


Tourism-driven carbon emissions and the innovation response: A cross-country analysis of extended QUAD economies

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ABSTRACT

Carbon emissions can be reduced by addressing robust environmental degradation. The current study examines the nuanced relationship between tourism and carbon emissions in the presence of technological innovation as a moderating variable for the Extended QUAD countries for 21 years (2000 to 2020). Using panel quantile regression and pre-diagnostic tests for cross-sectional dependence, slope heterogeneity, it emerged that technological innovation alone is not able to mitigate tourism's effect on carbon emissions. Results of quantile regression highlight a positive impact of technological innovation and tourism combined with emissions. Moreover, the variables employed, such as GDP, trade openness, and renewable energy show a strong correlation with emissions, underlining the necessity for policies targeting these factors to effectively reduce carbon footprints. Further, a positive correlation between trade openness and carbon emissions aligns with the pollution haven hypothesis; however, Environmental Kuznets Curve based hypothesis has been rejected by the presence of a positive relationship across different quantiles. The findings aim to offer insights for policymakers to harmonize economic growth with environmental sustainability pertaining to the tourism sector. The present study contributes to literature by exploring the role of technological innovation as a moderator in the tourism-emission nexus, providing a deeper understanding of sustainable tourism practices.

1. Introduction

The acceleration of growth worldwide has led to an exorbitant increase in emissions, leading to a fall in the overall living standards and drastic changes in the environment [1]. This has intensified the challenge of generating economic wealth while simultaneously preserving the environment, thereby making sustainable development a top priority in policy formulation across both developed and developing economies.

The existing literature has documented various factors that impact carbon emissions and, hence, climate change. Among all, economic growth is at the top to have a significant impact on emissions [2] followed by urbanization [3], renewable energy usage [4,5], technological innovation [6], trade openness [7], financial development [8], waste

management [9], and tourism [10–12]. Among these, the tourism sector holds a dual role: it is both highly susceptible to the effects of climate change and a notable contributor to global greenhouse gas (GHG) emissions (UNWTO, 2023). As per the report of UN Tourism, 2019, “CO₂ emissions from tourism are forecasted to increase by 25 % by 2030 from 2016 levels.”

Tourism as an industry is a conglomerate of various sub-parts ranging from accommodation and transportation to food services and entertainment, all of which require substantive energy [13]. The industry has, over the years, added hugely to the global carbon emissions [14,15], and hence there is an emergent need to scale up climate action in the sector to ensure that there is a progression towards sustainable tourism that complements green growth (Ben [8]). As technology has progressed and there has been a trend towards energy-efficient and

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technically advanced means in tourism, the evolution of sustainable tourism is documented to bring a reduction in carbon emissions (X [16]). Technological innovation is documented to be a major contributor to emission reduction with its multifaceted impact. A study by Pata & Naimoglu [17] for instance, highlighted how technological infrastructure is the major support factor for promoting renewable energy usage and thus supporting green growth.

The empirical investigations exploring the relationship between tourism and carbon emissions are well-established in the research literature but despite that, no previous study has analyzed this interrelationship with technological innovation as a moderator. This study bridges the gap by analyzing the intricate link between tourism and emissions, focusing on the moderating role of technological innovation in the Extended QUAD (EQUAD) countries (Australia, India, Japan, the United States, South Korea, Vietnam and New Zealand). Choosing the EQUAD countries provides a diverse mix of developed and emerging economies with significant tourism sectors (Fig. 1) and strong commitments to sustainability.

To allow for a broader context of understanding the tourism-technology-carbon emissions relationship in the Indo-Pacific area, the present research adds three new economies (South Korea, Vietnam, and New Zealand) to the classic QUAD group (consisting of the United States, Japan, India, and Australia) to construct what is increasingly spoken about in policy and scholarly communities as QUAD Plus. All these nations have been emerging as strategic players in the region because they have been increasingly aligned on issues of climate resilience, digital innovation, and sustainable economic development. South Korea and Vietnam are most prominent in tourism and manufacturing, respectively, while New Zealand is most prominent in terms of advanced sustainability and technology uptake. All three have shown proactive efforts towards carbon neutrality, clean energy transitions, and technological modernization. Placing these countries in this wider group enables a more multi-faceted analysis of cross-country variations and similarities in balancing economic growth through tourism with environmental protection, particularly under the impact of technological innovation. This broader group enables wider policy-relevant findings and region-specific recommendations.

The research utilizes Panel Quantile Regression, drawing on extensive panel data from 2000 to 2020. This approach accounts for heterogeneity within the relationship across different quantiles, enabling the examination of effects at various points (quantiles) within the

conditional distribution of the dependent variable [18]. In light of this, the study aims to answer the following research questions:

RQ1. How does tourism activity influence carbon emissions across EQUAD countries?

RQ2. To what extent does technological innovation moderate the relationship between tourism and carbon emissions?

RQ3. Does the impact of tourism and its interaction with innovation on emissions vary across different levels of the emissions distribution?

This article is organized as follows: after the Introduction, Section 2 outlines the theoretical framework, offering the rationale for conducting the study and reviewing the relevant literature. Section 3 details the research methodology, including data sources, variables, and the econometric techniques employed to test relationships. Section 4 presents the empirical findings, Section 5 offers the discussion, and Section 6 concludes the paper by addressing limitations and suggesting directions for future research.

2. Theoretical background

The Travel & Tourism sector contributed 9.1 % to the global GDP, in 2023, highlighting tourism as a notable contributor to economic growth and a major driver of rising emissions in the quest for economic wealth. Economists have explored the interplay between tourism and economic development through various lenses, resulting in two prominent hypotheses: the Tourism-Led Growth Hypothesis and the Growth-Led Tourism Hypothesis. These hypotheses elucidate how tourism can spur economic growth and how economic expansion can, in turn, foster tourism development, thereby illustrating the intricate dynamics between economic progress and environmental consequences [19]. Rising tourism increases the economic growth, the tourism-led growth hypothesis (TLGH) asserts that an increase in economic growth, which in turn, increases income and employment generation [20,21]. Where the growth-led tourism hypothesis (GLTH) explains how the rising economic growth fuels tourism. Therefore, one important underlying dimension that needs to be addressed here is the impact that rising tourism has on carbon emissions. Even energy consumption is increasing as tourism, being an energy-intensive sector, leads to an increase in energy consumption via increased transportation, accommodation, and

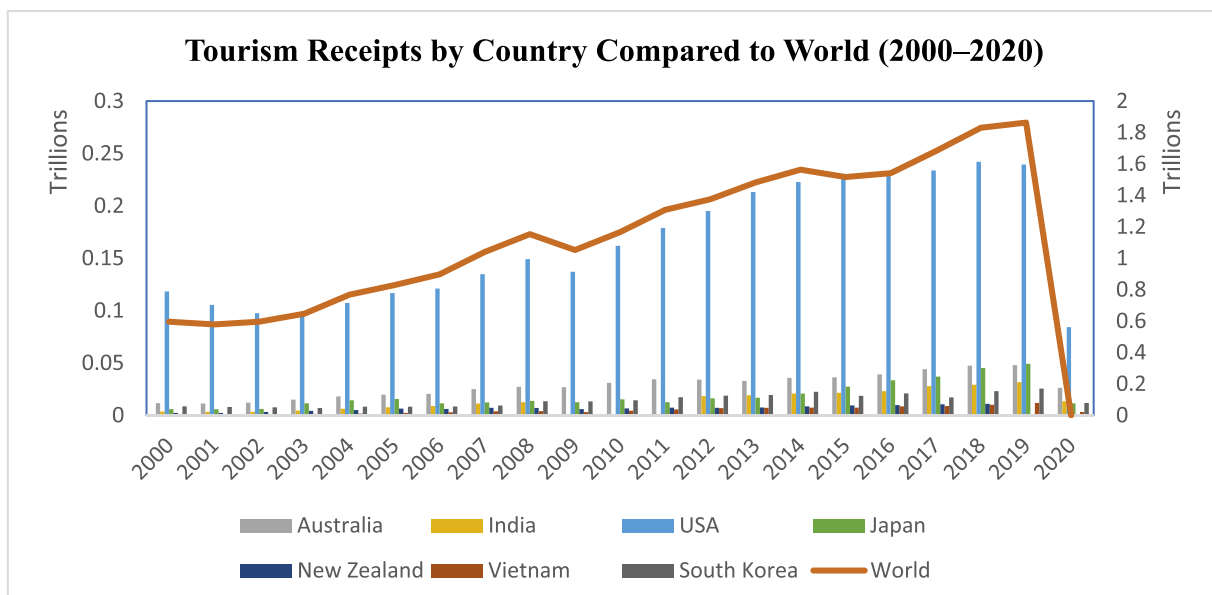


Fig. 1. Tourism of QUAD countries and the World.

infrastructure demand [22]. These increased emissions due to increased energy consumption because of tourism can be either positive or negative, depending on the energy source used. However, this relationship varies with the income level of an economy, and this rationale is backed by the Environmental Kuznets Curve (EKC) in the context of tourism [23,24]. The theory highlights an inverted U-shaped relationship between economic growth and emissions. It postulates how with an initial rise in income, there is a corresponding rise in emissions [25], which then starts falling after the income level reaches a certain threshold level. This is because of the positive spillover impact of technological innovation and a paradigm shift towards cleaner sources of energy [26]. The theory can be easily extended to the tourism-carbon emission nexus as initially, increased tourism leads to a rise in energy consumption, transportation, and infrastructure, which leads to increased emissions. However, a further rise in tourism coupled with economic growth leads to a shift towards eco-friendly tourism wherein sustainable practices and green technologies lead to a reduction in emissions and a move towards sustainable and green growth [20,27]. The three theories outlined above provide the theoretical basis for our study, in which we explore the dynamic relationship between tourism and carbon emissions, with technological innovation as a moderating factor. Additionally, we incorporate control variables such as GDP, trade openness, financial development, renewable energy use, and urbanization, among others, as derived from the theoretical constructs discussed earlier. This study aims to contribute to the existing knowledge base and further the concept of sustainable tourism in countries with high carbon emissions.

2.1. Empirical literature support

The link between tourism and carbon emissions has indeed become a significant focus in discussions around climate change in recent times. However, before the pandemic, the literature on this topic was relatively sparse [19]. The academic interest in the topic has been spiking since 2020, with researchers increasingly exploring the impact of tourism on carbon emissions and seeking sustainable solutions to mitigate this environmental challenge (Fig. 2).

Studies that have explored the connection between tourism and carbon emission along with other variables like economic growth, renewable energy, urbanization, technological innovation, and others have often found mixed results [17,28]. While a few studies assert that increased tourism leads to enhanced emissions, others provide that tourism rise helps in mitigating climate change. Additionally, studies by Wang et al. [29] underscore the role of technological innovation in decoupling tourism growth from rising carbon emissions, thereby

promoting sustainability in the sector.

Among the numerous studies documenting a reduction in carbon emissions due to tourism, the findings are heterogeneous, varying significantly based on the region studied, the econometric methodologies employed, and the time frames considered. Ben Jebli et al. [8], for instance, documented a negative relationship between tourism and emissions in the 22 Central and South American countries using panel causality and cointegration for the period 1995 to 2010 with similar results documented by Ahmad & Ma [30] and Voumik et al. [31] in the Asian countries wherein the reduction in the emission was attributed to industry and energy substitution effects. Similar results were documented by Sharif et al. [2] in the Malaysian economy using the quantile ARDL approach for the period 1995 to 2018 and in the Chinese Province [24]. The link between tourism and carbon emissions has been increasingly highlighted, showing a negative impact. Dogan & Aslan [19] for instance asserted that tourism not only mitigates CO₂ emissions but also shows a one-way causality from tourism to carbon emissions in the EU economies for the period of 1995 to 2011.

The studies that documented interaction between tourism and carbon emission were not limited to just two variables, as it is important to address the impact of various other variables that act as either moderators or control variables in discussing the relationship. For instance, X. Zhang et al. [16] tested the interaction between multiple variables like economic growth, tourism, energy consumption, and others in the G-7 economies for the period 1990–2021 and based on panel regression, asserted the need to move towards technological innovation to decouple sustainable tourism from rising carbon emissions. Lee & Brahmastre [32] provided support for tourism in the European Union countries for the period 1988 to 2009 and asserted a negative impact of the former on emissions in the presence of economic growth as the additional variable.

Not all research points to a negative relationship between tourism and emissions; in fact, a significant body of literature highlights the opposite, showing a positive correlation between the two. Raihan [21] examined the effect of tourism on carbon emissions in Brazil from 1990 to 2019, using the ARDL approach and found that a 1 % rise in tourism leads to a 0.57 % increase in total emissions. This underscores the impact of tourism on environmental deterioration and hence focuses on making a transition towards sustainable tourism practices. Similar results are obtained for the Kuwait economy, wherein increased tourist arrivals led to increased emissions for the period 1995 to 2019 [33]. The study by Danish & Wang [[34]8] analyzed the relationship between tourism and emissions in the BRICS countries from 1995 to 2014 and found that tourism contributes heavily to environmental degradation. The results align with the study of Uddin et al. [7], who also documented similar

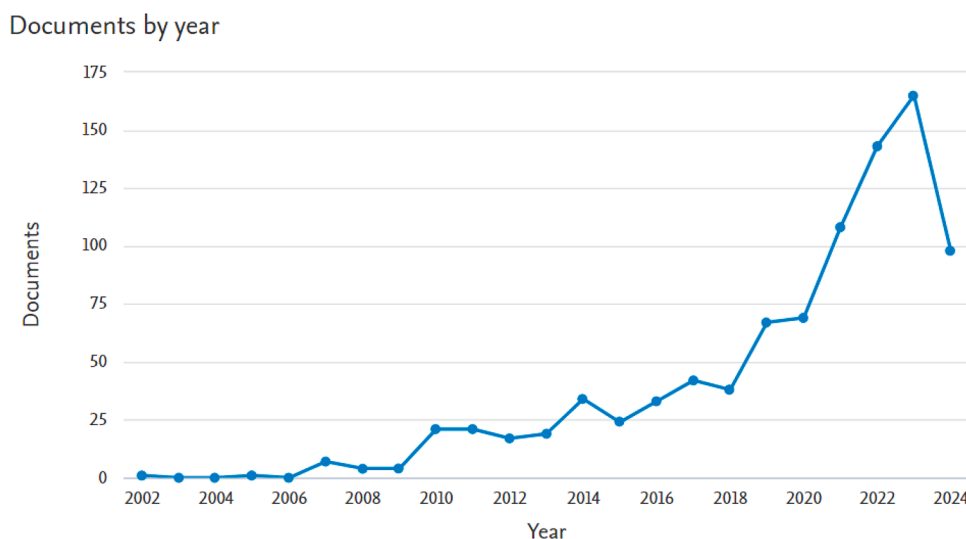


Fig. 2. Academic Literature Related to Tourism and Carbon Emission. Source: Scopus using Keyword TITLE-ABS-KEY ("tourism" AND "carbon emission").

evidence of environmental degradation in Thailand attributed to tourism rise.

In addition to studies showing either a positive or negative relationship between tourism and carbon emissions, few studies highlight a more complex, mixed relationship that varies depending on different levels of tourism activity. For instance study by Purwono et al. [23] found an inverted N-shaped relationship between Tourism and emissions, wherein initially, with a rise in tourism, there is a fall in emissions, which then rises to fall again. The results are supported by the study of Paramati et al. [35], wherein region-wise the results are mixed, with the Western European Union portraying a negative impact of tourism on carbon emissions and a positive relationship in the Eastern European Union. Thus, this relationship is influenced by policies related to sustainable tourism in that region. Therefore, the existing literature fails to address how the relationship varies at different stages of tourism development. This variability suggests that a new approach is needed to capture the complex dynamics between tourism and emissions. To address this gap, the use of quantile regression has been chosen in this study, rather than relying on simple panel regression, which tends to provide uniform results across different levels of the relationship. Quantile regression allows to understand how the impact of tourism on carbon emissions changes at different points across the spectrum of tourism development.

The study thus provides important implications for policymakers across different economies with diverse institutional, technical, and emission profiles. A study by Chovancová et al. [36], for instance illustrated that even renewable energy, commonly regarded as a keystone to sustainable development, also has different influences on emission reduction in regions, and thus, localized policy measures are warranted. Similar heterogeneity is applicable to the tourism-emission nexus as well, where dependence only on average or mean-based models might obscure significant heterogeneity.

Notwithstanding the expanding literature on the tourism-emission nexus, the gaps remain. To begin, most current studies are based on linear models that do not account for heterogeneous impacts along the conditional distribution of emissions. Second, there is little work examining the moderating function of technological innovation in the relationship. Third, regional studies on the Indo-Pacific or Extended QUAD countries are largely untapped. Considering these constraints, the current research employs a panel quantile regression to yield a more detailed analysis and incorporates a moderating view employing technological innovation in filling the theoretical and empirical gap (Fig. 3).

3. Data and methodology

The study employs a comprehensive approach to evaluate the impact of tourism on carbon emissions in the EQUAD countries, incorporating a moderating variable (Technological Innovation) to better understand

the relationship. The study utilizes an extensive panel dataset covering the period from 2000 to 2020, ensuring robustness and reliability by encompassing a substantial timeframe. The selection of the variables is based on extensive literature and a brief description of the same is provided in Table 1.

The main goal of the research is to determine the influence of tourism activities on carbon emissions across EQUAD countries and evaluate how technological innovation moderates this relationship. The dependent variable is carbon emission (metric tons per capita) which is considered a significant indicator in the measurement of environmental impact and, hence, is important in the study of sustainability. In addition, it uses international receipts in current US dollars as an independent variable for tourism, which influences emissions differently depending on the presence of different moderating and control variables. Technological innovation (TI), represented by the research and

Table 1
Variables Used in the Study.

Variable	Description	Measurement	Type of Variable
Carbon Emission	Total carbon dioxide emissions from the burning of fossil fuels	Carbon dioxide (CO2) emissions excluding LULUCF per capita (t CO2e/capita)	Dependent
Tourism	Total receipts on international tourist arrivals	International tourism, receipts (current US\$)	Independent
Technological Innovation	R&D expenditure	Research and development expenditure (% of GDP)	Moderator
Gross Domestic Product	Economic output measured in constant 2015 US dollars	GDP (constant 2015 US\$)	Control
Renewable Energy Consumption	Energy consumption from renewable sources	Renewable energy consumption (% of total final energy consumption)	Control
Trade-Openness	The sum of exports and imports of goods and services as a share of GDP	Trade as a % of GDP	Control
Financial Development	Level of domestic credit available to the private sector	Domestic credit to private sector (% of GDP)	Control
Urbanization	The proportion of the population residing in Urban Areas	Urban population (% of total population)	Control

Source: World Development Indicators Database.
<https://databank.worldbank.org/source/world-development-indicators>.

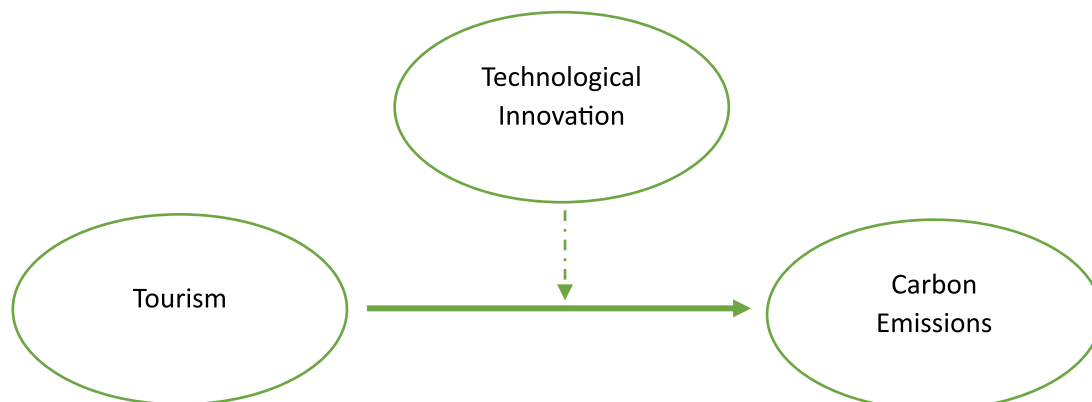


Fig. 3. Conceptual Model.

development expenditure as a percentage of GDP, serves as the moderating variable. The inclusion of TI as a moderator is based on the predicament that technological advancements can help in promoting sustainable ways of tourism, thereby reducing emissions [10]. The control variables include Gross Domestic Product (GDP) at constant 2015 US dollars, urban population as a percentage of the total population, renewable energy consumption as a percentage of total energy consumption, trade openness (trade as a percentage of GDP), and financial development (domestic credit to the private sector as a percentage of GDP).

The study examines cross-sectional dependency among the variables and determining the level of integration through the second-generation unit root test.

3.1. Cross-Sectional dependence test

To test cross-sectional dependency is necessary when it comes to panel data, because it allows to determine the correlation between different cross-section units. Ignoring this might result in skewed estimates and inconsistent findings [37]. Given the unbalanced structure of the panel dataset used in this study, characterized by varying time periods across countries, some widely adopted tests for cross-sectional dependence such as Pesaran’s CD test, scaled LM test, and the bias-corrected LM test could not be applied due to insufficient overlapping observations across panel units. In such cases, the Breusch-Pagan LM test remains a reliable alternative, as it does not require a strongly balanced panel. Therefore, this study employs the Breusch-Pagan LM test as a valid approach to assess the presence of cross-sectional dependence across countries.

Cross-sectional dependence was tested using the Breusch-Pagan LM test, which is suitable for panels with a small cross-sectional dimension and a moderate time period. The equation used for the CD test is provided here:

$$LM = \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^N T \cdot \widehat{\rho}_{ij}^2 \right)$$

Where T is the time dimension

N is the cross-sectional dimension.

$\widehat{\rho}_{ij}$ is the sample correlation coefficient of residuals between units *i* and *j*

3.2. Slope heterogeneity

To examine the presence of slope heterogeneity across panel units, we employ the Pesaran & Yamagata [38] test. The test helps determine whether slope coefficients are homogeneous across cross-sectional units, which is a critical assumption in panel regression models.

$$\widetilde{\Delta} = \sqrt{N} \left(\frac{N^{-1}S\% - k}{\sqrt{2k}} \right) \text{ and } \widetilde{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1}S\% - k}{\sqrt{\frac{2k(T-k-1)}{T+1}}} \right)$$

N: Number of cross-sectional units.

T: Number of time periods. k Number of regressors (excluding the intercept).

S % Sum of squared residuals or some related test statistic under the null hypothesis.

$\widetilde{\Delta}_{adj}$ accounts for small sample bias when T is not large.

Given the possible heterogeneity in structural characteristics, institutional frameworks, or policy regimes across countries/firms, testing for slope heterogeneity is essential to ensure the robustness of the estimated relationships. Slope heterogeneity, if ignored, can lead to incorrect policy implications as it assumes uniform responsiveness across units, which is rarely the case in real-world datasets.

3.3. Second generation unit root test

In regression it is necessary to ensure that the variables are stationary as if variables are non-stationary the results will be inefficient and spurious. So before proceeding for further analysis it is necessary to test for Unit root, and in case of cross-sectional dependence, traditional first-generation tests become unreliable as they are based on the assumption of cross-sectional independence. To address this issue, the study has used the second-generation panel unit root test given by Hashem Pesaran M. [39], known as the Cross-Sectionally Augmented IPS (CIPS) test.

This test extends the baseline ADF regressions by incorporating the average values across units for both the lagged levels and the first differences of each series to account for cross-sectional dependence. and thus it is especially appropriate for macro panels with spillovers or common shocks among units.

The test entailed computing the cross-sectionally augmented Dickey-Fuller (CADF) statistics for every cross-section and averaging them to derive the CIPS statistics.

3.4. Model estimation

In panel data analysis, heteroskedasticity, autocorrelation, and contemporaneous correlation between panel units can bias the standard error estimates and produce invalid inference. To counter this, the Panel Corrected Standard Errors (PCSE) approach, introduced by Beck and Katz [40], is utilized when the time dimension (T) is greater than or equal to the cross-sectional dimension (N), as it is in the present study. PCSE corrects for heteroskedasticity and contemporaneous correlation of error terms across panel units, providing accurate standard error estimates even in the presence of these violations. This renders PCSE particularly well-suited to macro-panel data environments with economic variables for countries or regions.

Moreover, the study employs Driscoll-Kraay standard errors to account for problems of cross-sectional dependence and serial correlation in the residuals, which are prevalent among macro-panel data. Driscoll & Kraay [41] developed this methodology to generate robust standard errors that hold even when residuals are correlated both over time and across units. In contrast to PCSE, Driscoll-Kraay standard errors are desirable when cross-sectional dependence and time autocorrelation are both an issue and do not need a highly balanced panel.

3.5. Quantile regression

To investigate the dynamic connections between economic, technological, and environmental variables, the study employs a quantile regression approach. It provides a detailed and robust analysis as it caters to the heterogeneous relationship among variables at different quantiles of the dependent variable distribution [42]. Quantile regression provides multiple response variables specific to every quantile, instead of providing a single estimate. It has a better estimation power over and above the linear regression as it can capture the non-linear relationship among the variables [43].

As our panel was heavily unbalanced (7 countries, 2000–2020), standard panel cointegration methods were unusable. As a result, the model was estimated with Panel Corrected standard Errors (PCSE) and Driscoll-Kraay standard errors to account for heteroskedasticity, autocorrelation, as well as possible cross-sectional correlation. In addition to that, quantile regression was used to preserve heterogeneous effects across the distribution of the dependent variable. This strong framework makes it possible to make valid inference under the existence of structural differences between countries and over time.

This study uses quantile regression because the impact of tourism on carbon emissions is expected to differ across varying levels of emissions. For example, tourism’s influence on carbon emissions in countries with lower initial emissions may contrast with its effect in nations with higher

emissions. By applying quantile regression, the study can account for these differences and offer a more detailed understanding of the relationship. A simple quantile regression equation used in the study is presented below:

$$Q_T(CO_{it}) = \alpha_T + \beta_T TO_{it} + \gamma_T TI_{it} + \delta_T(TO_{it} \times TI_{it}) + \sum_{k=1}^n \theta_{TK} CV_{it} + \epsilon_{it}^T$$

The model above provides the relationship between carbon emission (CO) at different quantiles (25 %, 50 %, and 75 %) for country i in the time period t. Coefficient β_T and γ_T reflects the effect of tourism and TI on carbon emission at different quantiles. $\delta_T (TO_{it} \times T I_{it})$ being the moderating term provides the effect of TI on the tourism-emissions relationship. The sum $\sum_{k=1}^n \theta_{TK} CV_{it}$ represents the impact of the control variables on carbon emissions at each quantile. The results of which are further tested for robustness using confidence ellipse.

A brief elaboration of the methods used in the study is presented in Fig. 4 below:

4. Results

The initial step in any data analysis involves identifying the essential features of variables used within the study. The results of descriptive statistics are stated in Table 2.

The mean carbon emissions (CO) are 9.74 CO2e metric tons per capita with considerable heterogeneity between countries and over time (ranging between 0.73 and 21.01), reflecting differences in the environmental footprint. GDP, expressed in trillion USD, has an average of 3.63, highlighting economic heterogeneity between the sampled nations. Renewable energy consumption (RE) has a mean of 18.22 % of the total energy, reflecting a steady trend towards sustainable sources of energy, although the figures differ considerably across economies (0.7 % to 57.7 %). Trade openness, averaging 59.21 % of GDP, reflects the economies' global linkage. The population in urban areas (UP) averages 69.07 %, underlining the urbanization trend. Tourism receipts are highly variable (1.4 to 242.2 billion USD), averaging 37.4, highlighting the uneven economic contribution of tourism. R&D spending (RD), a proxy for technological innovation, averages 2.22 % of GDP. Finally, financial development (FD) averages 122.73 % of GDP, pointing to

Table 2
Descriptive Statistics.

Variable	Mean	Std. Dev.	Min	Max	Unit
CO	9.74	6.33	0.73	21.01	CO2e metric tons per capita
GDP	3.63	5.58	0.09	20.2	Trillion USD
RE	18.22	15.68	0.7	57.7	% of total energy
Trade	59.21	37.25	19.56	164.7	% of GDP
UP	69.07	24.51	24.37	91.78	% urban population
Tour	37.4	58	1.4	242.2	Billion USD
RD	2.22	1.16	0.15	4.8	% of GDP
FD	122.73	50.65	28.34	218.34	% of GDP

Source: Authors' Computation.

differences in the depth of the financial sector. The extensive spread in the majority of variables warrants the application of quantile regression, which identifies differential effects across the distribution instead of concentrating on mean outcomes alone.

After descriptive statistics, the study tested for cross-sectional dependence. Before doing Quantile regression estimation, it is essential to verify the adequacy of the model which requires testing for CSD (Table 3).

Apart from the test for cross-sectional dependence (CSD), there is a need to control for slope heterogeneity to make panel data estimations robust. Slope homogeneity requires that the explanatory and dependent variables' relationship is constant across every cross-sectional unit (e.g., country), which in most macro-panel research with economies that are not alike is unrealistic. Failure to control for heterogeneity can result in biased and inaccurate conclusions. In order to overcome this, the research uses Pesaran and Yamagata's [38] slope heterogeneity test that

Table 3
Cross-Sectional Dependence Test.

Test	Statistic	P-Value
Breusch-Pagan LM	42.0000	0.0042

Source: Author's Computation.

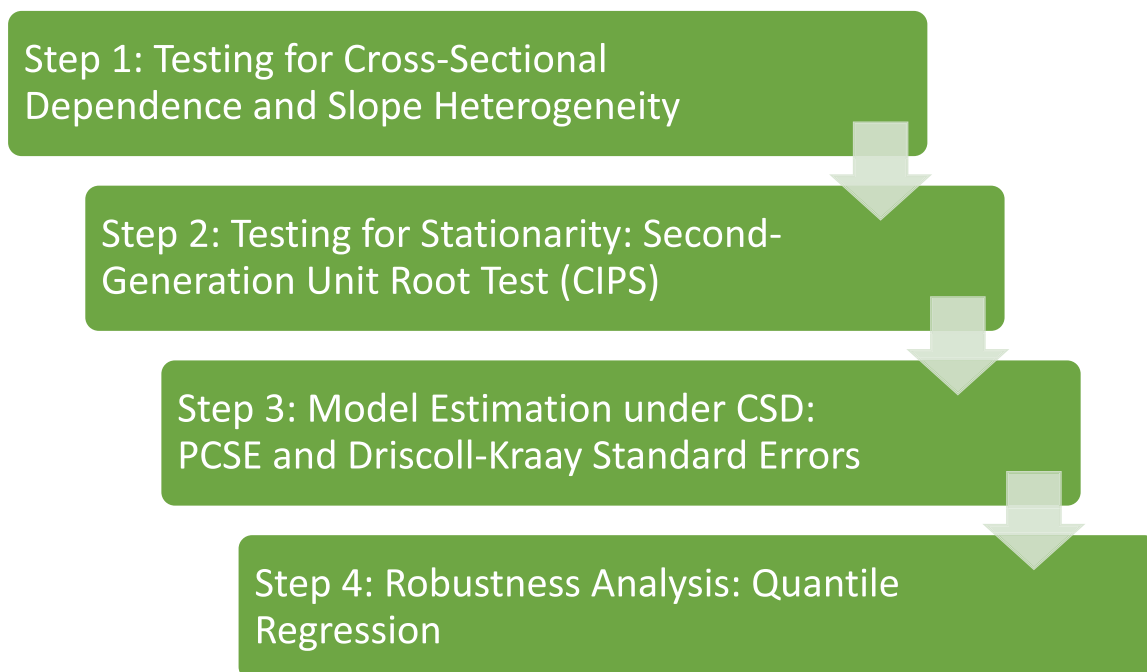


Fig. 4. Methodological Framework.

assesses if slope coefficients differ substantially between units. In case slope heterogeneity is established, it supports the use of models such as panel quantile regression capable of accommodating differential effects between observations and levels of distribution. This method recognizes the structural, economic, and institutional heterogeneity of the Extended QUAD nations, thus strengthening the validity of the estimated interactions between tourist arrivals, technological innovation, and carbon emissions (Table 4).

The significant heterogeneity in slope coefficients across countries highlights the contextual differences in how tourism, technological innovation, economic growth, and other factors influence emissions. Such differences necessitate the use of modeling approaches that can accommodate cross-sectional diversity.

The presence of cross-sectional dependence in the panel data asserts that there is a correlation in the error term across different cross-sectional units and hence first generation unit root (Levin-Lin-Chu, Im-Pesaran-Shin, and others) would fail to provide accurate results as they presume cross-section independence, hence in this case we need to use second-generation test (Table 5).

Given the relatively small cross-sectional dimension ($N = 7$ countries) and longer time series ($T = 20$ years), and evidence of cross-sectional dependence (CSD), we employed the Panel-Corrected Standard Errors (PCSE) estimator as proposed by Beck & Katz [40]. This approach corrects panel heteroskedasticity and contemporaneous correlation, and provide robust standard errors appropriate for macro-panel data structures.

The findings from the PCSE model (Table 6) confirm that although the direct impact of tourism on carbon emissions is statistically irrelevant, trade openness and GDP are positive with emissions in support of the growth-emissions and pollution haven hypotheses. This is because enhanced integration amongst economies backed by trade openness leads to a shift in energy-intensive and carbon emitting industries to economies with less stringent environmental laws thereby bringing an increase in their overall emissions.

On the other hand, renewable energy demonstrates a significant and negative correlation with emissions, emphasizing its potential for decarbonization. The tourism-technological innovation interaction term while not statistically significant at standard levels has a positive coefficient, indicating that innovation may have a role to soften the environmental impact of tourism.

To further confirm these results and mitigate concerns of cross-sectional dependence and autocorrelation, the research carries out a robustness check using Driscoll-Kraay standard errors in a fixed-effects specification (Table 7). This estimator is especially well-suited to panel data with $T > N$ and offers robust standard errors despite serial correlation, heteroskedasticity, and cross-sectional dependence. The outcomes are generally comparable: GDP and trade openness continue to be significant drivers of emissions, while renewable energy still has a reducing effect. Most importantly, the interaction term (tour_rd) becomes more statistically significant ($p = 0.106$), providing minor evidence to the hypothesis that technological innovation has the ability to mediate the tourism-emission interaction.

Therefore, the two-stage use of PCSE and Driscoll-Kraay estimators not only enhances the empirical robustness of the research but also confirms its central premise: technological advancement is a primary driver in making tourism more sustainable environmentally, particularly for the economies attempting to reconcile growth with reduction goals in emissions [44].

Table 4
Slope Heterogeneity Test.

Test Type	Statistic (Δ)	p-value	Adjusted Statistic (Δ_{adj})	p-value	Decision
Slope Homogeneity Test	2.7540*	0.0060	4.5670*	0.0000	Reject Null (Heterogeneous)

Null Hypothesis (H_0): Slope coefficients are homogeneous across panel units.
Source: Authors' Computation. (*significance level at 1 %).

Table 5
Panel Unit Root.

Variable	CIPS Value (At Level)	CIPS Value (At First Difference)	Level of Integration
ICO	-1.286	-3.285	I(1)
IGDP	-1.583	-2.918	I(1)
IRE	-1.029	-3.886	I(1)
ITrade	-1.400	-3.685	I(1)
IFD	-3.036	-	I(0)
IUP	-1.636	-2.35	I(1)
ITour	-1.045	-3.588	I(1)
IRD	-1.383	-2.810	I(1)

All values are significant at 5 %.

Table 6
Panel Corrected Standard Error.

Variable	Coefficient	Std. Error	P Value
tour	0.0037	0.0145	0.8000
gdp	0.7603**	0.1608	0.0000
rd	0.0551	0.0839	0.5110
re	-0.0938**	0.0328	0.0040
tr	0.0684*	0.0307	0.0260
fd	0.0055	0.0093	0.5550
up	0.3222	0.7779	0.6790
tour_rd	0.3819	0.2785	0.1700
_cons	-0.0482	0.0498	0.3330
rho	0.2455		

**significant at 1 %, *significant at 5 %.

Table 7
Robustness Check Using Driscoll-Kraay Standard Errors (Fixed Effects).

Variable	Coefficient	Std. Err.	P Value
tour	0.0069	0.0130	0.6020
rd	-0.0048	0.0864	0.9560
tour_rd	0.3180	0.1874	0.1060
gdp	0.7918**	0.1994	0.0010
re	-0.1126**	0.0369	0.0070
tr	0.0770*	0.0317	0.0250
up	-0.2417	0.7414	0.7480
fd	0.0195	0.0172	0.2720
_cons	-0.1114	0.0777	0.1680

**significant at 1 %, *significant at 5 %.

To further investigate the heterogeneous effects of economic and environmental variables on carbon emissions across different distributional points, we apply panel quantile regression with fixed effects as suggested by Koenker R. [45]. This method enables us to explore how the effects of explanatory variables vary across different portions of the lower (25th percent), median (50th percent), and upper (75th percent) quantiles of the conditional distribution of carbon emissions. In contrast to simple least squares (OLS) regression that merely estimates the mean effect, quantile regression picks up on distributional asymmetries and is therefore ideally placed to reveal non-linear relationships in environmental data.

With the panel nature of our data set of seven nations over an unbalanced time period, this method also corrects for unobserved country-specific heterogeneity with the penalized fixed effects estimator.

The model of panel quantile regression at 25th, 50th, and 75th

quantiles sheds light on the trends in how the effect of tourism and other control variables on carbon emissions differs across levels of emissions. The tourism coefficient is statistically insignificant at all levels, which suggests that tourism per se doesn't exert a strong direct effect on carbon emissions at lower, median, or higher levels of emissions. Nonetheless, the tourism and R&D interaction term is significant at the 25th and 50th percentiles, with positive coefficients (0.5556 and 0.5396, respectively), indicating that technological progress complements tourism's influence on emissions in lower- and medium-emitting environments, perhaps as a result of enhanced economic activity or infrastructure needs.

Renewable energy use has a persistently negative and substantial effect on emissions in all quantiles, in favor of the hypothesis that renewable energy reduces emissions, especially when emission rates are higher. GDP is positively significant, following the Environmental Kuznets Curve hypothesis by which economic growth first leads to higher emissions. Other controls such as trade openness, financial development, and urbanization have inconsistent or insignificant effects, implying restricted direct impact on emissions. The findings highlight the moderating influence of innovation and the role of renewable energy in constructing sustainable tourism-emission dynamics (Table 8).

5. Discussion

The fundamental question of this research discusses the influence of technological innovation in moderating tourism's impact over carbon footprint with respect to EQUAD countries. Rising GDP with a substantive increase in urbanization, trade, and tourism amongst others have led to an exorbitant rise in energy demand leading to rising emissions across the globe [43]. The rising ecological footprints forced countries to make a shift towards cleaner sources of energy which require technological upgrades and increased efficiency. Tourism also contributes to rising emissions. However, it has the potential to mitigate environmental degradation by transitioning to sustainable practices, in order to reduce its environmental impact while continuing to support economic growth.

The empirical results from the quantile regression analysis, incorporating technological innovation as a moderator, revealed a direct relation between tourism and emissions across various carbon footprint levels. The results suggest that increased tourism has been associated with a rise in emissions across a few quantiles in the sample countries, with technological innovation playing a crucial moderating role. The reason for increase in emissions can be because of the rise in infrastructure demand that offsets the benefits of using clean energy and enhanced efficiency in the tourism sector [46]. Results are similar to the study by Zhong et al. [47] that highlighted how tourism in China led to a subsequent rise in emissions from 2012 to 2017 owing to rise in electricity demand from transport and accommodation that outweighed the benefits of cleaner technology. Another study by Zhou & Choi [48] highlighted how there is a non-linear inverted U shaped relationship between tourism receipts and GHG emission. They further showed that green technological innovation moderates this relationship by flattening

the curve, thereby reducing the negative environmental impact of tourism to some extent in OECD economies.

The findings of this study integrate with and diverge from prior studies in important ways. The moderating role of technological innovation in enhancing tourism's ability to lower emissions are similar to what is documented by Nazneen et al. [10]. In addition to advancements in technology, other control variables such as renewable energy consumption and income levels (proxied by GDP) should also assist in mitigating deterioration of environment in the extended QUAD nations.

The relationship between GDP and emissions is found to be strong and consistent across different emission levels, challenging the applicability of the EKC hypothesis. These findings contradict those of Fafurida et al. [49], who reported that GDP per capita and international flight passenger volume have positive effects on emissions, while foreign tourist visits have a negative effect.

While, trade openness has been related to increase in the emissions level, supporting pollution haven hypothesis. This suggests that pollution related industries might have a tendency in relocating themselves to those countries having less stringent environment related regulations, thereby exacerbating emissions in the sample countries.

Results of the study highlight how to mitigate the impact of tourism on the environment, efficient policies need to be devised that focus on research and development, and technological innovation thereby making a shift toward sustainable tourism practices [50,51]. Governments around the world need to prioritize sustainable tourism within global objectives. Evidence suggests that economies often experience an initial rise in emissions when technological advancements occur across sectors like tourism. However, over time, these innovations can lead to significant emission reductions, supporting the transition toward sustainability [7]. In addition to promoting technological advancements across different spheres, the adoption of taxes for nongreen sources of energy can also help in making a shift toward a sustainable future. For instance, implementing a carbon tax policy in case of tourism industry can serve as a useful measure in promoting sustainable tourism. It can encourage the adoption of energy-efficient practices in accommodations, travel, and overall energy usage within the industry thereby helping the countries maximize the positive impact of tourism without hampering the environment (J [52]).

6. Conclusions

The findings of this study have direct relevance for policies seeking to balance tourism-driven economic growth with the need to reduce carbon emissions in the EQUAD economies. While technological innovation plays a significant moderating role in the tourism-emissions relationship, the results suggest that its benefits for the environment depend on how it is directed. Innovation policies should therefore be explicitly aligned with low-carbon objectives in tourism.

First, tourism development strategies should be supported by incentives for research and development in low-emission technologies. Examples include renewable-powered accommodations, electrified and fuel-efficient transport systems, and digital tools for managing energy

Table 8
Panel Quantile Regression Results.

Variable	Coef. 0.25	Std. Err.	P Values	Coef. 0.50	Std. Err.	P Values	Coef. 0.75	Std. Err.	P Values
tour	-0.0080	0.0147	0.5850	-0.0046	0.0131	0.7260	0.0004	0.0194	0.9850
rd	0.0414	0.1280	0.7460	-0.0082	0.1139	0.9430	-0.0791	0.1694	0.6410
re	-0.0729*	0.0375	0.0520	-0.0845**	0.0333	0.0110	-0.1011**	0.0494	0.0410
tr	0.0412	0.0478	0.3890	0.0501	0.0423	0.2370	0.0628	0.0628	0.3170
fd	0.0073	0.0393	0.8540	0.0109	0.0348	0.7530	0.0162	0.0515	0.7540
tour_rd	0.5556**	0.2598	0.0320	0.5396**	0.2296	0.0190	0.5167	0.3402	0.1290
up	0.1091	0.8176	0.8940	0.0014	0.7229	0.9990	-0.1528	1.0715	0.8870
gdp	0.8640***	0.2486	0.0010	0.8489***	0.2197	0.0000	0.8272**	0.3255	0.0110

***significant at 1 %, **significant at 5 %, *significant at 10 %.

and resource use in tourist facilities. Funding programmes for R&D should include sustainability criteria so that technological advances directly reduce the carbon intensity of tourism activities.

Second, renewable energy use shows a consistent negative association with emissions across all quantiles, making it a reliable tool for emission reduction in tourism. Policies should prioritize its integration into tourism-related infrastructure through measures such as tax credits, concessional loans, or minimum renewable energy requirements for hotels, airports, and leisure sites. This would help lower the sector's emissions while improving operational efficiency.

Third, the positive relationship between trade openness and emissions indicates that without adequate safeguards, cross-border economic activity can contribute to environmental pressure. Trade and investment agreements that cover tourism should include binding environmental standards and regular monitoring to ensure that expansion in tourism does not come at the cost of higher emissions.

Finally, the heterogeneity observed in the tourism–emissions relationship across the EQUAD countries suggests that policies need to be adapted to national contexts. Countries at different emission levels or with different institutional and economic structures will require tailored approaches. At the regional level, cooperation among EQUAD members could focus on sharing low-carbon tourism technologies, operational best practices, and financing models. Such collaboration could speed up the adoption of sustainable solutions and narrow the gap in environmental performance among member countries, as to ensure green growth it is necessary to make a paradigm shift towards sustainable sources [23].

In order to accomplish this, one should embrace technological innovation to promote more efficient energy resources for mitigating the emissions as concluded from the study. The study though impactful in the results still cannot be exhaustive and hence there is always scope for some future research. A few such gaps that can be addressed in future studies are highlighted in this section. Future studies can make a comparison between a few developed and underdeveloped economies along with identifying the key factors that influence the agreement with sustainable activities in these regions. Comparative studies between developed and developing economies could impart insightful information to deal with distinct issues along with prospects faced by each to implement sustainable technologies. Additionally, future research could delve into the role of governmental guidelines, cultural contexts, as well as financial incentives to facilitate transition to green growth. Moreover, investigating the effectiveness of international cooperation and technology transfer in reducing the green growth disparity between nations could offer crucial guidance for policymakers and global stakeholders.

CRediT authorship contribution statement

Shikha Daga: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kiran Yadav:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bhavna Yadav:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniele Bregoli:** Writing – review & editing, Writing – original draft, Validation, Data curation. **Marco Ciro Liscio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Data curation. **Paolo Sospiro:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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