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Uncovering the interconnectedness of tourism growth, green technological advancements and climate change in prominent Asian tourism destinations

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ABSTRACT

This study examines the relationship between tourism development, green technological innovation, and CO2 emissions in Asia's top tourist destinations from 1990 to 2022. It uses advanced statistical methods like CS-ARDL and Dumitrescu-Hurlin causality tests to explore the environmental impacts of tourism growth and technological change. Key findings reveal that while tourism and technological advancements initially increase CO2 emissions, they ultimately contribute to reductions when a certain innovation threshold is surpassed, supporting the Innovative Claudia Curve Theory. The research highlights significant regional variations in green technological innovation, underscoring the importance of tailored sustainable tourism strategies. This study contributes to understanding sustainable tourism development in Asia, emphasizing integrating green technology into tourism practices for effective climate change mitigation. The study's findings underscore the critical importance of data-driven policymaking in advancing global efforts toward sustainable tourism, demonstrating how informed strategies can effectively respond to the challenges posed by climate change.

1. Introduction

The rising temperatures caused by climate change are expected to profoundly impact freshwater availability, food security, and energy availability, particularly for the most vulnerable populations in developing countries and small island states. To counteract these effects, adaptation and mitigation efforts to combat climate change are now a worldwide trend. In this global context, the United Nations (UN) *2030 Sustainable Development Program* has identified climate change as a critical issue that "weakens all countries' ability to achieve sustainable development." Sustainable Development Goal 13[1] "*take immediate action to address climate change and its effects*", is grounded in the United Nations Framework Convention on Climate Change (UNFCCC). It advocates for integrating climate change mitigation into national policies, enhancing education and awareness, and building institutional capacity for adaptation, mitigation, and early warning. These efforts are particularly relevant in the context of tourism, a sector deeply intertwined with climate change.

Tourism and climate change are closely interrelated, as outlined by various studies (; Becken et al., 2020; Doran et al., 2022; Gössling et al., 2023; Gössling & Scott, 2018; Higham et al., 2022; Loehr & Becken, 2021; Loureiro, Guerreiro, & Han, 2021; Peeters et al., 2018, 2019; Rice, Cohen, & Scott, 2022; Rutty et al., 2015; Scott et al., 2016; Scott & Becken, 2010; Scott & Gössling, 2021; Scott, Gössling, & Hall, 2012; Scott, Gössling, & Comisión Europea de Turismo, 2018; Scott, Hall, & Gössling, 2016; Scott, Hall, & Gössling, 2019; Spasojevic, Lohmann, & Scott, 2018; Steiger et al., 2019). These studies highlight the dual role of tourism as both a contributor to and a victim of climate change. A growing body of research is aimed at evaluating the extent to which climate change has been integrated into tourism policies (Becken et al., 2020, 2021). Some researchers suggest that the rise of "flight shame" highlights the role of tourism in contributing to climate change and the need for sustainable tourism practices (Becken et al., 2021; Doran et al., 2022; Mandić, Walia, & Rasoolimanesh, 2023). A review of tourism and climate change mitigation indicates that carbon management is an essential strategy for mitigating the impact of tourism on climate change (Gössling et al., 2023). However, global tourism leaders face challenges in decarbonizing the industry (COP28, 2023; Gössling & Scott, 2018).

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[1] https://sdgs.un.org/goals/goal13.

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This impasse underscores the need to translate climate science into practical, actionable tourism policy (Higham et al., 2022; Mandić, Spenceley, & Fennell, 2024; Peeters et al., 2018; Peeters et al., 2019).

Given this context, our study examines Southeast Asia's leading tourist destinations (hereafter referred to as Asian destinations), noted for their substantial impact on global tourism and their susceptibility to climate change. By investigating the effects of tourism development, green technology, and structural changes on the environment in these destinations, our study seeks to provide empirical evidence of these factors' environmental consequences.

The study examines these factors from three different perspectives.

(A) Environmental impact analysis: This study investigates the environmental impacts of green technological innovation, tourism development, and structural change in several of Asia's prominent tourist destinations. Our analysis provides empirical evidence crucial for understanding these factors' environmental effects, contributing to the dialogue on Asia's transition to green technology and renewable energy in tourism. This transition is vital for carbon emission reduction and sustainable tourism. By providing empirical support for this investigation, this study offers unique insights into the specific ways in which green technology and renewable energy adoption can be integrated into tourism development strategies in Asia.

(B) Tourism's role in CO2 emissions: The study examines the effects of tourism growth and structural changes on CO2 emissions, which is a crucial step in understanding the impact of these factors on environmental quality. The research employs advanced analytical techniques, including error correction-based panel cointegration tests, cross-sectional augmented autoregressive distributed lag (CS-ARDL), and Dumitrescu-Hurlin (DH) causality, to evaluate the impact of observed indicators in carbon reduction models. These estimators provide unbiased estimates critical for deducing potential policy implications for achieving a sustainable environment in Asia's top tourist destinations. Throughout these rigorous analytical methods, the study seeks to quantify the link between tourism growth, structural changes, and CO2 emissions, enabling a more informed and evidence-based approach to sustainable tourism policy-making. Furthermore, the study's use of CS-ARDL is particularly noteworthy as it allows for assessing long- and short-run estimations while accounting for corrections to the model's short-run equilibrium distortions. This approach enables a more nuanced understanding of the impact of tourism growth and structural change on CO2 emissions in Asia's dominant tourist destinations.

(C) Innovative Claudia Curve Theory (ICC) exploration: The research seeks to validate the ICC theory in the context of Asia's most popular tourist destinations. The ICC theory proposes a nonlinear relationship between CO_2 emissions and technological innovation, suggesting that an initial increase in emissions may occur before innovation leads to emission reductions. The findings from this study will significantly contribute to the existing knowledge base and assist future researchers in looking at the issue from a different perspective than the conventional one, which maintains that any increase in CO_2 emissions will halt the innovation process. By exploring the implications of the ICC theory, this study offers a novel framework for understanding the dynamics of technological innovation and its potential for mitigating CO_2 emissions in the tourism industry.

The study's central research questions, framed within this cohesive theoretical framework, are:

- What are the environmental impacts of green technological innovation, tourism development, and structural changes in Asia's key tourist destinations?
- How can tourism development strategies effectively integrate green technology and renewable energy in these regions?
- What is the dynamic relationship between tourism growth, structural change, and CO2 emissions in these destinations?
- How does the ICC theory apply in the context of Asian tourism, and what insights does it offer for technological innovation and CO2 emission reduction?

1.1. Theoretical background

1.1.1. Tourism and climate change

The tourism industry has evolved into a sector that contributes significantly to economic expansion, and its viability is dependent on inputs that help the economy maintain or improve its overall financial health (Paramati, Alam, & Chen, 2017). An influx of tourists can benefit a nation's economy in many ways, including job creation, attracting foreign direct investment to improve tourism quality, and increasing national and household revenue (Sharif, Afshan and Nisha, 2017; Sharif, Saha, & Loganathan, 2017; Su, Umar, & Khan, 2021). Global tourism in emerging economies expanded twice as fast as in developed nations between 1995 and 2007 (UNWTO, 2007),[2] and least-developed nations heavily depend on tourism to generate desperately needed foreign currency (Gössling, Hall, & Scott, 2009).

The tourism sector is vulnerable to the impacts of climate change, including sea level rise, natural disasters, and changes in temperature and precipitation patterns (Scott et al., 2019). Consequently, the impact of climate change on the tourism industry has become a crucial global agenda in recent years. Gössling, Scott, and Hall (2020) and the United Nations Conference on Trade and Development (UNCTAD) (2020)[3] reported that the "COVID-19" pandemic traumatized the worldwide tourism sector, and future climate catastrophes will make this even worse. Further, the changing environment impacts demand, planning, and operations in the tourist business (Ma & Kirilenko, 2020). According to Scott (2021), "*any occurrence that would affect global economic growth, growing food insecurity, destroying health, rising death risks, high transportation costs, threatening cultural heritage, and increased security risk is not helpful to tourism development*". Despite international efforts to reap its benefits, international tourism as a strategy for economic progress has come under scrutiny (Chok, Macbeth, & Warren, 2007; Hall, 2007; Hall, 2010; Zapata, Hall, Lindo, & Vanderschaeghe, 2011; Hall, Scott, & Gössling, 2013; Telfer & Sharpley, 2015). Critics argue that an influx of tourists can increase the rate of environmental degradation and boost economic activity, leading to higher energy usage (Raza, Sharif, Wong, & Karim, 2017; Shi et al., 2020). In 2010, Peeters and Dubois (2010) evidenced that tourism was responsible for 4.4% of all global greenhouse gas emissions, and by 2018 (Lenzen et al., 2018), this share increased to 8%. According to a recent study (World Tourism Organization and International Transport Forum, 2019), transport accounts for 75% of the total emissions produced by the tourism sector. In Asia, most of these emissions (81%) are generated by intraregional tourist travel. Unfortunately, projections indicate that by 2030, both intraregional and interregional travel, particularly long-haul trips, will significantly increase, exacerbating emissions under the current development and transportation plans. This highlights the need for urgent action to discuss and address the environmental impact of the tourism industry, especially in terms of transport emissions and developing and emerging destinations, to ensure sustainable tourism practices and mitigate the impact of climate change.

The tourism sector's efforts toward mitigating climate change suffer from a lack of policy integration and coordination, as policies and actions are often disconnected and insufficient (Becken et al., 2020). Carbon management strategies need to consider different scales, scopes, stakeholders, and strategies to be effective, taking into account the individual, business, and destination levels, direct and indirect emissions, and technology and behavior change (Gössling et al., 2023). However,

[2] https://www.e-unwto.org/doi/book/10.18111/9789284413539.

[3] https://unctad.org/annual-report-2020.

tourism leaders hold differing views on the feasibility and urgency of decarbonization, with many perceiving it as expensive and challenging to implement (Gössling & Scott, 2018). For example, climate science is not effectively translated into tourism policy and decision-making in the Australasia region, leading to inadequate action on climate change mitigation (Higham et al., 2022). Simultaneously, the International Energy Agency's roadmap to net-zero emissions by 2050 requires a coordinated effort among industry, government, and tourists to achieve this goal (Scott & Gössling, 2021). Therefore, integrating climate science and tourism policy, enabling information sharing, and best practice adoption among various stakeholders is paramount (Loehr & Becken, 2021).

1.1.2. Green technology innovation and structural change

The use of green technology innovation has been widely recognized as an effective way to reduce CO2 emissions and achieve carbon neutrality. Recent eco-friendly technology developments have led to a significant decrease in CO2 emissions globally (Nikzad & Sedigh, 2017; Weina, Gilli, Mazzanti, & Nicolli, 2016), and many experts have drawn attention to new energy technologies due to growing concerns about climate change (Nawaz et al., 2021; Su, Naqvi, Shao, Li, & Jiao, 2020; Umar, Ji, Kirikkaleli, & Xu, 2020). Despite the potential benefits of investing in clean technologies that boost productivity and help the environment, the high cost of these innovations makes them unattainable for many businesses (Ibrahim, Ajide, Usman, & Kousar, 2022). Limited strategic options, such as supply chain collaboration, organizational agility, and green business practices, are available other than investing in cutting-edge technology (Ahmed, Wang, Mahmood, Hafeez, & Ali, 2019; Najmi & Khan, 2017). However, it is important to note that achieving operational gains is only possible if the business increases its innovation capacity in each scenario (Ahmed, Asghar, Malik, & Nawaz, 2020; Ahmed, Najmi, & Khan, 2020). The government has a critical role to play in supporting ecological innovation and ensuring environmental compliance, whether at the corporate or state level (Ahmad, Muslija, & Satrovic, 2021; Su et al., 2021).

The current model for structural change suggests that the secondary sector is more harmful to the environment than the tertiary sector; as a result, removing the secondary sector would improve the ecological quality (Grossman & Krueger, 1991, 1995). The economy's expansion appears to be transitioning from manufacturing and agriculture to the services sectors when viewed from this vantage point. This ensures that the economy will change from its current condition, which is tremendously harmful to the environment (both primary and secondary), to one that is environmentally sustainable (tertiary). The pollution rate in the industrialized sector is much higher than in the agricultural sector. There may be a shift toward the service sector as people's expectations of their living space rise in tandem with their income (Ali et al., 2020; Ali, Rahman, Zahid, Khan, & Kumail, 2020). Shifting the site of economic activity and improving the country's institutional framework may help slow environmental deterioration. A key goal of the structural change hypothesis is to encourage developing countries to diversify their domestic economies by emphasizing the industrial and service industries more than agriculture. This strategy incorporates cutting-edge, high-performance technology that primarily reduces reliance on non-renewable energy sources and promotes renewable energy. Major advancements in social and economic circumstances, international commerce, resource use, consumer spending, and industrial output are often attributable to structural shifts.

Several studies have extensively explored the intricate relationship between green technology innovation, structural change, tourism development, and climate change, shedding light on crucial insights relevant to our investigation. In their study, Gössling et al. (2020) and Scott and Gössling (2022) conducted a comprehensive examination of the role of green technology and sustainable tourism practices in reducing carbon emissions from the tourism industry. Their findings provided empirical evidence of the efficacy of incorporating eco-friendly measures in tourism operations, emphasizing the potential for mitigating the industry's environmental impact. Further, Fang, Yin, and Wu (2018) highlighted the importance of understanding the interplay between climate change and the tourism sector, underlining the need for integrating climate change considerations into tourism policy and decision-making processes. Michailidou, Vlachokostas, and Moussiopoulos (2016) employed multiple-criteria decision analysis to assess mitigation and adaptation options in tourism areas. Their research offered valuable insights into strategic approaches to address climate change impacts in tourism destinations, providing a foundation for effective and sustainable planning and development. Scott, Hall, and Gössling (2016) and Scott et al. (2016) reported on the Paris Climate Change Agreement and its implications for tourism, emphasizing the global significance of climate change mitigation efforts and underscoring the tourism industry's responsibility to contribute to the broader climate goals set by international agreements. Sheller (2021) discussed reconstructing tourism in the Caribbean through mobility justice, highlighting the need for sustainable practices that consider social and environmental justice aspects. This perspective brings attention to the equitable distribution of tourism benefits and environmental impacts on local communities. Steiger, Knowles, Pöll, and Rutty (2022) provide insights into the vulnerabilities and challenges faced by mountainous destinations. Their findings underscore the urgency of implementing adaptive measures to protect these fragile ecosystems and maintain sustainable tourism practices. Lenzen et al. (2018) provided valuable insight into global tourism's carbon footprint, quantifying tourism's environmental impact and emphasizing the significance of carbon reduction strategies in the industry's sustainability efforts. Further, another relevant study by Ali, Rahman, et al. (2020) and Ali et al. (2020) delved into the impact of structural change on the environment and explored the potential for the shift to the tertiary sector to promote sustainable development. Their findings highlight the need for economic diversification and sustainable development pathways that prioritize environmental stewardship. Likewise, the study by Higham, Ellis, and Maclaurin (2019) explored the connection between tourism development and climate change, underscoring the need for sustainable tourism practices to mitigate the industry's impact on the environment. Their research emphasizes the imperative of aligning tourism development with climate change mitigation and adaptation strategies. Collectively, these studies affirm the interconnected nature of green technology innovation, structural change, tourism development, and climate change. They emphasize the essential role of a coordinated effort from various stakeholders in achieving sustainable development goals and provide valuable insights to inform our investigation into the effects of tourism development, green technology, and structural changes on the environment in Asia's most popular tourist destinations.

1.1.3. Focus on Asia

The research conducted by Tang, Zhong, Fan, and Cheng (2015); Tang, Zhong, and Ng (2017); Tang, Zhong, and Jiang (2018); Tang, Zheng, and Ng (2019); Tang, Zheng, and Zhong (2022); Tang, Han, and Ng (2023) serves as a cornerstone for understanding the intricate relationship between tourism development and environmental sustainability in Asia, emphasizing the critical need for green development in tourism, particularly in the context of ecological conservation, energy efficiency, and carbon emission. Amidst the backdrop of Asia's burgeoning tourism sector, which has witnessed remarkable growth and global appeal in recent years, there are growing concerns about the long-term sustainability of this expansion. The research by Tang et al. illuminates these concerns and emphasizes the criticality of weaving

Table 1
Variables and data description.

Variables	Acronym	Measurement unit	Sources of Data
CO_2 emissions	CO_2	CO2 emissions kilo tonnes (kt)	WDI[a]
Tourism Development	T&T	Travel and Tourism direct contribution to GDP (%)	WTTC[b]
Green technological innovation	GTI	% of multiple registered environmental-related technologies	OECD[c]
Structural change	SC	Agriculture, industry, and services value-added as % of GDP	WDI
Economic growth	GDP	GDP per capita (constant 2015 US$)	WDI
Renewable energy	REC	Hydro, solar, geothermal, wind, and tide Million tons of oil Equivalent	BP Statistics[d]

[a] See for data; https://databank.worldbank.org/source/world-development-indicators.
[b] See for data; https://www.statista.com/statistics/233223/travel-and-tourism–total-economic-contribution-worldwide/.
[c] See for data; https://stats.oecd.org/#.
[d] See for data; https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

sustainable practices into the fabric of the tourism industry to address its increasing environmental impact.

This rapid growth, however, does not come without its challenges. As Peng, Song, Crouch, and Witt (2015) outlined, this sector's future hinges on strategic investments and a keen focus on economic factors. Additionally, the unpredictable nature of climate change (Colmer, Martin, Muûls, & Wagner, 2022; Giuliani, Lamontagne, Hejazi, Reed, & Castelletti, 2022) and the complexity of Asia's environmental issues, described as "wicked problems" by Carson (2010) and Stern (2004), further complicate the path to sustainable growth. These challenges highlight a gap that must be bridged – the increasing divide between private gains and social costs, which can only be addressed through effective environmental management and governance. While strides have been made toward mitigating the impacts of climate change, Asia continues to grapple with persistent environmental vulnerabilities.

In light of these insights, the implementation of adaptation and mitigation measures in critical sectors such as tourism is highly relevant for researchers and policymakers (Kärkkäinen et al., 2020; Waheed, Fischer, & Khan, 2021). Both domestic and global efforts are necessary to address the challenges posed by climate change, as it is crucial for the world's economic and social progress to prepare for its consequences. By developing new national laws, regulations, and institutional frameworks, as well as frameworks for participation, policymaking, and execution, countries can address their vulnerabilities and promote sustainable development.

This study examines the tourism industry in several Southeast Asian countries. Specifically, we selected Malaysia, Thailand, Singapore, the Philippines, Indonesia, Pakistan, India, and China, all of which rank among Asia's top ten most frequently visited countries (World Tourism Organization, 2021). While Pakistan may not be as well-known as some of the other destinations on the list, it has recently experienced an increase in tourism, particularly in regions such as Gilgit-Baltistan, which is famous for its natural beauty and adventure tourism opportunities (Hussain, Mandić, & Fusté-Forné, 2024). Therefore, it was deemed appropriate to include it in the study. Unfortunately, Myanmar, Laos, Cambodia, and Vietnam were excluded from the study due to a lack of available data.

2. Materials and methodology

2.1. Compilation of data and theoretical model

The current study investigates yearly statistics for the balanced panel data of the major tourist destinations in Asian[4] countries from 1990 to 2022.[5] This empirical study employs a neoclassical framework and a Hicks-neutral technological process that utilizes the conventional Cobb-Douglas production function presented as:

$$Y_t = F(K_t, AL_t) \quad (1)$$

Where Y_t denotes real GDP per capita, AL_t denotes effective labor, and K_t denotes capital land. Given that human economic and commercial activities are the primary source of CO_2 emissions and are also widely acknowledged as the primary cause of environmental deterioration, the functional form of CO_2 emissions can be stated as follows:

$$CO_2 = \nu(F(Y_t)) \quad (2)$$

where ν is the rate at which CO_2 is released by the production process.

Multiple human activities are blamed and implicated for the increasing CO_2 concentrations in the atmosphere; thus, the study considers other factors like tourism growth, environmentally friendly technological advancements, and structural changes. Starting with the development of green technology, recent changes in global warming have sparked new interest in how green technology can be used to stop the steady rise of CO_2 emissions. In particular, the latest resolutions made at the United Nations Climate Change Conference [COP26] provide strong evidence of how technology can help reduce the effects of global warming. There is a plethora of empirical proof that new, eco-friendly technologies help the planet lower CO2 emissions and make the environment healthier (Abbasi, Adedoyin, Radulescu, Hussain, & Salem, 2022; Khan, Ibrahim, Al-Amin, & Yu, 2022; Khan, Khan, & BiBi, 2022). The rationale behind this effect is that green technical advancements enable ecologically responsible production. It is argued that implementing novel technologies with a zero-waste approach enables greener production, and these innovations potentially benefit the ecology worldwide (Sadiq & Wen, 2022; Sadiq et al., 2023).

Tourism development may also boost economic growth; however, it may also accelerate the deterioration of the environment and the pollution of industrial sources (Liu, Kumail, Ali, & Sadiq, 2019). The inclusion of tourism development in a discussion about the environment and economic growth is justified because it will quicken the economic growth rate (Kumail, Ali, Sadiq, Wu, & Aburumman, 2020) and the environmental performance dynamics.

Similarly, empirical evidence has hinted that the agricultural, manufacturing, and service sectors all contribute to CO_2 emissions. Structural change describes the development of an economy from the concentration of contributions in agriculture to manufacturing and finally to the services sectors (Usman et al., 2021). Recent statements under the global advocacy for clean energy have echoed the prominence of renewable energy in the struggles to moderate the rising volume of air pollution and help achieve the goal of a carbon-neutral environment by 2050. Renewable energy has been proven to be very successful in a large number of empirical research regarding mitigating CO_2 emissions (Huang, Haseeb, Usman, & Ozturk, 2022; Sadiq & Wen, 2022).

The following is a relationship that can be drawn between the study's variables:

$$CO_2 = f\left(T\&T, GTI, GTI^2, SC, GDP, REC\right) \quad (3)$$

[4] Malaysia, Thailand, Singapore, Philippines, Indonesia, Pakistan, India, China. Myanmar, Laos, Cambodia, and Vietnam are excluded due to lack of data availability.
[5] Data accessibility for majority of variables limit the study period to 1990–2022 with 264 observations ($n = 8$, $t = 33$).

The study's variables were logarithmised to prevent outlier effects and homoscedasticity. Therefore, the log-transformed econometric model is established as follows:

$$LnCO_{2it} = \alpha_0 + \alpha_1 LnT\&T_{it} + \alpha_2 LnGTI_{it} + \alpha_3 LnGTI_{it}^2 + \alpha_4 LnSC_{it} + \alpha_5 LnGDP_{it} + \alpha_6 LnREC_{it} + \varepsilon_{it} \quad (4)$$

Where CO_2, $T\&T$, GTI, SC, GDP, and RE represent carbon emissions, travel and tourism contribution to GDP, green technology innovation, structural change, economic growth, and renewable energy usage, respectively. The GTI^2 is included to test the Claudia curve theory between CO_2 emissions and technological expansion. The Innovation Claudia Curve (ICC) theory predicts that although introducing environmentally friendly technologies will increase CO_2 emissions in the short term, subsequent developments will precede emissions reduction in the long run. α_0 is the intercept and ε_{it} is the error term, α_1 to α_6 are the slope coefficients of CO_2, $T\&T$, GTI, GTI^2, SC, GDP and RE, respectively. Table 1 lists the observed variables, their measurement units, and their respective databases.

2.2. Econometric techniques

The model in this article is estimated using a panel econometric approach. This section illustrates the underlying econometric process employing several techniques, including cross-sectional dependence (CSD), slope coefficient homogeneity (SCH), panel unit root, cointegration techniques, long-term elasticity estimators, and short-term causality among the variables.

2.2.1. CSD and SCH tests

In panel data econometrics, CSD is a critical issue that needs to be addressed to provide accurate results and select estimators appropriate for unit roots, cointegration, and long-run effects. Because of the global economy's interconnection and socioeconomic integration, CSD occurs in variables reflecting shock transmission between cross-sections (countries). To do this, we used the Lagrange Multiplier (LM) of Breusch and Pagan (1980), and the bias-corrected scaled LM of Baltagi, Feng, and Kao (2012) tests based on the null hypothesis of cross-sectional independence to determine whether or not CSD exists in the variable that was modelled. These tests are appropriate when T > N, as in this investigation. The estimated test statistics for Breusch-Pagan LM & Bias-corrected scaled LM is as follows:

$$\text{Breusch-Pagan LM} = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}^2 \quad (5)$$

$$\text{Bias-Corrected scaled LM} = \sqrt{\frac{1}{N(N-1)}}\left(\sum_{i=1}^{N-1}\times\sum_{j=i+1}^{N}\left(T\widehat{\rho}_{ij}^2\right)\right) - \frac{N}{2(T-1)} \quad (6)$$

Where $\widehat{\rho}_{ij}^2$ describes the cross-sectional dependency of i and j nations' data series as determined using regression with ordinary least squares. T denotes temporal cross-section and N panel cross-section.

In addition to CSD, the panel nations differ in their energy infrastructure, population, tourism development, and technological dissemination. Each nation's unique characteristics cause these similarities in slope coefficients across countries. To verify the validity of models with heterogeneous slopes, we use the two test statistics ($\widetilde{\Delta}$ and $\widetilde{\Delta}_{adj}$) proposed using the method developed by Pesaran, Ullah, and Yamagata (2008) to analyze slope homogeneity:

$$\widetilde{\Delta} = (N)^{\frac{1}{2}}(2k)^{\frac{-1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right) \quad (7)$$

$$\widetilde{\Delta}_{adj} = (N)^{\frac{1}{2}}\left(\frac{2k(T-K-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - 2k\right) \quad (8)$$

Where $\widetilde{\Delta}$ and $\widetilde{\Delta}_{adj}$define the variance and bias-adjusted variance, respectively. k refers to the number of repressors.

2.2.2. A panel unit root tests

The next major obstacle is to investigate the process of the variables becoming stationary. When conducting stationary tests, choosing an appropriate unit root test is imperative based on the outcomes of CSD tests. When CSD is present, conventional tests for the unit root produce misleading results. As a result, under the null assumption of a unit root, Pesaran's (2007) cross-sectional Im-Pesaran-Shin (CIPS) and cross-sectional augmented Dickey-Fuller (CADF) panel unit root tests were used. These tests perform well with small datasets and regulate cross-sectional dependency and residual series correlation. The test statistics for CADF regression and CIPS regression are shown in Eqs. (9) and (10), respectively:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + \delta_i \overline{y}_{it-1} + \lambda_i \Delta\overline{y}_{it} + \varepsilon_{it} \quad (9)$$

$$\text{CIPS} = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T) \quad (10)$$

Each cross-mean section's estimate of the lagged variable and first difference is shown in $\overline{y}_{it-1}$ and $\Delta\overline{y}_{it}$, respectively. $t_i(N,T) = CADF$ gives the findings of an OLS regression test for the i_{th} sample.

2.2.3. A panel cointegration test

After identifying the steady characteristics present in the data, we decided to use the panel cointegration technique proposed by Westerlund (2007). Unlike typical first-generation panel cointegration techniques, this methodology produces consistent and trustworthy evaluations of cointegrating characteristics by normalizing cross-sectional dependence constraints in panel data. The standard errors of four structurally oriented test statistics, Gt, Ga, Pt, and Pa, are estimated using an ECM bootstrapped technique under the null assumption of no cointegration. Another reason to use this cointegration test is that it outperforms residual-based cointegration tests when the explanatory factors are weakly exogenous. The following are the error correction panel-oriented test statistics:

Table 2
Summaries of descriptive statistics.

	$LnCO_2$	LnT&T	LnGTI	LnSC	LnGDP	LnREC
Mean	5.448463	0.654336	1.553684	1.990494	3.583233	1.269388
Median	5.299995	0.687248	1.537773	1.985199	3.488154	1.440828
Maximum	7.054775	1.052677	5.118000	2.072741	4.787982	1.761271
Minimum	4.567026	0.185296	0.504367	1.937302	2.657287	0.292256
Std. Dev.	0.666921	0.190280	0.511383	0.026711	0.523327	0.432929
Jarque-Bera	31.93483	10.36995	31.51769	54.68577	25.15437	38.06387
Probability	0.115243	0.176861	0.217226	0.187670	0.363163	0.158984
Observations	264	264	264	264	264	264

Table 3
The results of CSD and slope homogeneity tests.

Panel A. CSD tests						
Tests	$LnCO_2$	LnT&T	LnGTI	LnSC	LnGDP	LnREC
Breusch-Pagan LM	678.8440*	461.0769*	138.2179*	318.9387*	587.6486*	443.3272*
Bias-corrected scaled LM	86.84769*	57.74734*	14.60349*	38.75331*	74.66119*	55.37543*
Panel B: Slope Homogeneity tests						
Model				Delta (Δ)	Adjusted delta (Adj Δ)	
$LnCO_2$ = f (LnT&T, LnGTI, $LnGTI^2$, LnSC, LnGDP, LnREC)				16.566*	19.033*	

Note: * indicate significance at 1%.

$$\Delta y_{it} = \delta_i' d_t + \partial_i y_{i,t-1} + \lambda_i' y_{i,t-1} + \sum_{j=1}^{pi} \partial_{ij} \Delta y_{i,t-1} + \sum_{j=-qi}^{pi} \gamma_{ij} \Delta x_{i,t-1} + \varepsilon_{it} \quad (11)$$

Where $d_t$represents the deterministic factor and ∂_i is the error correction indicating the rate at which the dependent variable in each nation adjusts to its equilibrium status.

2.2.4. A panel long-run and short-run estimations

This work aims to examine the interconnections among travel and tourism, green technological innovation, structural change, GDP, renewable energy, and CO_2 emissions for the major tourism destinations in Asia. As a result of cross-section dependence and slope heterogeneity problems, conventional panel estimations, such as FMOL and DOLS, may produce inaccurate results (An, Razzaq, Haseeb, & Mihardjo, 2021). As a solution, CS-ARDL was used to estimate both the long-run and short-run coefficients. This technique considers SCH and CSD issues using dynamic common correlated impact predictors (Yao, Ivanovski, Inekwe, & Smyth, 2019). Besides, the CS-ARDL technique also accounts for variable mixed stationarity, small sample size bias, autocorrelation, endogeneity, and unobserved mutual shocks (Chudik, Mohaddes, Pesaran, & Raissi, 2017). The error correction-based CS-ARDL can be written in an econometric form as follows:

$$\Delta y_{it} = \alpha_i + \xi_i \left(y_{i,t-1} - \overline{\omega}_i' x_{i,t-1} \right) + \sum_{j=1}^{p-1} \lambda_{ij}^* \Delta y_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij}^* \Delta x_{i,t-j} + \sum_{j=0}^{K} \varphi_{ij} \overline{Z_{i,t-j}} + \sum_{j=1}^{p-1} \psi_{ij} \overline{\Delta y_{t-j}} + \sum_{j=0}^{q-1} \zeta_j \overline{\Delta x_{t-j}} + \varepsilon_{it} \quad (12)$$

Where $y_{i,t}$ is the study's dependent variable (CO_2 emissions), and x_{it} stands for all other explanatory factors. $\overline{Z} = (\overline{y}_i, \overline{x}_i)'$represents the average value and time lag of the researched variable over cross-sections, where K is the lag in time.

Pesaran's (2006) CCEMG model and Eberhardt and Bond's (2009) AMG model were used to assess the robustness and significance of CS-ARDL findings. These methods are resilient to biases introduced by endogeneity, SCH, and CSD.

2.2.5. Panel causality tests

The last phase in this empirical investigation is to look for causality between variables under study. In seminal research, Granger (1969) develops the framework for analyzing the causation between variables in time series data. Dumitrescu and Hurlin (2012) enhance this concept by allowing it to detect causation in panel data and thus is employed to ascertain the bidirectional or unidirectional causality among observed indicators. DH panel causality is a well-known method for assessing panel data that have heterogeneity and are cross-sectionally dependent. The following equation illustrates the proposed linear heterogeneous model of DH causality:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{k} \lambda_i^{(k)} y_{i,t-k} + \sum_{k=1}^{k} \beta_i^{(k)} x_{i,t-k} + \varepsilon_{it} \quad (13)$$

Where $\beta_i^{(k)}$ and $\lambda_i^{(k)}$ are the lag independent and dependent variable coefficient estimates, respectively.

3. Results and discussion

Table 2 shows the variables' descriptive statistics in logarithmic form. Every variable has a positive mean value, with LnCO2 having the highest mean and LnT&T having the lowest mean. LnCO2 has the highest standard deviation, while LnSC has the lowest. Moreover, the Jarque-Bera statistics for all variables show that the data series is normally distributed, allowing the study to conduct linear estimation modeling.

Table 3 shows the results of CSD and SCH tests. The findings in Panel A demonstrated the presence of CSD in panel data, evidently contradicting independence at the cross-sectional level for all variables under consideration. The significance of CSD at the 1% level draws attention to the interdependence and spillover among the economies of Asia. Similarly, the findings presented in Panel B provide evidence that slope heterogeneity exists, refuting the null of slope coefficient homogeneity. The significant relevant test statistics conclude that the estimates of the coefficients of independent variables seem to differ from country to country in the analyzed sample set.

Table 4 summarises the CIPS and CADF panel unit root tests. We find that the levels of $LnCO_2$, LnT&T, LnGTI, LnSC, LnGDP, and LnREC are not stationary. Nonetheless, the initial differences between them are stationary, so we can rule out the alternative hypothesis that they are not stationary at the 1% level of significance.

After ensuring that the variables were stationary, the Westerlund (2007) cointegration test was performed to analyze their long-term relationships. According to the data shown in Table 5, the model provides robust and statistically significant support for the hypothesis of long-term cointegration. A long-term cointegration can be inferred from the statistical significance of Gt, Ga, Pt, and Pa tests between $LnCO_2$ and the

Table 4
The Results of CIPS and CADF.

	CIPS		CADF	
Variables	Level	Difference	Level	Difference
$LnCO_2$	−1.510	−4.161*	−1.825	−2.586*
LnT&T	−1.363	−5.844*	−1.119	−4.440*
LnGTI	−1.809	−4.852*	−2.049	−3.689*
LnSC	−1.957	−4.431*	−1.892	−3.557*
LnGDP	−1.626	−3.673*	−2.195	−3.819*
LnREC	−1.101	−4.058*	−0.986	−3.070*

Note: * indicate significance at 1%; Critical values 5% = 2.330, 1% = 2.550.

Table 5
The results of Westerlund (2007) panel cointegration.

Model: $LnCO_2$ = f (LnT&T, LnGTI, $LnGTI^2$, LnSC, LnGDP, LnREC)			
Statistics	Value	*Z*-value	Robust *P*-value
Gτ	−2.768	1.230	0.000
Gα	−5.062	4.722	0.000
Pτ	−6.802	1.560	0.000
Pα	−4.360	3.936	0.000

Note: * indicate significance at 1%.

variables that explain it (LnT&T, LnGTI, LnGTI^2, LnSC, LnGDP, and LnREC) for the top tourist destinations in Asia.

Drawing upon the methodology outlined by Ditzen, Karavias, and Westerlund (2021), our analysis for structural breaks in Table 6 indicates that no significant breaks were detected in the datasets.

Table 7 displays the long- and short-run regression estimates acquired using the CS-ARDL. The long-run finding of CS-ARDL estimations reveals that LnT&T has significantly positive linkages with CO_2 emissions. The positive coefficient implies that tourism increases CO_2 emissions in top tourist countries in the Asian region. This outcome could be justified as tourism development involves roads, airports, infrastructure construction, resorts, shops, hotels, marinas, and golf courses, degrading the destination countries' environmental quality. It could harm the environment through air emissions, littering and solid waste, soil erosion, putting extra pressure on endangered species, and loss of natural habitats. This study outcome is supported by previous literature (Koçak, Ulucak, & Ulucak, 2020; Shaheen et al., 2019; Sharif, Afshan & Nisha, 2017; Sharif, Saha, & Loganathan, 2017).

Long-term data show that LnGTI positively affects CO2 emissions. This suggests that technological advancements in these countries are not up to par, which could result in inefficiency in the manufacturing and service sectors, leading to increased CO2 emissions into the atmosphere. To a lesser extent, this finding is supported by the results of Wang, Sun, and Wang (2018) and Su and Moaniba (2017). Various other studies came to the opposite conclusion, concluding that technological advancement improves the quality of the surrounding environment (Ali, Abdullah, & Azam, 2016; Chien et al., 2021; Omri, 2020; Suki, Suki, Sharif, Afshan, & Jermsittiparsert, 2022). Their results could be different because they use a single indicator, but this study utilised GTI by multiple registered environmental patents.

The study also utilised the squared term of GTI to observe the presence or absence of the Innovative Claudia Curve (ICC) by investigating the full characteristics of innovation and environment. The outcomes of the study state that the squared term of innovation accompanied negative and significant linkages with CO_2 emissions in the panel countries, supporting the Innovative Claudia Curve (ICC Theory). The ICC Theory states that initially, with the increase in the use of technology and patent creation, the ecological quality will deteriorate; however, after reaching a threshold level, additional innovations could be environmentally friendly that reduce emissions. This study outcome is supported by Khan, Ibrahim, et al. (2022) and Khan, Khan, and BiBi (2022).

Similarly, the long-term connection unequivocally demonstrates the considerable and favorable influence that structural improvements have had on CO_2 emissions in a key tourist destination in Asia. According to the findings, increasing industry value will cause increased CO_2 emissions. This finding proposes that shifting from agricultural to industrial activities is a hefty source of the high carbon dioxide levels in the air at these Asian tourist hotspots. Because industrial activities require more energy, they are responsible for a significant proportion of the total CO_2 emissions released into the atmosphere. Ali, Rahman, et al. (2020), Ali, Sadiq, et al. (2020), and Ali, Sadiq, Kumail, and Aburumman (2021) support the study's results.

In addition, the study's long-term estimates reveal a pervasive positive impact of LnGDP on CO2 emissions, even though rising GDP is associated with increased pollution in developing nations. This finding has wide-ranging implications because most economic activities consume substantial energy, and most of these resources are finite and add to the buildup of CO2 in the atmosphere because they release greenhouse gases. The research findings are supported by Ali, Abdullah, and Azam (2017), Liu, Kumail, Ali, and Sadiq (2019), and Omri and Kahouli (2014).

Finally, the long-run coefficient for LnREC is negatively significant, uncovering that increased renewable energy mitigates CO_2 emissions. Renewable energy is the most crucial source for continued economic growth and the preservation of the environment, and it helps to protect the environment and reduce the risks associated with global warming. Using energy sources that do not deplete the Earth's resources could help Asian nations contribute to the fight against global warming. The finding agrees with prior research (Farhani & Shahbaz, 2014; Liu, Zhang, & Bae, 2017), which acknowledged that using renewables results in lower CO_2 emissions. However, these empirics do not support the finding of Apergis, Payne, Menyah, and Wolde-Rufael (2010), who found that an increase in the utilization of REC is associated with an increase in carbon dioxide emissions.

Regarding the estimates derived from the CS-ARDL statistics, the short-run estimation produces outcomes identical to the long-run estimates, complete with the same signs for the coefficients in each scenario. The ECTt-1 coefficient, also known as the lag error correction term, has a negative value and is significant at 1%. The existence of ECTt-1 coefficients, which are harmful and highly significant, indicates long-term equilibrium and model stability between the variables of interest. The ECTt-1 coefficients showed a swift pattern for adjusting CO_2 output in the short term with an adjustment speed of 80% in a year to reach long-run equilibrium. This adjustment speed took place in response to any changes that took place in the factors that were being explained.

Table 8 presents a series of model diagnostics tests. The statistically significant p-value of the F-statistic at the 1% level confirms the overall goodness of fit of the model. Furthermore, other diagnostic tests,

Table 6
Ditzen et al. (2021) structural break.

Bai & Perron Critical Values				
	Test Statistic	1% Critical Value	5% Critical Value	10% Critical Value
F(1|0)	0.97	3.82	3.12	2.81
F(2|1)	0.00	4.05	3.45	3.11
F(3|2)	0.00	4.19	3.59	3.27
F(4|3)	−6.94	4.27	3.72	3.44
F(5|4)	−8.32	4.36	3.81	3.53

Detected number of breaks:
A Maximum number of breaks reached with null always rejected.
No breaks found, cannot estimate breakpoints.

Table 7
CS- ARDL Long-run and short-run results.

Variables	Long-run results			Short-run results		
	Coefficient	Std. Err.	p-value	Coefficient	Std. Err.	p-value
LnT&T	0.243*	0.073	0.000	0.342***	0.181	0.059
LnGTI	0.129**	0.056	0.021	0.225*	0.052	0.000
LnGTI2	−0.037***	0.02	0.064	−0.047**	0.021	0.025
LnSC	−0.424*	0.164	0.009	−0.363**	0.181	0.044
LnGDP	0.348***	0.202	0.084	0.455***	0.237	0.054
LnREC	−0.452**	0.183	0.014	−0.685**	0.287	0.017
ECT (−1)				−0.809*	0.096	0.000

Note: *, ** & *** indicate significance at 1%, 5% & 10%, respectively.

Table 8
Diagnostic tests results.

Diagnostic Tests	Statistic	p-value
Goodness of Fit (F-statistics)	19.68*	0.0000
Functional form/Omitted variable (Ramsey's Reset)	1.630	0.2430
Normality (Jarque Bera)	5.066	0.1794
Autocorrelation (Wooldridge)	296.636	0.3602
Heteroskedasticity (Modified Wald)	1036.16	0.1927

Note: * indicates significance at 1%.

Table 9
Results of CCEMG and AMG.

Variables	CCEMG		AMG	
	Coefficient	p-value	Coefficient	p-value
LnT&T	0.223**	0.010	0.261***	0.068
LnGTI	0.208***	0.054	0.181**	0.011
LnGTI2	−0.057*	0.002	−0.044*	0.001
LnSC	−0.279**	0.034	−0.621***	0.055
LnGDP	0.463**	0.031	0.419**	0.041
LnREC	−0.676**	0.011	−0.647**	0.012

Note: *, ** & *** indicate significance at 1%, 5% & 10%, respectively.

including Ramsey's Reset, Jarque Bera for error term normality, Wooldridge for autocorrelation, and Modified Wald for homoscedasticity, all yielded insignificant *p*-values, suggesting that the null hypotheses associated with these tests cannot be rejected. Consequently, the CS-ARDL empirical model estimated is deemed consistent, robust, and suitable for informing policy decisions in the leading tourist destinations across Asia.

Table 9 includes the findings of the CCEMG and AMG to ensure the data's accuracy and validate the CS-ARDL regression findings. The estimated statistics for each indicator ($LnCO_2$, LnT&T, LnGTI, $LnGTI^2$, LnSC, LnGDP, and LnREC) show comparable coefficient signs at different levels of significance for all three techniques, demonstrating the robustness and dependability of CS-ARDL estimations.

Table 10 presents the results of the CCEMG analysis for South Asian countries. The estimates reveal a positive correlation between tourism and CO_2 emissions in these nations. Specifically, a positive coefficient suggests an increase in CO_2 emissions in popular Asian tourist destinations. As shown (Table 6), this trend can be attributed to the expansion of tourist infrastructures, potentially degrading environmental quality. Environmental impacts include air pollution, waste buildup, soil erosion, and ecosystem degradation.

Interestingly, the LnGTI shows a beneficial effect on CO2 emissions in Thailand, Singapore, Philippines, India, and China but an adverse effect in Malaysia, Indonesia, and Pakistan. This pattern indicates that in these nations, technological progress may be insufficient, leading to inefficiencies in industrial and service sectors and, consequently, higher CO2 emissions. Additionally, the squared term of GTI was analyzed to investigate the presence or absence of the Innovative Claudia Curve (ICC) by analyzing the complete attributes of innovation and environment. The findings demonstrate that in Thailand, Singapore, the Philippines, and India, the squared term of innovation is negatively and significantly correlated with CO2 emissions, supporting the ICC theory. Our results indicate that these countries have surpassed this critical threshold, and their technological innovations are now contributing to reducing CO2 emissions.

Based on our analysis of the TI Index over 25 years across various Asian countries (Fig. 1), we observed significant disparities in technological advancement trends. These disparities offer valuable insights into the differential impact of green technological innovation on CO2 emissions observed in these countries. For instance, in countries like Thailand, Indonesia, Pakistan, India, and China, where we noticed either a consistent rise or significant fluctuations in the TI Index, there appears to be a beneficial effect of green technological innovation on reducing CO2 emissions. This aligns with the observed negative correlation between the squared term of innovation and CO2 emissions, supporting the ICC theory in these regions.

Conversely, in countries such as Malaysia, Singapore, and the Philippines, where the TI Index trends were either declining or relatively stagnant, an adverse effect on CO2 emissions was noted. This suggests that in these nations, the pace and nature of technological progress may be insufficient or misaligned with environmental efficiency needs. This leads to inefficiencies in their industrial and service sectors, contributing to higher CO2 emissions despite technological advancements. Our findings underscore the complex and multifaceted relationship between technological innovation and environmental outcomes. They highlight the necessity for tailored approaches in technological development and deployment to effectively mitigate environmental impacts. The transition observed in countries like Thailand, Indonesia, Pakistan, and India is indicative of a crucial shift toward more sustainable technological practices. It emphasizes the evolving and dynamic nature of green innovation in reducing environmental impact, underscoring the importance of continuous monitoring and adaptation of technological strategies to align with environmental sustainability goals.

Furthermore, the analysis reveals a consistent correlation between the LnGDP and CO2 emissions in Malaysia, Thailand, Philippines, Indonesia, Pakistan, India, and China, excluding Singapore. This relationship remains significant despite the common association of higher GDP levels with increased pollution in developing countries. The implication is profound: most economic activities require substantial energy, often from finite sources, leading to greenhouse gas emissions and CO2 accumulation.

Lastly, the negative significance of LnREC (logarithm of Renewable Energy Consumption) indicates that an increase in renewable energy use leads to a reduction in CO2 emissions in Malaysia, Thailand, Philippines, Indonesia, Pakistan, India, and China, with Singapore being the exception. Renewable energy emerges as a crucial element for sustainable economic growth and environmental preservation, helping mitigate climate change risks and protect the environment. Embracing renewable energy sources could empower Asian countries to address global warming effectively while preserving Earth's resources.

The results of the DH causality test are shown in Table 11. These estimates suggest that tourism, green technological innovation, structural change, GDP, and renewable energy all lead to changes in CO2 emissions, indicating a unidirectional causal relationship. This means that as these factors change, CO2 emissions are affected accordingly. Importantly, there is no evidence of reverse causality, implying that changes in CO2 emissions do not cause changes in these factors. Additionally, there is bidirectional causality among tourism, green technological innovation, structural change, and GDP, indicating their interconnectedness and importance as determinants of climate change. These results are consistent with previous research findings (Dogan & Turkekul, 2016; Liddle & Lung, 2015), Moreover, the causation investigation aligns with the long-run estimation findings, reinforcing the importance of these variables in explaining climate change dynamics.

Table 10
Countries-wise CCEMG results.

Countries	LnT&T	LnGTI	$LnGTI^2$	LnSC	LnGDP	LnREC
Malaysia	0.036**	−0.171***	0.081**	−0.148*	0.069***	−0.241*
Thailand	0.138*	0.087**	−0.031***	−0.922***	0.839*	−0.209***
Singapore	0.321***	0.074***	−0.041**	−0.822*	−0.098***	0.015***
Philippines	0.443*	0.151*	−0.091*	0.662**	0.594*	−0.213***
Indonesia	0.041***	−0.097*	0.051*	−0.436***	0.299***	−0.618*
Pakistan	0.071***	−0.048**	0.009***	0.607***	0.773**	−0.395*
India	0.093**	0.162**	−0.079***	−0.349**	0.508***	−0.422*
China	0.049*	0.112***	0.023**	0.742***	0.283***	−0.521*

Note: *, ** & *** indicate significance at 1%, 5% & 10%, respectively.

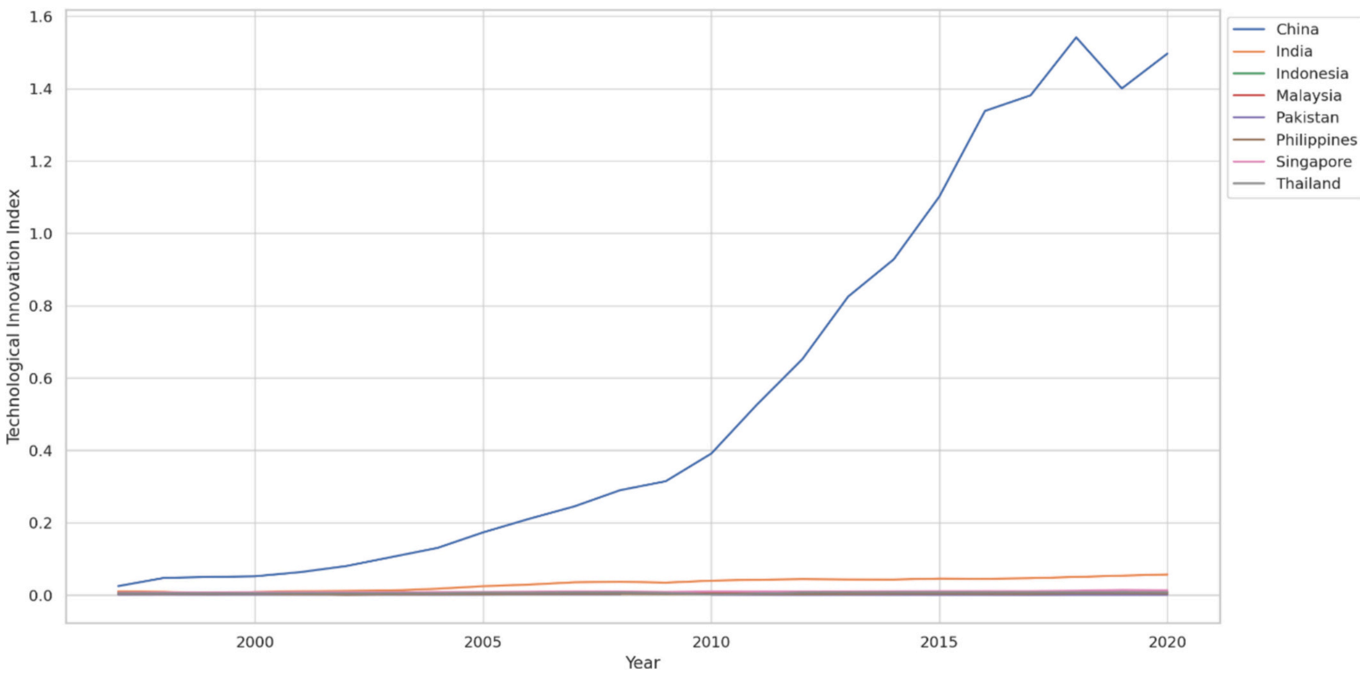

Fig. 1. The plot illustrating the Technological Innovation (TI) Index trends over time for each country in the dataset.

Table 11
Results of DH panel causality.

	$LnCO_2$	LnT&T	LnGTI	LnSC	LnGDP	LnREC
$LnCO_2$	–	4.8567	3.6377	4.6965	4.7492	5.2742
		3.2303	1.7665	3.0379	3.1012	3.7316
		0.1612	0.2773	0.3024	0.1134	0.9952
LnT&T	4.5001*	–	3.6849***	3.6876***	4.5738*	2.3839
	2.8021		1.8231	1.8264	2.8905	0.2608
	0.0051		0.0683	0.0678	0.0038	0.7942
LnGTI	4.2771**	4.5091*	–	2.5581	3.2005	3.1686
	2.5342	2.8129		0.4700	1.2415	1.2032
	0.0113	0.0049		0.6383	0.2144	0.2289
LnSC	9.3588*	5.4633*	2.8725	–	5.0495*	4.2288**
	8.6365	3.9587	0.8476		3.4618	2.4763
	0.0000	0.0000	0.3966		0.0005	0.0133
LnGDP	3.4851*	5.5573*	5.7136*	4.8857*	–	3.5121
	1.5831	4.0716	4.2592	3.2650		1.6157
	0.0019	0.0000	0.0000	0.0011		0.1062
LnREC	2.1616*	4.0131**	3.2893	3.7167***	3.8571**	–
	−0.0059	2.2171	1.3481	1.8613	2.0299	
	0.0002	0.0266	0.1776	0.0627	0.0424	

Note: The first value indicates the W-stat, the second value indicates the *Z*-stat, and the third value indicates the *P*-value; *, **, and *** indicate significance at 1%, 5%, and 10%, respectively.

4. Conclusion

In response to the climate crisis, both science and society have seen a surge of interest in environmental issues and tourism literature. The prevailing message in this literature is clear: sustainable tourism cannot exist without addressing climate change. With its global reach and potential to contribute to the United Nations' Sustainable Development Goals and their successors beyond 2030, tourism bears some similarities to the current COVID-19 pandemic, climate change, and the global response to these issues. This study examines the complex relationship between climate change, tourism development, green technological innovation, and structural change in Asia's top tourist destinations from 1996 to 2022. Our analysis of the Technological Innovation (TI) Index over this period reveals significant variations in green technological innovation trends across these countries, challenging the assumption of a consistent rate of innovation. This variability has implications for understanding the differential impact of green technology on CO2 emissions in these regions.

We apply a range of advanced statistical methods, including unit root, cointegration, and Dumitrescu–Hurlin causality tests, to analyze cross-sectional dependence in panel time-series data. We also utilize the CS-ARDL, a second-generation estimator that performs better than traditional methods for small samples, to estimate long-run indicator coefficients. The Westerlund cointegration test was conducted, and the results provided robust and statistically significant support for the hypothesis of long-term cointegration. The long-term findings from the CS-ARDL estimations show that tourism and technological advancement (measured by GTI) significantly positively affect CO2 emissions. Additionally, industrialization and GDP have a positive relationship with CO2 emissions, while renewable energy consumption is negatively associated with CO2 emissions. However, the nuanced trends in green technological innovation, as evidenced by our analysis of the TI Index, suggest a more complex interaction between technological progress and environmental impact than previously understood.

The squared term of GTI indicates that innovation could reduce CO2 emissions once a threshold level is reached. The study also examines the Innovative Claudia Curve theory, which suggests that innovation may initially lead to environmental degradation, but it could reduce CO2 emissions beyond a threshold level. Our findings, particularly the diverse trajectories of the TI Index, provide additional context to the ICC theory, emphasizing that the threshold at which innovation begins to positively impact the environment may vary significantly from one country to another.

4.1. Contributions of the study

This study makes a significant theoretical contribution to the topic of tourism and carbon emissions by providing a comprehensive and detailed analysis of the long-term relationships between various factors and CO2 emissions in Asia's top tourist destinations. Drawing on the urgency highlighted in the COP28 (2023) consensus and the Tourism Panel on Climate Change (2023), this study extends previous research on the impact of tourism on climate change and the need for sustainable practices in the industry (Gössling et al., 2020; Scott & Gössling, 2022; Tang et al., 2022). It aligns with global efforts to combat climate change, as outlined in these key international documents. Furthermore, the study's exploration of green technological innovation and its environmental effects resonates with the global call for sustainable tourism practices emphasized in the COP28 outcomes (COP28, 2023). By employing advanced statistical methods, such as the Westerlund cointegration test and the CS-ARDL, this study illuminates the factors contributing to CO2 emissions, including tourism development, technological advancements, industrialization, economic growth, and renewable energy sources. It underscores the critical role of green technology and renewable energy in tourism's transition to sustainability, as echoed in global policy discussions and further exemplified by Tang et al. (2017), particularly in this region.

Furthermore, the study examines the Innovative Claudia Curve, using the squared term of green technological innovation to observe the presence or absence of the curve. This theory, which has been previously explored in the literature (Fang et al., 2018), suggests that as new technologies and patents increase, the environment will deteriorate, but after a threshold level, additional innovations could be environmentally friendly and reduce emissions. By validating the ICC theory in the context of Asia's most popular tourist destinations, the study offers empirical evidence of the dynamic relationship and unique insights into how technological innovation can mitigate CO2 emission (; Ali, Rahman, et al., 2020), contributing to the broader understanding of sustainable tourism development in line with global climate goals.

Additionally, the study's focus on Asia's most popular tourist destinations, including Malaysia, Thailand, Singapore, the Philippines, Indonesia, Pakistan, India, and China, highlights the region's significance in global tourism and its pivotal role in climate change mitigation (World Tourism Organization, 2021). By demonstrating how the tourism sector contributes to carbon emissions in these countries, the study offers strong theoretical support for the necessary low-carbon transformation of the tourism industry in the Asian region. This regional focus (Peng et al., 2015) is crucial for developing targeted strategies and policies, aligning with international efforts to reduce carbon emissions in the tourism industry, as emphasized at COP28. Additionally, the integration of advanced statistical methods such as the CS-ARDL, CCEMG, AMG long-run estimators, and Dumitrescu-Hurlin short-run causality tests to measure tourism development and structural change in carbon reduction models in this study sets it apart from research that may have used more traditional analytical approaches (Michailidou et al., 2016). These advanced methods enable the study to provide policymakers with unbiased and reliable estimates to determine sustainable environmental policy implications effectively. By accounting for short-run equilibrium distortions and evaluating both long and short-term estimates, the study offers a more comprehensive understanding of the relationship between tourism growth, structural changes, and CO2 emissions in Asia's top tourist destinations (Steiger et al., 2022).

4.2. Study implications

The findings of this study have significant implications for sustainable tourism planning in Asia, providing valuable take-away messages for policymakers and destination management organizations. The study emphasizes the need for tailored approaches to sustainability in each Asian tourism destination. The authors acknowledge that individual countries in Asia, including China, have experienced exponential growth throughout the last three decades, which may lead to varying policies and temporal shifts in perception toward low-carbon initiatives.

First, the study's findings on the positive correlation between tourism, technological advancements, and CO2 emissions in South Asian countries underscores the urgent need for sustainable tourism practices. Acknowledging the varying impacts of green technological innovation across different Asian nations, policymakers must develop region-specific strategies to reduce the carbon footprint of tourism. The beneficial effects of green technology in countries like Thailand and Indonesia contrasted with adverse effects in Malaysia and Singapore, highlight the need for tailored approaches in integrating green technology and renewable energy. These insights, aligned with Becken et al. (2020) and Gössling et al. (2023) calls for policy integration, necessitate a dynamic policy framework that adapts to each country's unique technological and environmental context.

Secondly, the study emphasizes the need for a low-carbon transformation of the tourism industry in Asia. This transformation must take into account the contribution of Travel and Tourism direct contribution to GDP (%) in carbon emissions, which the study found to be a significant factor. Therefore, policymakers must prioritize the adoption of low-carbon policies and practices in the tourism industry to reduce the carbon footprint of tourism. These recommendations align with the views of Gössling and Scott (2018) and Scott et al. (2016), who argue that policymakers must prioritize the adoption of low-carbon policies and practices in the tourism industry to reduce the carbon footprint of tourism. This requires a comprehensive understanding of the specific factors influencing carbon emissions in each country, allowing for targeted interventions and policy integration. Additionally, our results underscore the importance of considering the environmental impact of tourism in sustainable tourism planning (Scott et al., 2019). By addressing temporal patterns and variations in policies, policymakers can develop content-specific strategies to mitigate the environmental impacts of tourism while supporting economic growth.

Lastly, the study underscores the potential of technological innovation for sustainable tourism development. The Innovative Claudia Curve theory provides evidence that technological innovation can reduce CO2 emissions beyond a threshold level, which should encourage policymakers to invest in green technological innovation in the tourism industry, providing empirical support to the views of Spasojevic et al. (2018) and Peeters et al. (2019), who argue that technological innovation is crucial for achieving sustainable tourism. To fully leverage the potential of technology, this study advocates for a threshold based approach in technology innovation. Policymakers should focus on surpassing the critical threshold where technological advancements begin to positively impact the environment. This requires continuous monitoring and investment in green technology fostering an environment conducting to sustainable tourism growth. Data-driven policymaking, as emphasized in recent research (Loehr & Becken, 2021), can play a pivotal role in identifying the most effective policies and practices for achieving sustainable tourism development in Asia's top tourist destinations.

In conclusion, the study calls for a nuanced, data-driven approach to sustainable tourism planning in Asia, considering the diverse economic and environmental landscapes of each destination. Tailored strategies that address the unique challenges and opportunities faced by each destination are essential to promote sustainable tourism development in the region. By aligning policy initiatives with empirical findings, Asian countries can effectively navigate the challenges of climate change and tourism development.

4.3. Study limitations

Despite its valuable contributions, this study has some limitations that should be acknowledged. **(1) *Generalizability and Spatial Distinctions*:** The study focuses on Southeast Asia's top tourist destinations, which may not fully represent the diversity of tourism practices and policies across all of Asia. Therefore, the findings may not be entirely generalizable to other countries or regions with different tourism characteristics. Further, the research merged data from all countries, but regional variations in tourism practices and policies can significantly affect the relationship between sustainable tourism and carbon emissions. **Additionally, the study did not incorporate spatial autocorrelation tests to ensure the independence of data points. Instead, the CS-ARDL methodology was chosen due to its robustness in handling cross-sectional dependence in panel time-series data.** These limitations highlight the need for further examination and a more robust justification of these methods in future studies. ***(2) Complexity of Factors*:** Climate change and CO2 emissions are influenced by a multitude of factors beyond those included in this study, such as political factors, policy implementations, cultural aspects, and more. The study's scope might not encompass all relevant variables, which could lead to an incomplete understanding of the complexities involved. ***(3)** Limited Time-frame and Long-Term Time Series*: The study's analysis covers the period from 1990 to 2022, which might not capture the most recent developments and changes in tourism practices and policies. The dynamics of the tourism industry and climate change might have evolved beyond this timeframe. However, it is worth noting that this research already includes more recent data regarding green technological innovations in Asian countries from sources such as Liu et al. (2022), Raza et al. (2017), and Amin et al. (2023), among others. ***(4)** Sustainable Tourism Indicators*: The study uses CO2 emissions as a primary indicator of sustainability in the tourism industry. While emissions are essential, sustainable tourism involves a broader set of social, economic, and environmental factors that could be further explored. ***(5) Innovative Claudia Curve Theory*:** While the study examines the Innovative Claudia Curve theory, it may not fully capture all the intricacies and nuances of the relationship between technological innovation and CO2 emissions in the tourism sector. *(7) Changing Policy Landscape*: The study's recommendations and implications are based on the existing policy landscape. However, policy priorities and frameworks might change over time, influencing the effectiveness of the suggested measures. ***(8) Sample Size and Variable Limitations*:** The study is limited by a sample of 25 observations per country over 25 years with a restricted number of variables. **This limitation may affect the robustness of the findings. In future research, we plan to include a broader range of variables and explore temporal analysis to understand long-term trends and cyclical patterns in CO2 emissions.**

4.4. Recommendations for future research

This study provides valuable insights into the complex relationship between sustainable tourism and carbon emissions in Southeast Asia's top tourist destinations, but several avenues for future research could further contribute to our understanding of this important topic. *Firstly*, future research could explore the impact of different types of tourism and tourism activities on carbon emissions. Such comparative analysis could help policymakers to develop targeted strategies to reduce carbon emissions in the tourism industry. *Secondly*, there is a need to prioritize distinguishing between regions to provide a comprehensive analysis that accounts for these differences and investigates the influence of regional variations on sustainability initiatives and emissions reduction strategies. Incorporating spatial autocorrelation tests into future research ensures data independence in a spatial context. Exploring spatial dependencies in emissions and sustainable tourism indicators can illuminate localized patterns and guide targeted policy interventions. Moreover, integrating a broader range of Asian countries and variables will allow for a more nuanced understanding of the factors influencing CO2 emissions, including economic growth, political contexts, and cultural aspects. *Thirdly*, there is a need for further research on the effectiveness of policy interventions aimed at reducing carbon emissions in the tourism industry. Evaluating the impact of policies such as carbon pricing, subsidies for renewable energy, and eco-labeling schemes could help policymakers to identify the most effective approaches for achieving sustainable tourism development. Additionally, conducting temporal analyses to uncover long-term trends and patterns will address potential structural breaks and changes in policy environments over time, providing deeper insights into the dynamics of the tourism industry and climate change. *Fourthly*, future research should focus on identifying specific technologies and innovations that can be leveraged to reduce carbon emissions in the tourism industry. This study suggests that green technological innovation can play a vital role in sustainable tourism development, and identifying the most effective technologies and innovations could help to accelerate the transition to a low-carbon tourism industry. *Lastly*, there is a need for research on the impact of the COVID-19 pandemic on the tourism industry and its potential implications for carbon emissions. The pandemic has led to a significant reduction in travel and tourism, and understanding its long-term impact on the industry and its carbon footprint could help to inform policies aimed at achieving sustainable tourism development in the post-pandemic world.

By addressing these limitations and exploring these future research avenues, we can significantly enhance our understanding of the intricate relationship between sustainable tourism and carbon emissions. This will lead to more effective and targeted policy interventions and practices, ultimately aiding in the achievement of a low-carbon tourism industry.

CRediT authorship contribution statement

Tafazal Kumail: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ante Mandić:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hui Li:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Farah Sadiq:** Writing – review & editing.

Declaration of competing interest

None.

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