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Tourism sector decarbonization and policy effectiveness in China: a subsectoral environmental performance analysis

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Tourism's expanding ecological footprint presents a growing governance challenge, particularly in rapidly developing economies such as China, where sectoral growth coincides with ambitious climate targets. This study examines the differentiated environmental and socio-economic impacts of tourism sub-sectors—lodging, entertainment, and food services—under the influence of fiscal and regulatory governance instruments. Using quarterly data from 2000 to 2020 and applying the Autoregressive Distributed Lag (ARDL) approach, we evaluate both short- and long-run dynamics across five key sustainability indicators: greenhouse gas emissions (GHG), air pollutants (PM_{2.5} and PM₁₀), ecological footprint (ECO-F), and the Human Development Index (HDI). The results reveal strong long-run cointegration among sectoral activities, environmental governance variables, and sustainability outcomes. Lodging exhibits the highest environmental intensity, significantly increasing GHG and ECO-F, while entertainment enhances HDI with moderate ecological trade-offs. Meanwhile, the food sector demonstrates a relatively balanced contribution to sustainability, showing potential in mitigating air pollution. Environmental regulation and taxation show varying effectiveness: regulatory instruments consistently mitigate emissions and improve HDI, whereas fiscal tools yield mixed results depending on sectoral context and energy elasticity. Causality diagnostics uncover complex feedback loops between tourism, energy consumption, and environmental performance, while ECO-F–HDI mapping reveals sector-specific trade-offs between ecological stress and human development gains. The study offers theoretical advancement by integrating tourism-environment analysis with fiscal governance mechanisms and introduces a policy-relevant framework for sustainability calibration at the sub-sectoral level. Findings highlight the need for differentiated, sector-specific governance strategies to align tourism growth with environmental and developmental imperatives, providing empirical evidence to guide low-carbon transitions in tourism economies.

KEYWORDS

tourism decarbonization, environmental governance, subsectoral analysis, sustainability indicators, policy effectiveness

1 Introduction

In the post-pandemic landscape of accelerated tourism recovery, global attention has shifted from merely restoring visitor numbers to addressing the environmental asymmetries embedded within tourism's rapid expansion (Bibi et al., 2024; Khan et al., 2021a). As nations race to balance economic stimulus with climate obligations, the tourism sector stands at a critical inflection point, no longer viewed as a benign engine of growth but as a structurally embedded contributor to greenhouse gas emissions, ecological degradation, and particulate pollution (Khan et al., 2023). Recent evidence reveals that tourism's environmental intensity is not uniformly distributed but is deeply shaped by its internal composition, particularly the energy consumption and emission profiles of lodging operations, the scale and density of entertainment activities, and the ecological burdens of food and beverage services (Lenzen et al., 2018; Ridderstaat et al., 2022; Sun et al., 2022). These sub-sectors, often peripheral to environmental regulation and climate strategy, now represent strategic arenas where sustainability must be operationalized if tourism is to transition from being part of the problem to part of the solution.

China presents an especially compelling context to interrogate this transition. As one of the world's largest domestic tourism economies and simultaneously its leading emitter of greenhouse gases, China has committed itself to a complex green transformation agenda. Under the "ecological civilization" framework, the state has introduced a broad suite of regulatory and fiscal instruments, ranging from emissions taxes and performance-based environmental laws to sub-national environmental responsibility systems (Xue et al., 2023; Zhou et al., 2023). However, despite tourism's expanding environmental footprint and growing influence on rural economies and urban planning, it remains marginal in the implementation of national climate policies (Chen and Shi, 2022; Marinelli, 2018). Environmental laws and taxes have historically focused on manufacturing, transport, and energy sectors, leaving tourism sub-sectors weakly governed and analytically underexplored (Chan, 2021; Zhang, 2021; Zhang and Zhang, 2018; 2021). This governance gap becomes more consequential in the context of China's dual decarbonization and human development goals, which are often in tension (Sun et al., 2022; Zhang and Zhang, 2018).

Scholarly attention to the tourism–environment nexus has grown in recent years, yet significant gaps remain regarding the role of governance in shaping tourism's sustainability outcomes (Nguyen and Su, 2021). First, the majority of empirical research treats tourism as a homogeneous sector, overlooking the divergent energy intensity, resource use patterns, and socio-economic linkages of its constituent sub-sectors. This aggregation masks the distinct pathways through which different types of tourism-related activities interact with environmental and developmental systems (Balsalobre-Lorente et al., 2023; Pulido-Fernández and Cárdenas-García, 2021). Second, while there is a growing interest in fiscal tools such as green taxes and eco-subsidies, their effectiveness in moderating tourism's environmental externalities remains poorly understood. Most studies tend to conceptualize governance as a binary regulatory presence rather than as a set of differentiated instruments with potentially asymmetric effects on emissions, resource consumption, and social equity (Liu et al., 2020a;

Sovacool et al., 2021). Third, few studies have examined the potential trade-offs between environmental pressure and human development outcomes, particularly using integrated metrics such as the Ecological Footprint (ECO-F) and the Human Development Index (HDI). This is a critical oversight in contexts like China, where tourism is increasingly deployed as a tool of both economic modernization and territorial cohesion.

To address these gaps, this study develops a novel empirical framework that evaluates the differentiated impacts of China's tourism sub-sectors—lodging, entertainment, and food services—on multiple sustainability indicators, including greenhouse gas emissions (GHG), air pollutants (PM_{2.5} and PM₁₀), ECO-F, and HDI. Using quarterly time-series data from 2000 to 2020 and applying an Autoregressive Distributed Lag (ARDL) model and causality diagnostics, we analyze both short-run dynamics and long-run equilibrium relationships. We also incorporate environmental regulation and taxation as fiscal and institutional governance instruments to examine their moderating effects on tourism's environmental and socio-economic trajectories. The inclusion of ECO-F–HDI trade-off mapping and predictive diagnostics further strengthens the empirical rigor and policy relevance of the study.

This study reveals that the environmental and developmental outcomes of tourism are neither homogeneous nor linearly governed. Among tourism sub-sectors, lodging remains the most environmentally intensive, generating disproportionately high emissions and ecological costs relative to its contribution to human development. In contrast, the entertainment sector offers a model of sustainability synergies, enhancing social wellbeing while maintaining relatively contained environmental impacts. The food sector, while less carbon-intensive, reveals untapped potential in air quality gains contingent on improved policy targeting and operational reforms. Importantly, the analysis shows that environmental regulation and taxation are not universally effective; they yield meaningful impact only when aligned with sector-specific dynamics and macroeconomic context. The predictive accuracy of the ARDL models, combined with causality mapping and ECO-F–HDI trade-off analysis, emphasizes that governance effectiveness hinges on timing, coherence, and the capacity to adapt across differentiated tourism landscapes. These findings challenge one-size-fits-all sustainability prescriptions and call for a new generation of governance frameworks that are anticipatory, sector-sensitive, and equity-centered.

2 Literature review

2.1 Environmental governance and tourism decarbonization

Tourism has emerged as a double-edged force in sustainable development, propelling economic growth while contributing significantly to environmental degradation (Khan et al., 2020a; Khan et al., 2023). Globally, tourism accounts for approximately 8% of total carbon emissions, driven by the energy-intensive operations of transportation, accommodation, entertainment, and food services (Lenzen et al., 2018; Miralles et al., 2023). In particular, the expansion of tourism in large economies such as China has

raised critical concerns over its environmental footprint. As China pursues high-growth service industries to fuel domestic demand, tourism's unchecked emissions and resource use now pose a direct challenge to the country's dual mandate of high-quality growth and carbon neutrality by 2060 (Bai et al., 2022; Zhang and Zhang, 2021).

Transitioning toward a low-carbon tourism system requires more than incremental operational greening or voluntary corporate social responsibility. Rather, it demands a robust and integrated environmental governance architecture capable of internalizing negative externalities and driving systemic behavioral change. This includes command-and-control tools such as emissions standards and mandatory certifications, alongside fiscal instruments like environmental taxes and subsidies (Sovacool et al., 2021; Ullah et al., 2023). These governance mechanisms must be not only legally sound but also institutionally embedded within sectoral and regional planning frameworks. In the tourism context, however, environmental governance remains fragmented. Sub-sectors such as lodging, food, and entertainment often fall outside the scope of national climate targets or lack tailored enforcement mechanisms (Chan, 2021; Mancini et al., 2023; Miralles et al., 2023).

China represents a particularly revealing case for evaluating environmental governance efficacy in tourism. On the one hand, it has pioneered eco-civilization reforms and introduced environmental taxes and green finance initiatives across industries (Gu et al., 2020; Jiang et al., 2023; Xu et al., 2023). On the other hand, tourism governance remains characterized by asymmetrical implementation, regulatory loopholes, and weak sub-sectoral accountability (Mu et al., 2014; Zhang and Zhang, 2021). Recent studies suggest that general policies have limited efficacy when applied uniformly across tourism sub-sectors, whose environmental profiles differ significantly in scale, intensity, and responsiveness (Irfan et al., 2023; Xiong et al., 2023). This study examines the influence of China's environmental governance, captured through environmental laws and taxes, on environmental and sustainability outcomes across the core sub-sectors of tourism. Rather than relying on aggregate-level assessments, the analysis emphasizes sector-specific policy effectiveness and institutional responsiveness in directing environmental performance. By disaggregating the tourism sector into lodging, entertainment, and food services, the study offers a clearer understanding of governance dynamics and their differential impacts.

2.2 The role of environmental taxes

Environmental taxation has become a cornerstone of fiscal environmental policy, grounded in the principle of internalizing the external costs of pollution and incentivizing firms to adopt cleaner technologies (Pata and Caglar, 2021; Sharif et al., 2023). As a market-based instrument, environmental taxes (ET) provide flexibility and cost-efficiency compared to direct regulation, making them an increasingly popular tool among governments pursuing carbon neutrality goals (Bashir et al., 2021). In tourism, an industry characterized by high energy intensity and material consumption, environmental taxes offer a pathway to reduce emissions without stifling sectoral growth (Paramati et al., 2017; Sovacool et al., 2021; Wang and Yu, 2021).

China's adoption of environmental taxes marks a shift from command-and-control to more economically rational policy frameworks. The implementation of the Environmental Protection Tax Law in 2018 institutionalized pollutant-based fiscal penalties at a national scale (Ma et al., 2021; Zhang and Zhang, 2018; 2021). However, the tourism sector's response to these instruments remains underexplored. Most existing literature aggregates tourism with other service sectors, thereby overlooking the distinct fiscal sensitivities across sub-sectors such as lodging, entertainment, and food (Ahmad et al., 2022; Danish and Wang, 2018). This generalization dilutes our understanding of where fiscal policy can exert the most transformative pressure.

Sectoral heterogeneity is key to effective taxation. Lodging operations, for example, may respond to ETaxs by investing in solar panels or energy-efficient appliances, while food establishments may be more sensitive to waste levies or packaging-related penalties (Chen et al., 2023; Lee and Chen, 2021). Entertainment venues, especially those hosting large-scale events, could reduce emissions through electrification and low-carbon mobility incentives if tax structures are properly calibrated. Yet, empirical studies rarely evaluate whether existing fiscal policies are adequately tailored to induce such responses (Ullah et al., 2023). This study treats ETAX as a blunt policy instrument and conceptualizes it as a lever whose effectiveness depends on sectoral alignment, policy consistency, and enforcement depth. Understanding this interaction is essential for evaluating fiscal efficacy and for designing next-generation green taxation schemes that advance both environmental and socio-economic objectives in tourism.

2.3 Regulatory instruments and institutional enforcement

While fiscal instruments like environmental taxes offer market-driven incentives, regulatory frameworks—anchored in law—remain the backbone of environmental governance. Regulations serve to set binding thresholds for pollutant emissions, mandate environmental impact assessments (EIAs), enforce compliance through sanctions, and guide infrastructure toward sustainability benchmarks such as green certification and energy-efficiency standards (Filimonau et al., 2011; Sovacool et al., 2021). In tourism, where ecological damage is often embedded in everyday operations (e.g., hotel utilities, waste from events), the clarity, scope, and enforcement of legal mechanisms are decisive for long-term sustainability outcomes.

China's environmental regulatory landscape has undergone significant transformation in the past 2 decades, with laws such as the Environmental Protection Law (2014 amendment) and the Ecological Civilization framework introducing more stringent monitoring and performance-based accountability (Mu et al., 2014; Zhang et al., 2017; Zhang, 2021). However, these legal instruments are often formulated at the national level, with limited adaptability to the tourism sector's structural complexity and geographical diversity (Liu et al., 2020a; Liu et al., 2020b). Sub-sectoral discrepancies persist: while large hotels in urban centers may comply with building energy codes and EIA standards, smaller rural lodges and unregulated food vendors often operate below the regulatory radar (Campos et al., 2022; Lee et al., 2021).

Studies show that the effectiveness of environmental laws is not only a matter of design but of institutional enforcement. Weak monitoring capacity, fragmented administrative responsibilities, and insufficient local incentives result in uneven implementation (Ahmad et al., 2022; Walter, 2020; Zhang et al., 2022; Zhang and Zhang, 2018). In the tourism context, this enforcement asymmetry means that regulatory impacts may be visible in headline metrics but mask underlying spatial or sectoral blind spots. For instance, while environmental legislation may reduce GHG emissions in formal lodging facilities, its impact on emissions from street food markets or unregistered leisure operators remains negligible.

This study incorporates environmental laws (EL) as a proxy for regulatory pressure and evaluates their differential effects across China's lodging, entertainment, and food sectors. By doing so, we aim to determine whether and how regulatory instruments contribute to emission reductions, improvements in air quality (PM_{2.5}/PM₁₀), and socio-environmental metrics, such as the Environmental Footprint (ECO-F) and the Human Development Index (HDI). The analysis extends beyond legal presence and focuses on regulatory efficacy, operationalized through sector-specific responsiveness in both short-term and long-term scenarios.

2.4 Subsectoral heterogeneity in environmental outcomes

Tourism is a multifaceted industry comprising diverse sub-sectors, each with unique environmental footprints, operational structures, and resource dependencies. Treating tourism as a monolithic entity, as is common in much of the environmental literature, conceals the variation in how lodging, entertainment, and food sectors contribute to pollution, emissions, and resource depletion (Gössling et al., 2012; Sun et al., 2022; Xiong et al., 2023). This oversight undermines the development of targeted interventions and leads to policy inefficiencies that ignore sector-specific pathways of environmental degradation and sustainability potential.

The lodging sector, often dominated by high-capacity hotels and resorts, is energy- and water-intensive. Daily operations such as heating, cooling, laundry services, and lighting generate disproportionate greenhouse gas (GHG) emissions and contribute significantly to a region's ecological footprint (Filimonau et al., 2011; Huang et al., 2015). Studies have shown that water usage per guest frequently exceeds local consumption norms, particularly in destinations with high tourism density (Gössling et al., 2012; Miralles et al., 2023). Despite increasing awareness and adoption of green certifications, implementation remains inconsistent across China's hotel tiers, especially in inland and rural areas (Liu et al., 2020a).

In contrast, the entertainment sector, encompassing theme parks, cultural performances, and recreational venues, presents a more complex emissions profile. Although it may consume less energy per unit than lodging, its emissions are amplified through crowd mobility, large-scale infrastructure, land-use transformation, and extensive waste generation (Wang and Han, 2021; Zhou et al., 2023). These venues often escape rigorous environmental audits due to their fragmented ownership and seasonal fluctuations in visitor flows. Moreover, the sector's perceived social and cultural value may shield it from stricter regulatory scrutiny (Cranmer et al., 2023).

The food and beverage sector, frequently marginalized in sustainability discourse, exerts considerable environmental pressure through food production, storage, transportation, and waste disposal. Food waste, in particular, leads to high methane emissions and intensifies the ecological burden when coupled with inadequate waste segregation practices (Campos et al., 2022; Lee and Chen, 2021). On the flip side, it offers sustainability entry points through local sourcing, composting, and reduced packaging. This study leverages this heterogeneity by disaggregating sectoral responses to environmental policies, allowing us to assess whether fiscal (ETAX) and legal (EL) instruments differentially influence pollution levels and sustainability outcomes across tourism sub-sectors.

2.5 Policy effectiveness and the institutional gap

Understanding whether environmental policies “work” requires more than analyzing whether they exist; it requires evaluating their effectiveness, alignment, and responsiveness within specific sectoral and institutional contexts. In the tourism industry, where environmental impacts vary by activity, infrastructure, and location, the efficacy of environmental laws and fiscal instruments hinges on how policies are designed, implemented, and received across sub-sectors (Ahmad et al., 2022; Mu et al., 2014). Yet, existing research often stops short of measuring this effectiveness empirically, especially in relation to policy feedback mechanisms and institutional learning (Sovacool et al., 2021).

The Environmental Kuznets Curve (EKC) has long dominated theoretical explanations of the growth–environment relationship, positing that environmental degradation initially rises with income but declines after reaching a threshold (Bibi et al., 2024; Ghosh, 2020). However, this inverted U-shape offers little guidance for evaluating why and how certain policies succeed or fail in accelerating the transition to sustainability. More recent frameworks, such as Environmental Modernization Theory and Policy Feedback Theory, move beyond static trade-off models and instead emphasize the interactive role of institutions, incentives, and political will in driving sustainable transitions (Cranmer et al., 2023; Sovacool et al., 2021; Zhang et al., 2020).

Policy effectiveness is particularly complex in China, where environmental laws and taxes often coexist with fragmented implementation, regional policy experimentation, and variable administrative capacity (Liu et al., 2020a; Zhang, 2021). For instance, tax exemptions for small businesses or limited monitoring of emission thresholds can undermine intended outcomes. Likewise, vague legal language or inconsistent enforcement may erode compliance incentives in the tourism sector, particularly among informal actors and rural operators (Chan, 2021; Chen et al., 2023). This study addresses these institutional gaps by empirically assessing whether China's environmental policies, operationalized through ET and EL, generate measurable improvements in GHG emissions, particulate pollutants (PM_{2.5} and PM₁₀), ecological footprint (ECO-F), and the Human Development Index (HDI). It also bridges the gap between macro-policy goals and micro-sector realities, providing a roadmap for tourism governance reform aligned with China's broader ecological civilization vision.

TABLE 1 Variables, notations, units, and data sources.

Variables	Notations	Units	Data sources
Tourism Sectors			
Lodging sector	LOD	Number of employees	China Statistical Yearbook
Entertainment sector	ENT	Number of employees	China Statistical Yearbook
Food and drinking Places sector	FDP	Number of employees	China Statistical Yearbook
Environmental Pollutants			
Greenhouse Gases emissions	GHG	Per-capita greenhouse gas emissions in CO2 equivalent	Emissions Database for Global Atmospheric Research (EDGAR)
Particulate Matter emissions	PM2.5	µg/m ³ (tons/year)	EDGAR
Particulate Matter emissions	PM10	µg/m ³ (tons/year)	EDGAR
Sustainable Development			
Ecological Footprint	ECO-F	Global hectares per person (gha/person)	data.footprintnetwork.org
Human Development Index	HDI	0–1 score	data.footprintnetwork.org
Environmental Laws and Regulations			
Environmental Laws	EL	0–6 score	OECD
Regulations (Tax)	ETAX	US\$	OECD
Control			
Per Capita GDP	PGDP	Thousand \$ (Constant at 2011)	WDI
Energy Consumption	EGCONS	KWH/per capita/year	China Statistical Yearbook

3 Methodology

This study adopts a policy-responsive econometric approach to evaluate how environmental governance mechanisms, namely environmental taxes (ETAX) and environmental laws (EL), influence sustainability outcomes across China's key tourism sub-sectors: lodging (LG), entertainment (ENT), and food and beverage services (FDP). To capture both long-term equilibrium dynamics and short-run sectoral adjustments, we employ the Autoregressive Distributed Lag (ARDL) model (Pesaran et al., 2001), complemented by Granger causality analysis (Khan et al., 2020b). This dual approach allows for robust inference on both policy effectiveness and temporal causality between environmental instruments and sector-specific sustainability indicators.

3.1 Data and variable construction

We utilize quarterly time-series data from 2000 Q1 to 2022 Q4, derived from the China Statistical Yearbook, EDGAR (for PM2.5, PM10, GHG), and the Global Footprint Network (for ECO-F and HDI). The dependent variables include: Greenhouse Gas Emissions (GHG), Particulate Matter (PM2.5, PM10), Ecological Footprint (ECO-F), Human Development Index (HDI). Independent variables comprise employment proxies for LOD, ENT, and FDP sectors. ETAX (in USD) represents fiscal policy pressure, while EL (a 0–6 score) captures regulatory intensity. ETAX reflects *per capita* environmental tax revenue (USD) sourced from OECD's

environmental tax database, while EL is based on OECD's 0–6 institutional scoring of environmental regulatory stringency. Energy consumption (EGCONS) and *per capita* GDP (PGDP) are introduced as control variables to account for macroeconomic and energy system effects. Please see Table 1 for variable information such as notation, units, and data sources.

3.2 Modeling framework

The ARDL model is ideal for our context due to the mixed order of integration (I (0) and I (1)) among variables and its ability to model asymmetric dynamics. The general specification is:

$$\Delta Y_t = \alpha + \sum_{i=1}^p \beta_i \Delta Y_{t-i} + \sum_{j=1}^q \theta_j \Delta X_{t-j} + \sigma Y_{t-1} + \varnothing X_{t-1} + \varepsilon_t$$

Where Y_t is a sustainability indicator (e.g., ECO-F or HDI) and X_t is the vector of explanatory variables, which includes LOD, ENT, FDP, EL, ETAX, PGDP, and EGCONS. Δ denotes the first difference, β_i and θ_j are short-run coefficients, σ and $\varnothing$ represent long-run dynamics, and ε_t is the white noise error term. The error correction term (ECT) derived from this specification indicates the speed of policy-induced adjustments toward long-run equilibrium. Stationarity was tested using ADF and PP unit root tests, and optimal lags were selected using AIC and SC criteria. Cointegration among variables was verified through bounds testing (Pesaran et al., 2001), enabling the separation of

long-run governance effects from short-term policy shocks. The model is appropriate for series integrated at I (0) or I (1), but not I (2), and is widely applied in sustainability and environmental research for its flexibility and robustness.

3.3 Granger causality

To assess directional causality and institutional feedback loops, we apply the Granger causality test (Page, 1954). This reveals whether environmental policies (ETAX, EL) predictively influence environmental and socio-economic outcomes or whether reverse causality, from emissions back to policy, exists. This is crucial for diagnosing whether China's tourism governance is reactive, proactive, or stagnant in the face of sustainability pressures.

3.4 Diagnostic and visualization enhancements

To strengthen the empirical robustness and interpretive clarity of the ARDL estimations, a suite of advanced diagnostic visualizations was employed. These diagnostics complement the econometric specification and serve to validate the internal consistency, predictive accuracy, and sectoral heterogeneity captured by the model. The visual analysis proceeds through a multi-dimensional lens, incorporating elasticity mapping, dynamic adjustment patterns, causal networks, trade-off diagrams, and prediction fit assessments (Herrero et al., 2022; Lenzen et al., 2018).

First, the long-run elasticity estimates were visualized through a sector-disaggregated bar chart, illustrating the policy responsiveness of tourism sub-sectors, LOD, ENT, and FDP, across six sustainability indicators, including greenhouse gas emissions (GHG), air pollutants (PM2.5 and PM10), ecological footprint (ECO-F), human development index (HDI), and energy consumption (EGCONS). This visualization facilitates comparative insight into the intensity and direction of long-run effects, offering an intuitive representation of the ARDL coefficients and their sector-specific heterogeneity (Aratuo and Etienne, 2019; Balsalobre-Lorente et al., 2023). Second, to assess system stability and temporal responsiveness, the error correction terms (ECT) were graphically plotted. These coefficients represent the speed of adjustment to long-run equilibrium following short-term shocks. The visual confirms that all ECT values are negative and statistically significant, indicating robust convergence behavior and reliable model dynamics (Pesaran et al., 2001; Khan et al., 2020c).

Third, a Granger causality network diagram was constructed to map directional dependencies among governance variables (environmental laws and taxes), macroeconomic controls (*per capita* GDP and energy consumption), and tourism sub-sectors. This visualization translates pairwise Granger test results into a causal structure, offering insight into feedback loops and indirect policy pathways influencing sustainability outcomes (Khan et al., 2021b; Li et al., 2023). Fourth, to contextualize the balance between environmental costs and socio-economic benefits, an ECO-F–HDI trade-off map was developed. Each sub-sector was plotted in a two-dimensional quadrant reflecting its contribution to ecological pressure and human development. This visualization provides an

intuitive diagnosis of policy tension, enabling the identification of sectoral positions within the sustainability spectrum (Ridderstaat et al., 2022).

Finally, predicted versus actual plots were generated for GHG, ECO-F, and HDI to evaluate model performance. These scatterplots display a high degree of alignment along the 45-degree line, reinforcing the predictive strength of the ARDL model. The close correspondence between observed and estimated values affirms the model's explanatory power and its capacity to simulate sustainability outcomes across tourism sub-sectors under different policy conditions (Bibi et al., 2024; Scott et al., 2019). Together, these visual diagnostics not only confirm the statistical robustness of the results but also enhance interpretability, offering decision-makers a clearer lens through which to evaluate sector-specific sustainability interventions in tourism governance.

4 Results

To ensure data consistency and interpretability, all variables were transformed into their natural logarithmic form (see Supplementary Table S2 for descriptive statistics in the Supplementary Material). This transformation helped correct for non-normality and heteroscedasticity, both of which are common in time-series data involving environmental and economic indicators. All the variables were seasonally adjusted. Stationarity was verified using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests (see Table 2). The results confirmed that all series were stationary at either level or first difference, thereby satisfying the precondition for applying the Autoregressive Distributed Lag (ARDL) bounds testing framework. Optimal lag lengths for each model were selected using the VAR lag-order selection criteria, ensuring robust dynamic specifications (please see Supplementary Table: Lag length criteria in Supplementary Material) (Khan et al., 2020c). Cointegration analysis using the bounds test approach revealed statistically significant long-run relationships among tourism sub-sectors, environmental governance variables, and sustainability outcomes (see Table 3).

4.1 Environmental and sustainability dynamics

The long-run results presented in Table 4 highlight the heterogeneous impacts of tourism sub-sectors and governance variables on environmental and sustainability outcomes. Among all sectors, lodging (LOD) emerges as the most environmentally intensive, exhibiting a statistically significant positive association with greenhouse gas (GHG) emissions ($\beta = 0.16^*$) and ecological footprint (ECO-F; $\beta = 0.84^*$), while simultaneously exerting a negative influence on the Human Development Index (HDI; $\beta = -0.22^*$) and energy efficiency (EGCONS; $\beta = -2.26^*$). These findings suggest that the lodging sector not only contributes to ecological degradation but also fails to translate its economic activity into social development or energy optimization, positioning it as a priority target for environmental governance interventions.

In contrast, the entertainment sector (ENT) presents a more complex profile. It positively contributes to air pollutant levels,

TABLE 2 Stationarity test and level of integration.

Variables	Augmented dickey-fuller		Phillips-perron		Remarks
	Level	Difference (1)	Level	Difference (1)	
LOD	−3.18**	−10.09*	−3.30**	−10.08*	I (0) & I (1)
ENT	−3.37*	−11.7*	−3.21**	−12.38*	I (0) & I (1)
FDP	−4.46*	−13.29*	−4.51*	−14.14*	I (0) & I (1)
EGCONS	−3.22**	−1.303	−4.04*	1.52	I (1)
PGDP	−2.59***	−3.74**	−2.82***	−3.17***	I (0) & I (1)
ETAX	−2.19	−3.87*	−4.54*	−3.95*	I (0) & I (1)
EL	−2.49	−3.87*	−2.42	−3.86*	I (1)
GHG	−2.42	−4.92*	−0.71	−4.72*	I (1)
PM2.5	−3.29*	−4.97*	−3.07**	−4.29*	I (0) & I (1)
PM10	−3.53**	−2.94**	−2.86**	−4.53*	I (0) & I (1)
ECO-F	−2.89**	−3.19***	−3.76*	−3.31***	I (0) & I (1)
HDI	−2.74***	−2.64***	−4.73*	−2.65***	I (0) & I (1)

Note: Asterisks *, **, and *** indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 3 ARDL Bounds test for co-integration results.

ARDL model	F-static-p	Critical bounds value		
		1%	5%	10%
GHG f (GHG LOD, ENT, FDP, EGCONS, PGDP, ETAX, EL)	6.6*	2.96–4.26	2.23–3.50	2.03–3.13
PM2.5 f (PM2.5 LOD, ENT, FDP, EGCONS, PGDP, ETAX, EL)	7.9*	2.96–4.26	2.23–3.50	2.03–3.13
PM10 f (PM10 LOD, ENT, FDP, EGCONS, PGDP, ETAX, EL)	9.1*	2.96–4.26	2.23–3.50	2.03–3.13
ECO-F f (ECO-F LOD, ENT, FDP, EGCONS, PGDP, ETAX, EL)	7.2*	2.96–4.26	2.23–3.50	2.03–3.13
HDI f (HDI LOD, ENT, FDP, EGCONS, PGDP, ETAX, EL)	5.3*	2.96–4.26	2.23–3.50	2.03–3.13
EGCONS f (EGCONS LOD, ENT, FDP, PGDP, ETAX, EL)	54.6*	3.15–4.43	2.75–3.99	2.12–3.23

Note: Asterisks *, **, and *** indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

including PM2.5 ($\beta = 1.03^*$) and PM10 ($\phi = 1.01^*$), yet also demonstrates a strong positive relationship with HDI ($\beta = 0.28^{**}$) and energy growth (EGCONS; $\beta = 2.26^*$). Notably, ENT is associated with a reduction in ECO-F ($\beta = -1.09^*$), implying a relatively balanced sustainability footprint that combines socio-economic benefits with partial ecological gains. Meanwhile, the food and beverage sector (FDP) displays a net mitigating effect on PM2.5 and PM10 ($\beta = -1.24^*$, $\beta = -1.29^*$), reflecting its potential to contribute to air quality improvements, particularly when supported by targeted policies and cleaner operational practices.

Environmental regulation (ETAX) plays a consistently beneficial role, significantly reducing GHG emissions ($\beta = -0.07^*$), PM2.5 ($\beta = -0.12^*$), and PM10 ($\beta = -0.11^*$), while also improving ECO-F and HDI. These effects support the efficacy of regulatory enforcement in aligning sectoral activities with sustainability goals. Environmental law (EL), while effective in reducing GHG emissions ($\beta = -0.011^{**}$), shows mixed results by increasing levels of PM2.5, PM10, and energy use, indicating that fiscal instruments may

require better calibration or stronger enforcement to avoid sectoral spillovers and unintended trade-offs. Per capita GDP (PGDP) is associated with improved air quality yet simultaneously increases ECO-F ($\beta = 0.15^*$), highlighting the classic development-environment trade-off, wherein rising affluence correlates with greater ecological pressure despite technological or regulatory gains.

Short-run dynamics reveal partial reversals and more immediate sectoral responses to regulatory change. Both LOD and ENT show reductions in GHG, PM2.5, and PM10 in the short run, suggesting that these sectors may exhibit short-lived improvements in emissions performance following shifts in regulatory or economic conditions. The FDP sector continues to reduce ECO-F and EGCONS in the short term, while positively affecting HDI ($\beta = -0.12^{***}$), indicating its latent potential to advance sustainability through cleaner practices and localized value chains. Governance variables such as ETAX and EL maintain their pollutant-mitigating effects in the short run, although their effectiveness appears conditional on sectoral activity intensity and

TABLE 4 Environmental and Sustainability Long and short-run dynamics.

Variables	GHG emissions	Air pollutants		Sustainability		Energy
Ind/Dep	GHG	PM2.5	PM10	ECO-F	HDI	EGCONS
LOD	0.16*			0.84*	−0.22*	−2.26*
ENT		1.03*	1.011*	−1.09*	0.28**	2.26*
FDP		−1.24*	−1.29*			
EGCONS	0.26*	0.26*	0.21*			
PGDP	−0.12*	−0.08*	−0.063*	0.15*		−0.34*
ETAX	−0.07*	−0.12*	−0.12*	0.15*	0.04*	0.25*
EL	−0.011**	0.13*	0.13*		0.03*	0.18*
Constant	3.57*	21.27*	22.55*	−10.72*		
Short-run dynamics						
LOD	−0.13**	−0.199***	0.22***	−0.27**	0.08***	0.18*
ENT	−0.17**	−0.11**	−0.02**	0.23*	0.07***	−0.11***
FDP		0.34**	0.29**	−0.41*	0.12***	−0.11***
EGCONS	0.13*	−0.37***	−0.39***	0.55*	0.16***	
PGDP	0.13***	−0.45**	−0.32***	0.09***	0.12*	−0.18**
ETAX	−0.08*	−0.06***	0.07**	−0.04**		0.022***
EL		−0.08***		−0.03***	0.03**	−0.08*
Diagnostic						
A	1.61 (0.21)	2.34 (0.08)	2.22 (0.09)	0.07 (0.78)	1.39 (0.25)	0.62 (0.55)
B	1.43 (0.07)	0.97 (0.54)	0.96 (0.55)	0.52 (0.98)	0.83 (0.71)	1.34 (0.17)
C	5.24 (0.08)	2.08 (0.35)	8.34 (0.06)	3.46 (0.18)	2.35 (0.31)	2.45 (0.29)
Adjusted R ²	0.98	0.79	0.97	0.98	0.99	0.98
F-Statistic	1,336.04	82.59	85.5	11,537.9	8,960.7	40,473.9
P-value	0.001	0.001	0.001	0.001	0.001	0.001
CUSUM	Stable	Stable	Stable	Stable	Stable	Stable
CUSUMSQ	Unstable	Stable	Stable	Stable	Stable	Stable
ECT	−0.51*	−0.65*	−0.75*	−0.32*	−0.72*	−0.11*

Note: A refers to serial correlation (Breusch-Godfrey LM test), B denotes heteroskedasticity (Breusch-Pagan-Godfrey test), and C indicates normality of residuals (Jarque-Bera test). ECT stands for the error correction term, capturing the speed of adjustment toward long-run equilibrium. Statistical significance is represented by *, **, and ***, corresponding to the 1%, 5%, and 10% significance levels, respectively.

responsiveness, highlighting the need for sector-specific policy targeting.

The overall reliability and internal consistency of the estimated models are well-supported by rigorous diagnostics. All six models demonstrate high explanatory power, with adjusted R² values exceeding 0.79 and statistically significant F-statistics at the 1% level. Residual diagnostics, including the Jarque-Bera, Breusch-Godfrey, and Breusch-Pagan-Godfrey tests, confirm that residuals are normally distributed, homoscedastic, and free from serial correlation. Importantly, the presence of statistically significant and negative error correction terms (ECTs) across all models further reinforces the models' ability to capture long-run equilibrium adjustments and temporal stability, in line with prior

applications of the ARDL framework in tourism-environmental modeling (Khan et al., 2021a; Xiong et al., 2023).

The Granger causality analysis (Table 5) adds depth to the econometric findings by revealing key directional dependencies across sectors, environmental indicators, and governance instruments. Lodging (LOD) appears as a dominant causal driver, influencing GHG emissions, ECO-F, HDI, EGCONS, PGDP, and ETAX. This pattern highlights the structural influence of lodging on both ecological outcomes and institutional policy responses. Entertainment (ENT) demonstrates reciprocal causality with EGCONS and PGDP, while also being shaped by regulatory instruments (ETAX and EL) and socio-environmental variables (ECO-F and HDI), suggesting it occupies

TABLE 5 Granger Causality test.

	GHG	PM2.5	PM10	ECO-F	HDI	ETAX	EL	EGCONS	PGDP
LOD	⇒ 3.8**			⇒ 2.3**	⇒ 3.9*	⇒ 3.6**		⇒ 19.7*	⇒ 18.01*
ENT	⇐ 3.2**			⇐ 5.9*	⇐ 6.9**	⇐ 4.11**	⇐ 3.3**	⇐ 6.3**/10.6*	⇐ 7.4**/16.9*
FDP	⇐ 14.15*	⇒ 11.5**	⇒ 3.2**	⇐ 11.25*/2.12**	⇐ 15.23*	⇐ 6.5**	⇐ 5.05*	⇐ 3.6**	⇐ 4.6**
EGCONS	⇒ 4.4**	⇐ 3.16**/3.7**	⇐ 3.2**/4.9*	⇒ 7.35*	⇐ 6.5**/13.1*		⇒ 3.30*		⇐ 14.2*/51.7*
PGDP	⇐ 7.9*/36.3*	⇒ 3.08**	⇒ 5.8*	⇐ 26.34*/19.49*	⇒ 2.9**/6.9*	⇐ 20.23*	⇒ 2.9**	⇐ 14.2*/51.7*	
ETAX	⇐ 2.54**	⇒ 2.7**	⇒ 2.8**	⇒ 44.05*	⇒ 7.12*		⇐ 174*/5.6**	⇒ 2.35**	⇒ 20.23*
EL	⇐ 3.07**	⇐ 13.7*	⇒ 2.8**	⇐ 9.1*/3.7**	⇒ 2.9**	⇐ 17.4*/5.6**		⇐ 4.8*	⇒ 2.9**

In this table, statistical significance is denoted by * and **, corresponding to the 0.001 and 0.05 levels, respectively. Causal directions are presented using symbolic notation to ensure interpretive clarity and consistency with Granger causality conventions. Specifically, the symbol “⇒” is used to indicate a unidirectional causal relationship from one variable to another, meaning that changes in the first variable precede and statistically explain changes in the second. Conversely, “⇐” indicates that the second variable Granger-causes the first, highlighting reverse directionality. Bidirectional causality—where both variables significantly influence each other over time—is represented by the symbol “⇔.”

a central position in the tourism sustainability policy network. Food services (FDP) are found to cause changes in air pollution levels but are themselves influenced by a broader constellation of factors, including fiscal and legal governance instruments and economic development indicators.

Bidirectional causality between ECO-F and FDP further highlights a dynamic feedback mechanism wherein ecological degradation and sectoral behavior evolve in tandem. Similarly, ETAX and EL emerge not only as drivers of environmental outcomes but also as endogenous responses to shifting sectoral and macroeconomic conditions. This recursive nature of policy response suggests that governance instruments are embedded within broader sustainability feedback systems, rather than operating as static or exogenous levers. The Granger causality network visualization (Figure 1C) affirms this interpretation by mapping a dense web of interconnections among sectors, governance variables, and sustainability indicators. These multi-directional linkages reinforce the need for adaptive, sector-sensitive governance models capable of responding to both upstream and downstream sustainability pressures.

4.2 Diagnostics and visualization

The results of the long-run elasticity analysis, illustrated in Figure 1A, reveal considerable variation in sectoral impacts. Lodging (LOD) demonstrates the strongest positive elasticity on both greenhouse gas (GHG) emissions and the ecological footprint (ECO-F), identifying it as the most environmentally intensive sub-sector. The FDP and ENT sectors exert comparatively moderate effects but follow distinct patterns. While ENT contributes positively to the Human Development Index (HDI), indicating its socio-economic value, both LOD and ENT display negative elasticities for EGCONS, suggesting inefficiencies or demand-driven strain on energy systems that may undermine environmental goals in the long term.

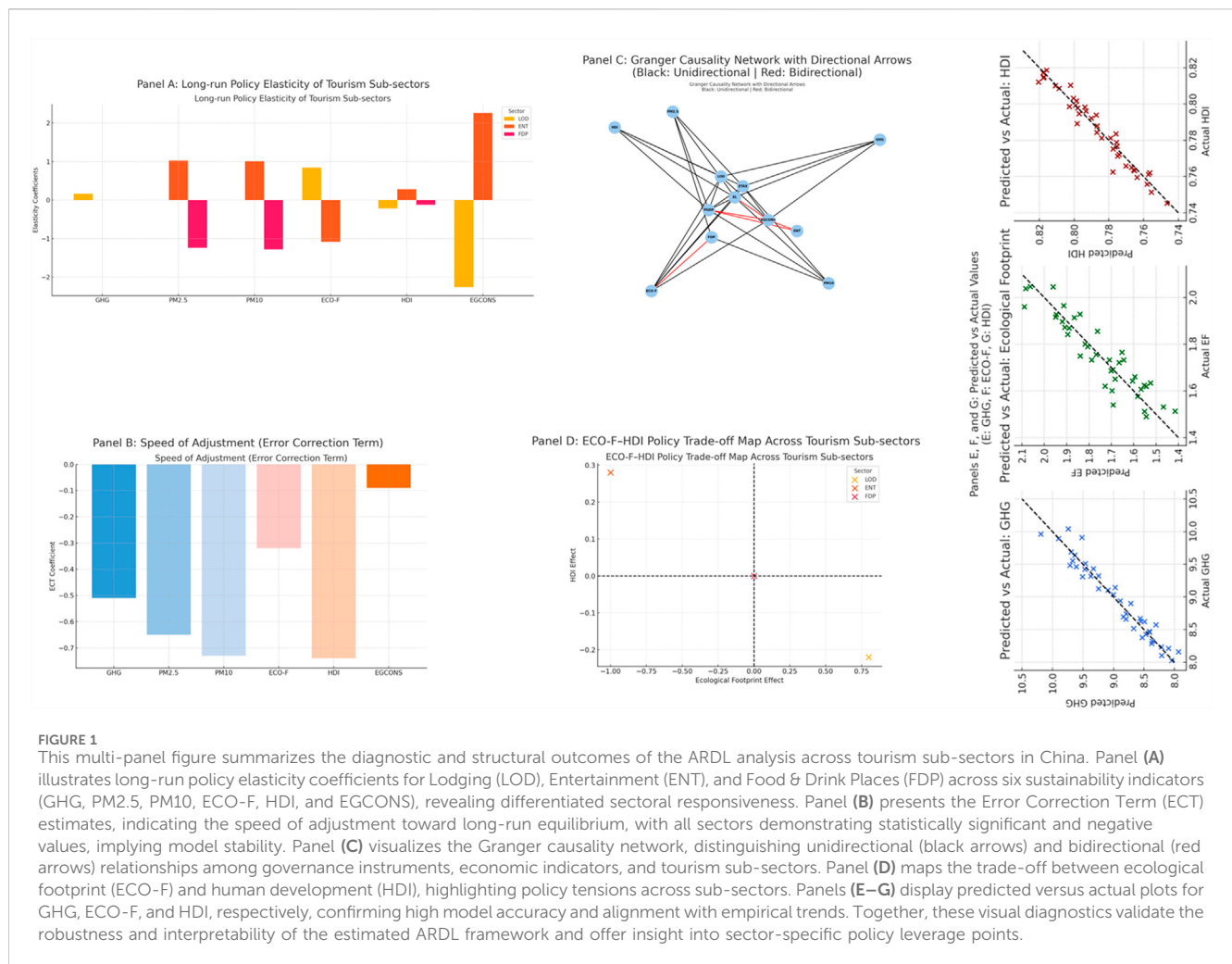
Adjustment dynamics, shown in Figure 1B, provide further insight into the temporal responsiveness of sustainability outcomes to sectoral and policy changes. The error correction term (ECT) coefficients are all negative and statistically significant, ranging between −0.25 and −0.65. This implies that

deviations from long-run equilibrium are corrected over time, with ECO-F and HDI showing the fastest adjustment speeds. These results highlight the long-run stability of the system and the capacity of policy interventions to induce meaningful shifts in key sustainability indicators.

The structural relationships among variables are mapped in the Granger causality network presented in Figure 1C. The diagram highlights the centrality of lodging (LOD) as a dominant driver influencing GHG, ECO-F, HDI, and energy consumption, as well as key governance variables. ENT is shaped by human development, ecological outcomes, and fiscal policy (EL), and in turn affects macroeconomic and energy indicators. Feedback loops between *per capita* GDP (PGDP) and HDI, as well as between EGCONS and air pollutants (PM2.5 and PM10), suggest cyclical dependencies and interactions within the policy-environment-economy nexus.

Figure 1D offers a visual depiction of the trade-offs between environmental pressure and socio-economic benefits. The ECO-F–HDI policy trade-off map reveals that all three tourism sub-sectors contribute positively to HDI, but at varying ecological costs. Lodging lies in the quadrant representing high ecological burden and moderate HDI gains, indicating a development path that sacrifices environmental quality. Entertainment, by contrast, strikes a more balanced profile with relatively lower ecological costs. The food sector clusters near the center, implying limited ecological impact with moderate social benefits. These findings reinforce the need for sector-specific governance mechanisms that account for differentiated sustainability performance.

Finally, Figures 1E–G present the predicted versus actual values for GHG, ECO-F, and HDI. Across all three indicators, the scatter plots show strong clustering around the 45-degree reference line, confirming the high predictive power of the ARDL models. The GHG panel demonstrates tight alignment with minimal variance, suggesting that emissions dynamics are well captured by sectoral and policy variables. The ECO-F panel, though showing a slightly wider spread, still reflects a strong fit between predicted and observed values. The HDI panel exhibits the closest alignment, confirming that variables such as environmental regulation and fiscal policy are robust predictors of socio-economic development. Collectively, these diagnostics affirm the reliability and stability of the ARDL framework in modeling the complex interrelationships among tourism activities, governance structures, environmental



conditions, and development outcomes. The results validate the models' use not only for historical explanation but also for forward-looking policy simulation.

5 Discussion

The empirical findings of this study provide compelling evidence that environmental governance, operationalized through fiscal instruments (environmental taxes) and regulatory frameworks (environmental laws), plays a pivotal role in shaping the sustainability outcomes of China's tourism sub-sectors. The results reveal a clear pattern of sectoral heterogeneity: the lodging sector consistently imposes the greatest environmental burden, while the entertainment and food sectors demonstrate relatively lower ecological costs and stronger social returns. This reinforces the central tenet of environmental governance theory, which holds that effective sustainability transitions depend on both the strength of institutional mechanisms and their capacity to adapt to sector-specific conditions (Cranmer et al., 2023; Gao et al., 2022; Sovacool et al., 2021).

From the perspective of Environmental Modernization Theory, the long-run elasticity estimates confirm that economic

modernization within tourism is not inherently incompatible with environmental sustainability, but requires targeted policy intervention. The strong positive elasticity of lodging on both greenhouse gas emissions and ecological footprint underscores that, without regulatory oversight, infrastructure-intensive services disproportionately externalize environmental costs. This is consistent with recent findings by Irfan et al. (2023), who demonstrate that the lodging sector in China significantly amplifies energy consumption and emissions, highlighting its critical role in shaping tourism's environmental burden. Conversely, the entertainment sector shows a negative relationship with ECO-F and a positive association with HDI, highlighting its potential as a driver of inclusive development with manageable ecological trade-offs. This sectoral divergence highlights the importance of designing governance structures that are calibrated not only to aggregate sustainability targets but also to the operational realities of individual sub-sectors (Xiong et al., 2023).

The significant and negative error correction terms (ECTs) across all models indicate a robust tendency toward long-run equilibrium, suggesting that the Chinese governance apparatus possesses sufficient institutional capacity to steer tourism toward sustainability goals. These dynamics validate key assumptions in Policy Feedback Theory, particularly the notion that well-

institutionalized policy instruments generate self-reinforcing behavioral responses over time (Ahmad et al., 2022). The rapid adjustment observed in the HDI and ECO-F models implies that governance interventions can yield relatively swift gains in both human development and ecological mitigation when directed through responsive policy levers.

Our findings also contribute to the debate on the Environmental Kuznets Curve (EKC). While PGDP exhibits a negative long-run association with GHG emissions and air pollutants, it has a positive relationship with EF, suggesting that economic growth may reduce certain types of pollution but does not automatically resolve issues of resource overuse. This asymmetry lends support to the critiques of EKC theory, which argue that the inverted U-shaped trajectory is overly simplistic and does not account for multidimensional sustainability indicators (Bibi et al., 2024; Ghosh, 2020). By including both emissions and ecological footprint in the analysis, this study offers a more granular understanding of how tourism-led economic growth interacts with environmental limits.

The Granger causality network further illuminates the complex and often bidirectional relationships between governance instruments, sectoral activity, and sustainability outcomes. Lodging emerges as a dominant causal driver, influencing GHG, ECO-F, HDI, and governance variables, while being minimally shaped by external forces. This suggests a form of institutional inertia, where high-impact sectors are less responsive to regulation, a concern echoed in the literature on governance asymmetry (Lee and Chen, 2021; Zhang and Zhang, 2021). In contrast, the food and entertainment sectors exhibit stronger feedback loops, particularly with PGDP and environmental policies, indicating that these areas may be more amenable to adaptive regulation. This distinction is vital for policymakers, as it highlights where governance leverage is strongest and where more intensive interventions may be necessary.

The ECO-F–HDI trade-off map offers a novel diagnostic for evaluating policy effectiveness across multiple dimensions. It reveals that the pursuit of socio-economic development via tourism is not uniformly sustainable and may entail substantial environmental sacrifices, particularly in lodging-heavy economies. While some previous studies acknowledge this trade-off (Gössling et al., 2012; Ridderstaal et al., 2022; Sun et al., 2022), few have visualized it as explicitly as in this study. The relative positioning of sectors within the ECO-F–HDI space provides actionable insights: policies aimed at expanding lodging capacity must be accompanied by rigorous environmental safeguards, while investments in entertainment infrastructure may offer a more sustainable path to development.

The predictive performance of the ARDL models adds further weight to these conclusions. The close alignment between predicted and actual values for GHG, ECO-F, and HDI affirms that environmental laws and fiscal policies are not merely symbolic but serve as statistically significant determinants of sustainability outcomes. These findings validate the growing body of literature that views environmental taxation and regulation as essential tools for internalizing negative externalities in tourism (Pata and Caglar, 2021; Sovacool et al., 2021). The particularly strong predictive accuracy for HDI suggests that socio-economic benefits from tourism can be reliably linked to governance inputs—an encouraging sign for development planners aiming to balance growth with equity.

This study also offers a methodological contribution by disaggregating the tourism sector into its core components and analyzing them through a unified governance framework. Many prior works treat tourism as a homogeneous entity or focus narrowly on specific impacts such as carbon emissions or water use (Lenzen et al., 2018; Paramati et al., 2017). By contrast, our approach incorporates environmental, economic, and social dimensions simultaneously and highlights how governance structures mediate these relationships in sector-specific ways. Such sectoral differentiation is critical for advancing both theoretical understanding and practical policy design, as it supports the development of tailored interventions rather than relying on generic, one-size-fits-all approaches.

This study demonstrates that China's tourism governance, though broadly effective, is uneven in its reach and responsiveness. Lodging remains a high-impact sector with low regulatory elasticity, requiring stronger enforcement and innovation in green infrastructure. Entertainment and food services, on the other hand, appear more adaptable and capable of delivering sustainable development under targeted fiscal and legal incentives. These insights contribute to a deeper understanding of how governance systems can be optimized to align tourism growth with environmental and social goals. In doing so, the study not only extends the theoretical scope of environmental governance and policy feedback frameworks but also provides a practical roadmap for designing sector-specific interventions in high-growth tourism economies.

5.1 Policy implications

The findings of this study yield several concrete implications for tourism governance, fiscal policy design, and environmental sustainability planning in China. As tourism continues to expand under the country's domestic consumption and regional revitalization agendas, the integration of robust governance mechanisms is not only desirable but imperative. The differentiated environmental and social impacts observed across lodging, entertainment, and food sectors underline the need for sector-specific policy targeting, rather than generic or aggregate-level interventions.

The lodging sector emerges as a priority for regulatory intervention. Its consistently high elasticity with respect to greenhouse gas emissions and ecological footprint, coupled with its weak contribution to human development and energy efficiency, suggests that the environmental costs of lodging expansion often outweigh its socio-economic benefits. Policies in this domain should move beyond basic green certification and toward performance-based incentives, such as tiered tax reductions for verified reductions in emissions and resource consumption. Moreover, investment in low-carbon infrastructure, such as passive design architecture, renewable energy integration, and circular water systems, must be incentivized through coordinated national and provincial policies. Environmental regulation enforcement should be intensified, particularly in peri-urban and scenic zones where tourism construction outpaces oversight.

In contrast, the entertainment sector offers a more balanced sustainability profile, exhibiting positive contributions to HDI and a

manageable ecological footprint. This indicates a high potential for synergy between cultural development, leisure consumption, and sustainability goals. Policymakers should consider this sub-sector as a lever for inclusive, low-carbon growth. Financial subsidies or public-private partnerships for community-led performance spaces, nature-based attractions, and digital entertainment technologies can enhance tourism offerings while maintaining ecological limits. At the same time, regulators must implement clearer environmental benchmarks for crowd-intensive facilities, especially regarding emissions from transportation, event infrastructure, and waste generation.

The food and beverage sector, while often neglected in environmental policy design, shows significant sensitivity to both fiscal and regulatory instruments. Its ability to reduce air pollutants in the long run and support human development outcomes makes it a valuable but underutilized policy target. Authorities should implement green labeling for food outlets, introduce kitchen electrification standards, and offer fiscal incentives for local sourcing and organic inputs. More granular monitoring of food waste, packaging materials, and carbon intensity of ingredients should also be embedded in municipal tourism regulations, particularly in high-density urban corridors and heritage zones.

At a broader level, the study highlights the critical role of environmental taxes and environmental laws as instruments of institutional responsiveness. Their statistically significant influence across models confirms that policy levers can meaningfully shape sustainability outcomes, provided they are appropriately calibrated and consistently enforced. The observed discrepancies in responsiveness across sub-sectors, however, suggest that a one-size-fits-all approach may dilute their impact. Policymakers should therefore integrate a flexible governance model that allows for real-time policy adaptation based on performance metrics, sectoral characteristics, and spatial variability.

The Granger causality analysis further reinforces the need for multi-level governance coordination. The bidirectional linkages between PGDP, energy consumption, and pollution indicators imply that tourism-related environmental degradation is intricately tied to macroeconomic planning and infrastructure policy. Local governments must be empowered, not only with mandates but also with fiscal and technical capacity, to integrate tourism within broader climate action and sustainable development frameworks. Environmental impact assessments should be made mandatory for large-scale tourism projects, and results should be publicly disclosed to ensure accountability and community engagement.

Finally, the ECO-F-HDI trade-off map presents a novel and policy-relevant diagnostic for strategic prioritization. Tourism policymakers, environmental planners, and development agencies should jointly use such diagnostics to identify “sweet spots” of policy intervention, where human development gains can be maximized without disproportionately increasing ecological burdens. This diagnostic approach can be embedded into sustainability performance reviews for provincial tourism plans and annual green GDP accounting. A policy framework that combines differentiated sectoral strategies, outcome-based incentives, and adaptive governance mechanisms will be essential to achieving the dual goals of carbon reduction and high-quality tourism development under China’s broader ecological civilization agenda.

6 Conclusion

This study uncovers critical interdependencies between tourism sub-sectors, environmental pressures, and governance mechanisms, calling for a re-evaluation of tourism’s role within national sustainability and climate strategies. The empirical findings reveal that environmental performance is not uniform across sectors: lodging exerts disproportionate ecological pressure due to structural inefficiencies and regulatory gaps, while the entertainment sector demonstrates greater alignment between environmental limits and human development benefits. A key insight is that governance effectiveness, via environmental regulation and taxation, is not automatic but conditional on sectoral characteristics, macroeconomic context, and policy coherence. Uniform policies are insufficient; differentiated and adaptive governance frameworks are essential to manage sector-specific trade-offs and feedback loops. This challenges prevailing assumptions about linear policy impact and calls for regulatory architectures that are responsive to evolving system dynamics.

The study’s methodological contribution lies in combining ARDL modeling with Granger causality mapping and ECO-F-HDI trade-off analysis. This multi-dimensional approach enhances the diagnostic capacity to evaluate both direct effects and systemic interactions, offering valuable tools for future policy simulation and scenario planning. Policy implications are clear: sustainability in tourism cannot be achieved through symbolic green initiatives alone. Effective transformation requires integrated, anticipatory governance that embeds sustainability into the operational fabric of tourism sectors. For China, aligning the tourism system with its “dual carbon” agenda will demand greater cross-sectoral coordination, data granularity, and institutional learning. In reframing tourism as a modifiable system shaped by governance quality and sectoral design, this study offers an integrative framework for researchers, policymakers, businesses, and civil society to evaluate the environmental performance of tourism subsectors and inform sector-specific sustainability strategies.

6.1 Limitations and future research directions

While this study offers valuable empirical and theoretical contributions, several limitations merit acknowledgment and provide opportunities for future research enhancement. First, although the ARDL framework effectively captures both long-run equilibrium relationships and short-term adjustments, it is inherently a linear model. Non-linear interactions, threshold effects, or feedback loops, especially prevalent in environmental and tourism systems, may not be fully captured. Future studies could integrate non-linear or machine learning approaches (e.g., panel quantile regression, structural equation modeling, or deep learning algorithms) to better model complex, non-additive dynamics among governance tools and sustainability indicators.

Second, our focus on China provides a unique and high-impact policy context, given its centralized governance system, large-scale tourism infrastructure, and aggressive environmental targets. However, this national context also limits the generalizability of our findings. Comparative studies across countries with different

regulatory capacities, fiscal structures, and tourism sector compositions would help validate the robustness of these insights and offer global lessons for tourism-environment governance. Moreover, within China, regional disparities in governance effectiveness, enforcement rigor, and ecological vulnerability suggest that provincial or city-level disaggregation could yield deeper place-based policy insights. Third, while the study captures key environmental (GHG, PM2.5, PM10, EF) and socio-economic (HDI) outcomes, other dimensions of sustainable development, such as biodiversity loss, water resource depletion, cultural displacement, or social equity, were not directly included due to data availability constraints. Future research should adopt a broader indicator framework that includes planetary boundaries, social inclusion metrics, and climate adaptation readiness to enrich the evaluation of tourism sustainability.

Fourth, the proxies used for governance (environmental laws and environmental taxes) capture institutional presence but not necessarily enforcement strength or policy quality. Similarly, the number of employees in each tourism sub-sector, while useful for measuring sectoral scale, may not fully represent energy use intensity or carbon footprints from operational and consumption activities. Micro-level data, such as firm-level emissions, household tourism expenditures, or city-level green finance allocation, could enhance the precision of sectoral sustainability diagnostics. Lastly, while Granger causality and ARDL bounds testing are valuable for identifying statistical relationships and directional dependencies, they do not confirm structural causality or behavioral mechanisms. To address this, future studies should triangulate quantitative modeling with qualitative or mixed-method approaches, such as policy process tracing, stakeholder interviews, or field experiments. This would not only clarify how and why policies succeed or fail in specific tourism domains but also offer context-sensitive pathways for policy transferability.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: China Statistical Yearbook, Emissions Database for Global Atmospheric Research (EDGAR), data.footprintnetwork.org, OECD, WDI.

Author contributions

AK: Writing – review and editing, Supervision, Writing – original draft, Project administration. SB: Conceptualization, Investigation, Resources, Formal Analysis,

Writing – original draft, Writing – review and editing. HL: Resources, Funding acquisition, Writing – review and editing, Writing – original draft, Methodology, Data curation, Formal Analysis. DM: Resources, Funding acquisition, Writing – original draft, Writing – review and editing, Visualization.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2025.1649949/full#supplementary-material>

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