options to drive the SDG agenda of the nation.

4.3.5. Causality analysis

At the final stage of the analysis, the causal paths between the response variable and each of the explanatory variables including the interactive effects are explored.[1] From the results displayed in Table 9, unidirectional causalities from tourism and population to environmental pollution are disclosed. This means the rise in tourism and population growth harms the nation's environmental quality but not the opposite. These findings align with the studies of Ullah et al. (2021) and Rahman et al. (2020) respectively. Besides, development in the financial sector has no causal relationship with environmental pollution. This implies the variables are independent of each other. The studies of Nyeadi (2023) and Chen et al. (2023) deviate from this finding. Moreover, eco-technologies and environmental pollution are flanked by a bidirectional causal relationship. This implies the variables are dependent on each other. Ju et al. (2023) discovered a similar result for 21 Arab nations supporting the outcome of this investigation. Additionally, the interaction between eco-technologies and tourism has a bidirectional relationship with environmental pollution suggesting that the series are dependent on each other. Finally, no causal connection is observed for the environmental pollution and the interaction between financial development and tourism. This indicates that the variables are not reliant on each other. The causal relationships established between nitrous oxide and the respective explanatory variables together with the interactions are summarized in Fig. 10.

Table 8
DARDL simulation results.

Dependent variable = Nitrous oxide emissions (N_2O)		
Variables	Short-Run	Long-Run
lnTR	0.35[0.91]	1.90[0.45]***
lnFD	0.57[3.23]	6.53[1.57]***
lnECO	3.95[0.99]***	8.19[1.57]***
lnFD*lnTR	−0.03[0.17]	−0.35[0.08]***
lnECO*lnTR	−0.22[0.05]***	−0.45[0.09]***
lnURB	2.40[1.42]	0.88[0.27]***
ECT	−0.83[0.18]***	–
F-statistic	18.50(0.00)***	Adjusted R^2 0.90
R-squared (R^2)	0.96	Root MSE 0.01

Notes: Values in [.] denote standard errors while those in (.) denote probabilities. ***, **, * denote significance at the 1%, 5% and 10% levels respectively.

[1] Due to brevity, the study only aimed at the causal relationships among the dependent variable and each of the independent variables but not among the explanatory variables.

Table 9
Granger causality test results.

Null Hypotheses	F-statistic	Prob.	Causality Flow
lnTR⇏lnN_2O	9.30	0.00***	Unidirectional
lnN_2O⇏lnTR	0.57	0.57	
lnFD⇏lnN_2O	0.18	0.84	No causality
lnN_2O⇏lnFD	1.55	0.24	
lnECO⇏lnN_2O	14.84	0.00***	Bidirectional
lnN_2O⇏lnECO	15.49	0.00***	
lnFD*lnTR ⇏lnN_2O	1.11	0.35	No causality
lnN_2O⇏lnFD*lnTR	1.91	0.18	
lnECO*lnTR ⇏lnN_2O	13.67	0.00***	Bidirectional
lnN_2O⇏lnECO*lnTR	14.27	0.00***	
lnPOP⇏lnN_2O	4.81	0.02**	Unidirectional
lnN_2O⇏lnPOP	1.67	0.22	

Note: ***, and **, denote significance at the 1% and 5% levels respectively.

5. Conclusions, policy implications and limitations

5.1. Conclusions

Greenhouse gas emission mitigation has become increasingly important due to the rising rate of climate change and environmental pollution. China, one of the fastest-growing economies, has become vulnerable to the consequences of climate change. This calls for more explorations to come up with policy options to help the nation reduce climate change and its adversities. Hence, this study investigates the relationship between tourism and environmental pollution in China, accounting for the roles of financial development and eco-technologies

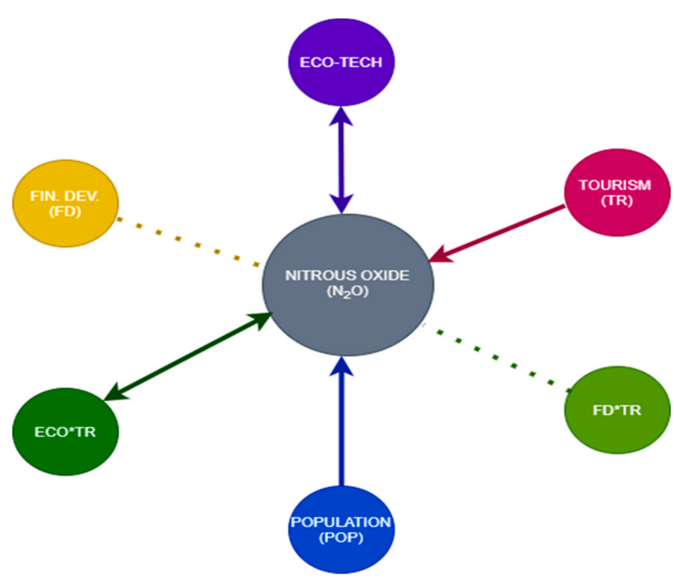

Fig. 10. Causal pathways between Nitrous Oxide and each of the explanatory variables including interactions. **NB:** double-headed arrows represent bi-directional causality; single-headed arrows represent uni-directional causality and dotted lines without heads represent no causality.

over the period 1990–2020. Employing the novel DARDL technique, the study reveals the series possess a mixed order of integration and are flanked by a long-run cointegration association.

The major findings indicate that tourism and financial development worsen environmental quality in the long run but insignificantly influence it in the short run. Besides, eco-technologies as a standalone factor were found to be detrimental to environmental sustainability in both the long and the short run against the general a priori expected environmental benefits. This unexpected exacerbating environmental degradation roles of eco-technologies can be understood through the channels of rebound effect and resource-intensive production mechanisms. Additionally, financial development significantly mitigates the harmful environmental effects of tourism in the long run but insignificantly influences that impact in the short run. Meanwhile, the interactive impacts of eco-technologies significantly reduce the environmental externalities of tourism in both the long and the short run. Moreover, population growth has an insignificant effect on environmental quality in both periods.

5.2. Policy implications

Overall, the findings suggest that tourism worsens China's environmental quality in the long run but not in the short run. Hence, the Chinese government should prioritize green and sustainable tourism strategies to mitigate the adverse effects of tourism on the nation's environment. Some specific actionable strategies could include, formulating policies to transform environmentally unsustainable consumption patterns in the tourism sector. This can be done by promoting green transportation in the sector, supporting eco-friendly housing initiatives in hotel projects, and advancing technological innovations to decrease reliance on natural ecosystems. Also, the government should encourage tourism firms to embrace the SDGs and circular economy, enact regulations and policies for sustainable tourism, promote awareness and responsible travel behaviors in the tourism industry, encourage the development of technologies that promote sustainable tourism, promote sustainable water management techniques in tourism businesses, support eco-lodges and sustainable accommodation options, and should encourage waste reduction and recycling practices in the tourism sector.

Also, financial development harms environmental quality in the long run but not in the short run. This implies the current role of financial development in environmental pollution necessitates a strategic redirection towards environmental sustainability. This shift involves guiding financial resources into eco-friendly projects and energy sources, enforcing regulations for financial institutions to fund green initiatives, and taxing services that contribute to environmental damage. To further address environmental concerns related to financial development, the government should promote cooperation between financial institutions and civil society, encourage the development of sustainable financial instruments like green bonds, stimulate global collaboration on environmental protection and sustainable financing, and encourage the integration of environmental, social, and governance (ESG) concerns into investment decisions.

Moreover, eco-technologies have proven to be harmful to China's environmental quality in both the long and the short run. Hence, it is recommended that the nation should invest in green technologies that encourage waste reduction and sustainable behavior, establish ethical and sustainable sourcing procedures for the manufacturing of green technologies, invest in clean energy sources to stimulate the production of eco-technologies, give manufacturers of green technologies extended producer responsibility, provide closed-loop solutions for the recycling and production of green technologies, encourage research and development on materials and industrial techniques related to eco-technologies, and should promote innovation and collaboration to solve environmental footprint of green technologies.

Besides, financial development mitigates the damaging environmental effects of tourism in the long run but not in the short run. Hence, it is recommended that the financial sector should promote investment in environmentally friendly transportation systems in the tourism industry; support training and education on sustainable tourism; stimulate investment in sustainable infrastructure, waste, and water management systems; promote green energy and energy-efficient technologies in the tourism sector, stimulate the development and implementation of sustainable tourism regulations and policies, and should promote monitoring and research on the environmental impacts of tourism.

Likewise, the interactive effect of eco-technologies and tourism enhances environmental quality in the long run but not in the short run. Hence, the Chinese government should urge policymakers to give precedence to environmental sustainability in the development of tourism, fund the advancement of technologies that prioritize environmental sustainability in the tourism industry, evaluate and track how well green technologies are working to lessen the negative effects of tourism on the environment, promote innovation in the development and deployment of eco-technologies in the tourism industry, as well as develop eco-friendly certification schemes that consider the environmental impacts of green technologies. Furthermore, more support is needed for the training and education about green technology usage and sustainable tourist practices by promoting cooperation among stakeholders to guarantee that eco-technologies complement the environmental goals of the tourism industry.

Finally, population growth insignificantly negatively influenced nitrous oxide emissions in both the long and the short run. To make population more environmentally friendly, it is recommended that China should encourage urban planning and design that promotes sustainability, support training and education on family planning, put in place effective resource management systems, encourage community participation in sustainability initiatives, and promote sustainable lifestyle decisions and practices. Also, there is a need to consistently track and assess the success of sustainability initiatives, invest in energy efficiency and clean energies, support research and development of technologies linked to pollution reduction, and promote sustainable industrialization and circular economy. The population needs wider access to develop sustainable waste and water management systems, and there should be more support for global collaboration and information exchange on pollution control, support efforts on the conservation and restoration of biodiversity, encourage sustainable transportation as well as promote eco-friendly consumption habits among the Chinese citizenry.

5.3. Limitations

A key limitation of this study is its relevance to aggregated national-level data, which may obscure regional or provincial variation in the relationships between tourism, financial development, eco-technologies, and environmental pollution. China's regional or provincial diversity in economic development, industrial composition, and environmental policies could result in significant disparities in these dynamics. Future research should therefore explore regional or provincial-level analyses to capture localized nuances and provide targeted policy recommendations that address the unique environmental and economic contexts of different regions within China. Also, while the studies focus on tourism, financial development, and eco-technologies as determinants of environmental pollution, other important variables such as energy consumption patterns, industrial activities, and waste management practices, are excluded. Future studies could incorporate these additional factors to provide a more holistic understanding of the determinants of environmental quality.

CRediT authorship contribution statement

Mohammed Musah: Methodology, Formal analysis, Data curation, Conceptualization. **Isaac Adjei Mensah:** Writing – original draft, Formal analysis, Data curation. **Stephen Taiwo Onifade:** Writing –

review & editing, Writing – original draft, Supervision, Conceptualization. **Isaac Ankrah:** Writing – original draft, Investigation, Formal analysis. **Bright Akwasi Gyamfi:** Formal analysis, Data curation.

Availability of data and materials

The data for this present study are sourced from the Organization for Economic Co-operation and Development – OECD, (https://www.oecd.org/), and the database of the World Bank's World Development Indicators (https://data.worldbank.org).

Funding

There is no specific funding received by the author for the study.

Declaration of competing interest

The authors wish to disclose here that there are no potential conflicts of interest at any level of this study.

Data availability

Data will be made available on request.

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