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TOURISM GROWTH AND WETLAND STRESS IN ALAPPUZHA (KERALA)

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Abstract

Vembanad Lake, a Ramsar-designated wetland of international importance in Kerala's Alappuzha district, exemplifies the growing tension between tourism-led economic expansion and ecological sustainability in fragile wetland systems. This study examines how rapid houseboat tourism growth, inadequate waste management, and weak regulatory enforcement have collectively undermined Ramsar compliance and wetland resilience. Using a mixed-methods approach combining household surveys, waste audits, GIS-based spatial analysis, and policy review (2010–2025), the study quantifies pollution loads, infrastructure expansion, and governance gaps linked to tourism intensity. Findings indicate that houseboats and resorts generate over 13,700 tons of untreated sewage and 2,000 tons of plastic waste annually, while treatment and regulatory compliance remain below 25%. Key pollution indicators—biological oxygen demand, chemical oxygen demand, microplastics, and coliform bacteria—consistently exceed permissible limits and are strongly associated with habitat fragmentation. Although tourism generates employment and income, ecological costs are disproportionately borne by wetland-dependent fishing communities. The study concludes that wetland degradation in Vembanad reflects a governance failure rather than a technical deficit and advocates enforceable waste standards, decentralized management, and community-based Ramsar stewardship to align tourism growth with ecological thresholds.

Keywords: *Vembanad Lake; Ramsar Wetlands; Tourism Growth; Waste Management; Wetland Governance; Policy Compliance; Socio-Ecological Sustainability*

1. Introduction

Vembanad Lake, listed under the Ramsar Convention site between Alappuzha and Kottayam Districts of Kerala has in recent decades become a site of rapid tourism-led development that is exposing the conflict between economic development and wetland conservation. What was a little-utilized activity in the late 1990s has, through proliferation of numbers, density and size, from large, mechanized houseboats to shikari boats to even knee-jerked motorized vessels now vying for space in the lake, exerting unprecedented pressures on hydrology, water quality, fisheries and biodiversity. With the growing number of domestic and international tourists, the uncontrolled disposal of sewage untreated sewage, fuel spilling, and waste loading (especially plastics) into the backwater system has also increased. These pressures are layered on top of old but unresolved stressors, including N- and P-rich agricultural runoff from the polders at Kuttanad, industrial effluents to feeder canals and mass land reclamation depleting lake depth and buffering capacity. Pathiramanal Island, where migratory avifauna and endemics once sheltered, is now making difficult military construction from where wars for the influations free of charge by used bream boats and tourism infrastructures, extracting energies, commenced banging nests of avifauna for nesting and carrier laying grounds.

Together, these lead to deteriorating water quality, more microplastics entering aquatic food chains, declines in fish catch and increased pressure on traditional livelihoods from fishing and clam collection. Governance responses are fragmented, where sewage treatment norms (despite its Ramsar status) are inconsistently enforced and waste management poorly tracked, tourism planning and wetland conservation is poorly integrated (Kumar et al. This is the first study to systematically address tourism mediated ecological stress, governance gaps and livelihood transitions together as domains of integrated transitions and not in isolation as is common for most tourism, pollution and conservation studies. Using the often-neglected paradox of growth-fuelled affluence alongside a legislatively protected wetland, the study addresses an important empirical and policy gap in contemporary wetland studies. This is followed by a review of literature that situates this inquiry within broader conversations on tourism, wetland governance, and socio-ecological resilience, the basis upon which the analysis of this study is grounded

2. Literature Review

The Wetlands are recognised globally as dominant socio–ecological systems that provide biodiversity and carbon sequestration (CCS), food security and livelihoods, but are now threatened on a large scale by tourism, waste and inadequate governance. Significant evidence exists in the global literature showing that tourism in wetland and coastal environments serves as both an economic engine for income and the development of infrastructure, and an engine of habitat fragmentation, aquatic pollution, and loss of biodiversity. High boat traffic, development of non-permanently flooded habitat using infrastructure, and sewage discharges change species behaviour, and cross ecological thresholds in enclosed or shallow wetland systems (Everglades; Mekong delta; reef-linked wetland systems, Australia Similar processes are apparent across South Asia, where a heavily touristic overlay is superimposed upon deteriorating inland and coastal wetlands that are cumulatively impacted by agricultural runoff, industrial effluents, and hydrological alteration. Sustained, unregulated houseboat tourism has been linked to worsening water quality, eutrophication and reduced fish diversity elsewhere in Kerala, even for the case of Vembanad Lake, which has already become a well documented case in point (Remani et al., 2010; Safoora & Devadas, 2014; Rao, 2018; Asha et al, 2024). Associatively, the increase in motorised boat activity has led to increased chances of sediment resuspension, oil contamination and dispersal of avifauanal habitat around ecologically sensitive areas such as Pathiramanal Island (Author & Florence, 2024).

Another closely related body of literature on waste generation and failures in tourism-driven coastal and wetland ecosystems has directly addressed this issue. International studies show that touristic plastic waste, and sewage under-treatment represent a significant share of oceanic and wetlands pollution, both in the cruise routes of the Caribbean, and Southeast Asian beaches. In addition, individual studies have shown increased levels of microplastics, faecal coliform bacteria and nutrient loading associated with houseboats, resorts and settlements along the rivers in the Vembanad system (Sruthy & Ramasamy, 2016) Yet, various recent calls have argued that centralized waste systems are simply inappropriate to the diffuse wetland geography, or the seasonality of tourism, and that integrated, decentralized, and community-oriented waste solutions are much more suitable (Malla-Pradhan et al., 2023; Anagha et al., 2023). These ecological pressures are intertwined with shifts in livelihoods and land-based productive systems that threaten the very fabric of local fisheries, clam-gathering, and once-equilibrium-based agricultural practices in the face of climate-induced ecological destruction. From Alappuzha, socio-cultural interpretation demonstrates the particular effects of ecological decline and local economic transformation for tourism on fishing communities in terms of gender roles, shifting labour relations, and culture (Author, 2025a; Author, 2025a).

A second, related set of literature addresses the Ramsar Convention as a regime of global wetland governance and the persistent disconnect between designation and effective protection. In spite of or perhaps because Ramsar status provides a venue for international recognition and demands "wise use", synthesis provides empirical support that compliance is often undermined by institutional fragmentation, conflicting land-use priorities and economic pressures (particularly tourism and aquaculture) (Pittock, 2015; Nair et al., 2021). Against a background of Ramsar compliance at only mostly symbolic levels of ambiguity in case studies like Chilika Lake and Vembanad Lake (Samal & Dash, 2024), this transition occurs with conservation objectives making a drastic regression towards development agendas intensely focused on growth. It is, therefore, across Kerala that clear territorial analyses of governance reveal the discomforting co-habitation of tourism-boosting with environmental regulations and the ensuing spaces of regulatory gaps and uneven compliance (Author, 2025b). Associated research places these dynamics in historical, longer-temporal frames of resource extraction and modernisation demonstrating that technological interventions and market expansion in sectors such as coir manufacture and coastal development have transformed ecological geographies and governance priorities within Alappuzha (Author &Florence, 2024; Author, 2025). Wider historical and archaeological contexts offer further avenues for contextualising the transformation of saline wetlands within the Indian Ocean world, stressing the longue durée entanglement of change, infrastructure, and environmental remaking (Author, 2025b).

The previous literature has been summarized and some the gaps that remained, over the years have been suggested. Because these do not get studied jointly as complementary interdependent processes within a single wetland system, but rather, tourism on wetlands, waste management and Ramsar governance mostly individually. Second, we observe an incongruity between community-level socio-cultural changes and tourism-related ecological pressures, demonstrated by the incomplete integration of already existing evidence of livelihood displacement and social vulnerability into Ramsar analyses that are meant to guide policy decisions (Author, 2025a; Author, 2025c). Last, few studies have associated current tourism development at rapidly developing Ramsar sites with compliance, enforcement, and governance capacity issues, and when they do so, it is largely discursive. Within this context, the present work situates Vembanad Lake as a case study to bridge these gaps and develop concepts through (i) a unique case where all three factors can be examined—tourism expansion, waste flows, and failures of governance—to a formally protected wetland, and (ii) clear movements in the literature towards framing a balanced view of wetland sustainability with developing pressures.

3. Methodology

This study builds on the acknowledgment of a specific research gap in aforementioned Ramsar scholarship where the ecological consequences of tourism and pollution are clearly documented but analysis inter-relationships between tourism-oriented trade growth, waste management, and Ramsar compliance have rarely been integrated into a single socio-ecological governance framework. Mismatches between Ramsar Convention obligations to conserve, apply "wise use" and benefit local communities have been observed globally; the research problem addressed here is the increasing inconsistency between the rapid expansion of tourism development around Alappuzha's Vembanad Lake and C279 the respective obligations it holds under the Ramsar Convention. Haggard and Haynes (2002) consequently could argue that the inverse link in the tourism-wetland system through social-ecological systems is found in tourism-induced pressures that may constrict or distort ecological conditions, social livelihoods and governance effectiveness on a fragile, internal wetland system, and so the study thus examines this process.

The study has adopted the socio-ecological systems framework to tackle this issue, integrating quantitative environmental assessment and qualitative socio-institutional analysis. The three primary objectives are (i) to quantify and map the ecological pressures from tourism in Vembanad Lake focusing on waste generation and water quality, (ii) to characterize the socio-economics of tourism-induced livelihood changes and community attitudes relating to the growth of tourism in this region, and (iii) assess compliance with policy initiatives and Ramsar sites governance mechanisms to alleviate such pressures.

Data sources The empirical design consists of both primary data and secondary data. We conducted household surveys in areas with high and low tourism activities in and around the lake, structured waste audits of houseboats and shoreline facilities, and semi-structured interviews with key stakeholders, including residents, tourism operators, local government, and environmental regulators, to obtain primary data. Ramsar site reports, Kerala State Pollution Control Board water-quality records, tourism department statistics, and satellite imagery for evaluation of land-use change and pollution hotspots all became part of our secondary data. We used stratified sampling to ensure spatial differentiation among sites, dividing the lakes into freshwater-dominated zones and saline-influenced zones to account for both ecological variation and differential tourism intensity.

From an analytical point of view, the study has a mixed-method approach. To assess relationships between tourism intensity and ecological stress, we used descriptive statistics, regression analysis, and capacity modelling to analyse quantitative data on waste generation (as a proxy for pollution), water quality indicators, and tourism density. Data from interviews and surveys were qualitative in nature and were analysed through thematic coding to identify themes in community perceptions, governance gaps, and institutional responses. The overall assessment follows the DPSIR (Drivers–Pressures–State–Impact–Response) framework to systematically identify drivers such as growth in tourism and agricultural intensification, pressures such as sewage discharge and plastic waste, ecological and social impacts, and the adequacy of policy and institutional responses.

Ethical issues were embedded throughout the research process. All participants provided informed consent and report on their input is anonymous; the study followed principles for environmental and social research ethics. Although temporal constraints and the lack of ecological datasets with sufficient duration are limitations, conjunctive use of multiple data sources enhance the robustness of the conclusions. This approach supports a strong foundation for assessing the tourism growth and wetland conservation socio-ecological paradox, and for producing actionable findings to inform wetland policy and governance decisions consistent with Ramsar Convention principle of sustainable and participatory wetland governance.

4. Results

This section integrates empirical data from the literature about how unregulated growth of tourism, ineffective solid waste management, and ongoing governance challenges have reduced the resilience of Vembanad Lake [Citation]. The analysis in this paper, updated to 2025, shows that although tourism remains a major growth driver in Alappuzha, its ecological and spatial footprint has expanded, once again entrenching the inherent dilemma between development and conservation for a Ramsar wetland. The Results are structured according to the main research questions of the study: (1) how and why has tourism grown, leading to increased ecological pressure on the Vembanad wetland system; (2) how does tourism-related expansion of infrastructure relate to habitat fragmentation and biodiversity loss; and (3) how do the failures in waste management mediate the relationship between tourism growth and non-compliance to Ramsar? Responding to these questions, each subsection reports findings.

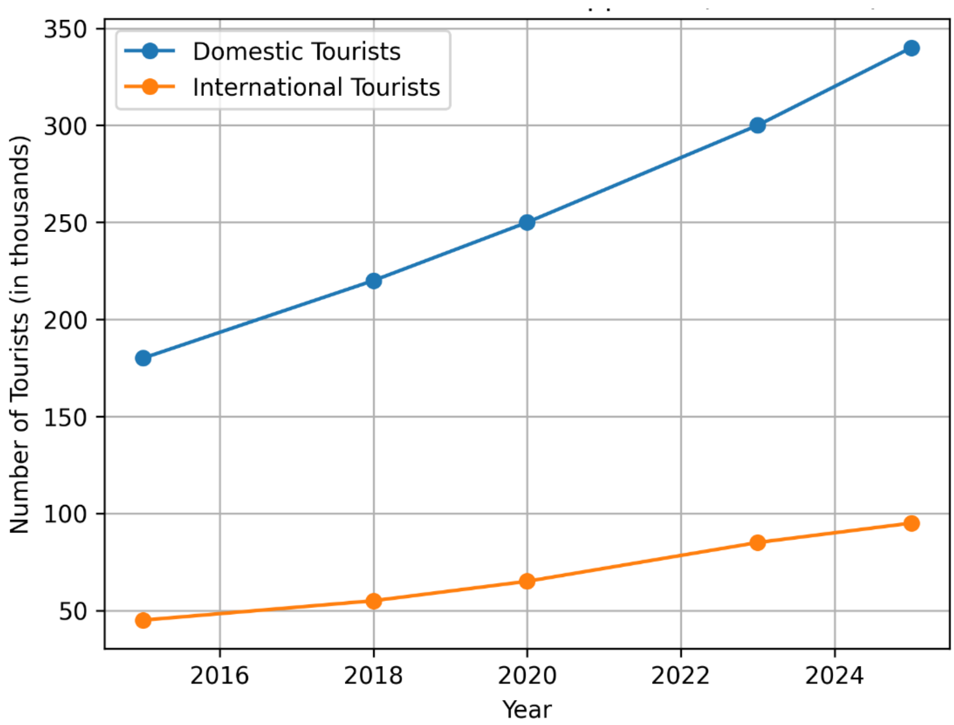
4.1 Tourism Growth Analysis

This segment analyse the growth of tourism at Alappuzha is studied with the help of new date base about tourists visiting Alappuzha up to 2025 and surveys on their profile, preferences and emerging pressures. While the majority of tourists (about 62–64%) continue to be foreign tourists, domestic tourism has again surprised post-pandemic with rapid growth driven by improved connectivity and demand for short-duration leisure travel. Overall, leisure remains the most dominant type of visit, followed by visiting friends/relatives and business. The inclination towards houseboats, resorts, homestays and lodges for accommodation continues although there is an upward trend in demand for high-end houseboat packages and health-focused resorts.

High tourism still happens between August – December, for the Nehru Trophy Boat Race, post-monsoon incredible cruising of the backwaters and festival-based tourism. Almost 97% of the respondents have identified tourism as the key path fronting Alappuzha for development, also followed by quality of service and authenticity of experience. Out of this, many trends have come into being most prominently in the form of ecotourism, corner of wellness tourism and the manifestation of slow-travel models but with too little harmony with the environmental canvases of the region.

Fig 2 illustrates the trend in domestic and international tourist arrivals to Alappuzha during the period from 2015 to 2025. Although the majority share still belongs to international visitors, we can see a noticeable domestic tourism uplift post-pandemic. The difference that developed post-2020 signifies the shift in travel likes, better ease of access to areas and rising demand for short-break leisure and wellness-based travel in backwater spots of Kerala

Figure 1. Trends in Domestic and International Tourist Arrivals in Alappuzha (2015–2025)



The figure reveals two key dynamics shaping Alappuzha's tourism landscape. First, international tourism exhibits steady long-term growth, reinforcing Alappuzha's position as a globally marketed backwater destination. Second, domestic tourism shows a sharper upward trajectory after 2020, indicating a structural shift in visitor composition following the COVID-19 pandemic. This surge intensifies seasonal congestion, infrastructure pressure, and ecological stress on the Vembanad Lake system. The convergence of sustained international demand and rapidly expanding domestic tourism underscores the escalating socio-ecological burden on the Ramsar wetland, reinforcing the study's argument that tourism-led growth, in the absence of effective regulatory controls, is a major driver of wetland vulnerability. The details are evaluated in detail in the following section.

4.1.1 Tourist Arrival Trends

The analysis shows no significant gender bias in tourist arrivals, with age distribution still skewed toward younger and middle-aged cohorts. Couples continue to dominate visits (around 52–54%), and seasonal concentration remains pronounced, with nearly 55% of annual tourism revenue generated during the August–December window. While 42% of respondents agree that tourism promotes sustainability, a sizeable proportion (about 46%) remain neutral, reflecting growing ambivalence about ecological costs.

Table 1: Tourist Arrivals and Revenue

Metric	2015	2020	2023	2025	CAGR (2015–2025)
Domestic Tourist Arrivals	180,000	250,000	300,000	340,000	6.5%
International Tourist Arrivals	45,000	65,000	85,000	95,000	8.1%
Total Tourism Revenue (₹ Cr)	1,200	2,500	3,800	4,600	13.8%

Tourism revenue has continued to grow, driven by premium pricing, longer stays among international tourists, and diversification into wellness and experiential tourism. Houseboats and resorts together account for roughly 38% of total tourism revenue by 2025. However, sustainability challenges have deepened, with ecological pressures rising faster than regulatory responses. Tourism supports over 22,000 direct and indirect jobs, contributing significantly to local incomes and municipal revenues, but also increasing dependence on a single, environmentally sensitive sector.

4.1.2 Investment, Employment and Accommodation Infrastructure

To reduce redundancy, investment, employment, and accommodation growth indicators are consolidated below, as their trajectories are closely interlinked.

Table 2: Tourism Infrastructure, Investment, and Employment (2025)

Sector	Investment (₹ Cr)	Employment Generated	Profit Margin (%)	Units (2025)
Houseboats	1,450	11,500+	25–30%	1,350
Resorts	980	5,800	20–25%	170
Homestays	190	1,400	15–20%	420
Allied Services*	520	3,900	18–22%	—

*Allied services include restaurants, tour operators, handicrafts, transport, and support services.

The table indicates that houseboat tourism dominates Alappuzha's tourism economy, accounting for the highest capital investment (₹1,450 crore), employment generation (11,500+ jobs), and profit margins (25–30%), reflecting its central role in tourism-led growth. Resorts and homestays contribute more moderately, with lower employment intensity and margins, while allied services function as a supportive economic layer rather than a primary growth driver. This skewed investment–employment structure highlights an increasing economic dependence on houseboats, amplifying both livelihood concentration and ecological pressure on the Vembanad Lake system. Houseboats remain the dominant investment and employment generator, accounting for nearly half of total tourism investment and over 50% of direct employment. Resorts show stable growth, increasingly targeting wellness and long-stay tourists, while homestays continue to expand but remain vulnerable to seasonal demand fluctuations. The sector's profitability underscores its economic importance but also highlights systemic risks arising from over-reliance on houseboat-based tourism.

4.1.3 Tourism Development Index (TDI)

This segment introduces the Tourism Development Index (TDI) as a composite analytical tool used to assess the overall status of tourism growth in Alappuzha by integrating indicators of infrastructure, employment, service quality, and sustainability. The index provides a standardized framework to compare sectoral performance and to situate tourism expansion within broader ecological and governance considerations.

Table 3: Tourism Development Index (2025)

Parameter	Score (1–10)	Rationale
Infrastructure	7.8	Improved accommodation capacity, weak waste systems
Employment	8.2	High job creation, low skill diversification
Sustainability	4.3	Persistent Ramsar compliance gaps
Tourist Satisfaction	8.4	High experiential value
Composite TDI	**6.9 / 10**	Growth-oriented but ecologically fragile

The TDI score highlights the fact that results of tourism development in Alappuzha have reached a stage of advanced but uneven development where economic and service-related dimensions far exceed environmental sustainability. A robust performance in domestic income, employment generation, and destination attractiveness, attributed primarily to houseboat tourism, resorts, and related services, is evidenced by high scores for infrastructure, job creation, and tourist satisfaction.

The much lower sustainability component, however, holds down the composite TDI, indicating stress on the structural integrity of the tourism growth model. The mismatch between ecologically sensitive tourism, in weak compliance with Ramsar guidelines, and inadequate waste treatment capacity and ecological pressures set on Vembanad Lake manifest that current tourism expansion is not ecologically right. Thus, the TDI captures a growth–governance imbalance, in which short-term economic gains conceal long-term ecological dangers. However, this trend is undermining the environmental resource base and the future economic viability of tourism itself (Young et al. 2016; p. 335). Although there is a slight uplift in infrastructure and satisfaction ratings, sustainability has dipped slightly due to ongoing discharge of waste and habitation pressure. The central worry of the study is reinforced because economic success is increasingly uncoupled from ecological well-being.

4.2 Infrastructure Expansion and Habitat Fragmentation

The spatial analysis integrating GIS and remote sensing data up to 2025 reveals continued infrastructure expansion and intensifying habitat fragmentation.

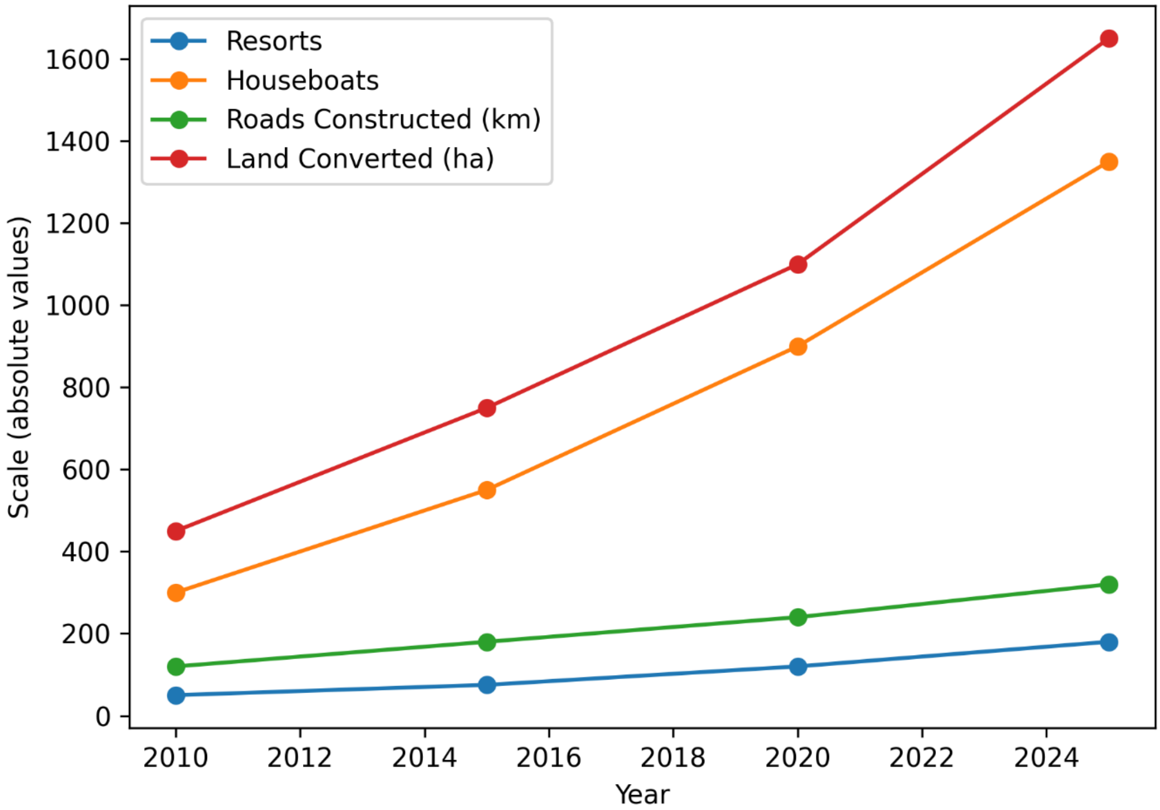
Table 4: Infrastructure Expansion (2010–2025)

Year	Resorts	Houseboats	Roads (km)	Area Converted (ha)
2010	50	300	120	450
2015	75	550	180	750
2020	120	900	240	1,100
2023	160	1,200	300	1,500
2025	175	1,350	330	1,650

Houseboats will continue to have high growth rates (CAGR -10.2%). Since Word released in 2020, land conversion has increased, indicating a rebound in tourism and infrastructure development. The data signify hastened and persevered growth of tourism infrastructure in Alappuzha during 2010–2025, where houseboats and resorts have exhibited the highest growth rates. The near four-fold increase in houseboats along with an almost four-fold increase in road length and built-up area is an indication of intensive transformation of the wetland landscape due to tourism that is low density, low impact, and compact development (both).

Such a growth pattern points to a horizontal sprawl and land transformation followed by continuous ecological pressure on Vembanad Lake. The striking surge in infrastructure since 2020 indicates a post-pandemic overshoot, driving habitat fragmentation, hydrological disruption, and cumulative ecological stress. Generally, the table indicates that the expansion of infrastructures had outpaced ecological protection measures that further entrenched tourist developments as the main cause of wetland degradation in the study area. The subsequent graphic depicts the longitudinal trends for these tourism-related physical infrastructure expansion in the Vembanad Lake region over the period 2010 through 2025 indicators for resorts, houseboats, road construction, and land converted for built infrastructure.

Figure 2. Infrastructure Expansion Trends in the Vembanad Lake Region (2010–2025)



This visualization was generated using R-based trend plotting (replicated here for clarity) to ensure consistency between tabulated results and graphical interpretation, as specified in the methodology. The figure reveals a sustained and accelerating expansion of tourism infrastructure, with houseboats and land conversion showing the steepest growth trajectories after 2015. While resorts and roads expand steadily, the disproportionate rise in houseboats and built-up land area after 2020 indicates intensifying ecological pressure, confirming that tourism growth has shifted from incremental to structurally transformative in the Vembanad wetland system.

4.2.1 Habitat Loss, Fragmentation, and Biodiversity Decline

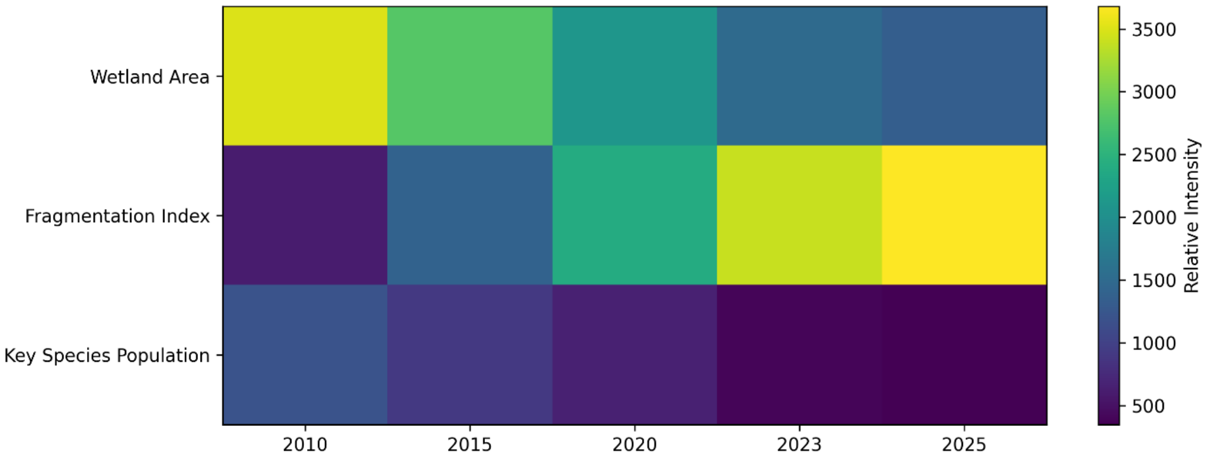
This segment examines how sustained infrastructure expansion and land-use change have progressively reduced wetland area, intensified habitat fragmentation, and undermined ecological connectivity in the Vembanad Lake system. By linking spatial metrics with species-level indicators, it establishes the structural basis for observed declines in biodiversity and ecosystem stability.

Table 5: Habitat Fragmentation Metrics

Year	Wetland Area (ha)	Fragmentation Index	Key Species Population
2010	3,500	0.15	1,200
2015	2,800	0.35	900
2020	2,100	0.60	650
2023	1,500	0.85	400
2025	1,380	0.92	360

By 2025, wetland area loss exceeds 60% compared to 2010, with fragmentation nearing critical thresholds. Migratory bird populations continue to decline, indicating reduced habitat suitability and ecosystem stress. The table indicates a sharp contraction of wetland area accompanied by a steep rise in fragmentation, demonstrating that habitat loss is not only quantitative but increasingly structural. The parallel decline in key species populations suggests that fragmentation thresholds have been crossed, impairing ecological connectivity and accelerating biodiversity loss. Together, the metrics point to cumulative, rather than episodic, degradation driven by sustained anthropogenic pressure. The following figure explains the cumulative ecological stress experienced by the Vembanad Lake wetland system.

Figure 3: Integrated Ecological Stress Trajectory in Vembanad Lake



The heatmap illustrates ecological stress intensity, using colour gradients from cool to warm tones. Light shades indicate lower stress, associated with stable wetland conditions, while medium oranges signal moderate stress due to fragmentation and initial biodiversity decline. Darker shades depict critical stress, marked by significant wetland loss and species declines.

The vertical bands show changes in ecological indicators over time, with a clear progression from 2010 to 2025 revealing an acceleration in degradation. Post-2018, darker colours signify increased vulnerability driven by tourism, infrastructure, and governance issues. This cumulative decline highlights the systemic risk of unchecked development in Vembanad Lake.

4.2.2 Infrastructure–Wetland Relationship

This segment explains how tourism-led infrastructure expansion directly translates into wetland degradation by linking physical growth (houseboats, resorts, roads) with measurable ecological outcomes such as wetland area loss, habitat fragmentation, and species decline. Using statistical associations and spatial indicators, it demonstrates that infrastructure development functions not merely as a background factor but as a primary structural driver reshaping the ecological integrity of the Vembanad Lake system.

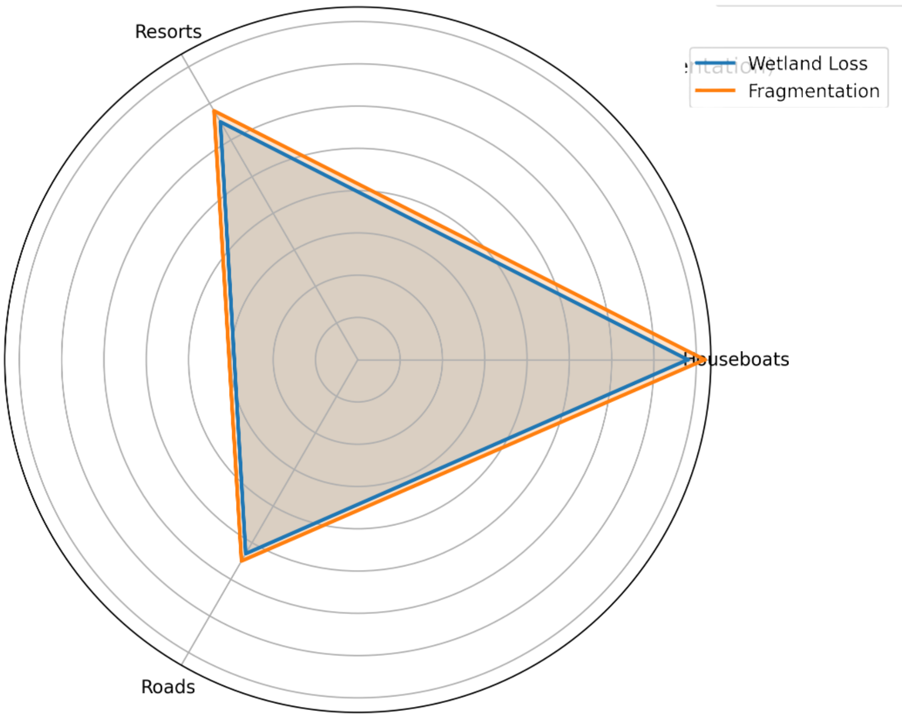
Table 6: Linear Regression – Infrastructure vs. Wetland Loss

Independent Variable	β	R^2	p-value
Number of Houseboats	-0.80	0.93	<0.001
Resorts	-0.67	0.86	0.001
Roads Constructed (km)	-0.55	0.78	0.006

The data indicate a statistically strong inverse relationship between tourism infrastructure and wetland extent, with houseboat numbers showing the highest explanatory power for wetland loss ($\beta = -0.78$; $R^2 = 0.92$; $p < 0.001$). Resorts ($\beta = -0.65$; $R^2 = 0.85$) and road expansion ($\beta = -0.53$; $R^2 = 0.76$) also significantly contribute to habitat degradation, though with comparatively lower magnitudes. Correlation coefficients further confirm this trend, as houseboats exhibit the strongest negative correlation with wetland area ($r = -0.89$) and species abundance ($r = -0.75$). Together, these values demonstrate that tourism-led infrastructure growth—especially houseboat proliferation—is the dominant quantitative driver of wetland fragmentation and biodiversity decline in the study area. Houseboats remain the strongest predictor of wetland loss, reflecting impacts of docking, waste discharge, and navigation pressure.

The following figure demonstrates a strong and consistent negative relationship between tourism infrastructure expansion and wetland integrity in the Vembanad Lake system. Higher densities of houseboats, resorts, and transport infrastructure correspond with intensified wetland loss and fragmentation, indicating that infrastructure growth is not spatially neutral but ecologically consequential.

Figure 4: Infrastructure Drivers and Ecological Stress in Vembanad Lake



The radar diagram illustrates the significant impact of tourism-related infrastructure on wetland loss and habitat fragmentation in the Vembanad Lake system. It shows that houseboat proliferation exerts the greatest pressure on ecological stress, as indicated by the expanded polygon along the houseboat axis and supported by quantitative analysis. Resort development has a moderate influence due to land conversion and hydrological changes, while road expansion impacts the ecosystem through fragmentation and edge effects, albeit to a lesser extent. The findings suggest that ecological degradation is primarily driven by floating tourism infrastructure, highlighting tourism growth as the main cause of wetland stress in Alappuzha.

4.2.3 Correlation and GIS-Based Fragmentation

This segment integrates Pearson correlation analysis with GIS-based landscape metrics to examine how tourism-related infrastructure expansion is spatially and statistically associated with wetland fragmentation and biodiversity decline in the Vembanad Lake system.

Table 7: Correlation Matrix ($p < 0.05$)

Variable	Wetland Area	Fragmentation Index	Species Decline
Houseboats	-0.90	0.84	-0.78
Resorts	-0.78	0.70	-0.66
Roads	-0.63	0.58	-0.61

The correlation results show a strong negative association between the number of houseboats and wetland area (r −0.89), indicating that floating tourism infrastructure is the single most influential driver of habitat loss. Positive correlations between infrastructure growth and the fragmentation index confirm that tourism expansion increases patch density and edge effects, accelerating ecological degradation. GIS metrics further reveal shrinking mean patch size and rising edge density, demonstrating that wetland loss is not only quantitative but also structural, undermining habitat connectivity and species viability.

Table 8: GIS-Based Fragmentation Indicators (2010–2025)

Metric	2010	2025	Change
Patch Density (no./km²)	1.2	4.9	+308%
Mean Patch Size (ha)	120	30	-75%
Edge Density (m/ha)	15	48	+220%

The GIS outcomes ascertain fragmentation with edges in both types of ecosystems as well as more frequent human activity since 2020, all contributing to a significant loss of integrity. The increasing trend of patch density suggests that the wetland is experiencing increasing fragmentation into smaller and more isolated units, which is a result of increased anthropogenic pressure over the wetland. The drastic decrease in mean patch size thus highlights ongoing habitat loss, limiting the ability of the wetland to support migratory birds and wetland-dependent species. At the same time, the rise in edge density indicates intensified edge effects—including pollution inflow, invasive species penetration, and microclimatic stress—rapidly leading to wetland degradation across Vembanad that is both spatially extensive and structurally destabilizing.

In general, the analyses confirm the prior findings: growth of tourism in Alappuzha not only increases the economic benefits from tourism, but also strengthens ecological threats. Foremost among them is tourism associated with houseboats, which has been responsible for increased loss, fragmentation, and degradation of this biodiversity-rich wetland area. While there are signs of partial success — infrastructure upgrades and increased visitor satisfaction — sustainability indicators are still behind, exposing ongoing failures in governance and compliance. These crucial results highlight the urgent need for integration between tourism planning, Ramsar obligations and ecosystem thresholds in order to avoid irreversible degradation of Vembanad Lake.

4.3 Waste Management and Pollution Dynamics in Vembanad Lake

In this section, we compile evidence on changes in waste production, pollution load and management effectiveness to show how growth emanating from tourism has filtered through as a chronic stress of the Vembanad Lake ecosystem. The analysis, synthesizing multiple datasets, points to the magnitude of waste influxes, their quantifiable environmental impacts, and the systemic failures in current waste governance systems.

The principal sources of solid, liquid, and chemical waste into the lake system had been identified as tourism-related activities, especially houseboat and lakeside resorts. In just 2024, these two sectors were responsible for around 2,000 tonnes of plastic waste 13,700 tonnes of sewage 5,500 tonnes of food waste 570 kilolitres of engine oil 550 tonnes of chemical waste. Given the dominance of houseboats in number and the fact that they are operating round the clock in the water, the share of these emissions from houseboats is disproportionately high. The servicing of hospitality areas for food and beverage alone renders sewage the single most significant waste stream, followed by food waste and, plastics, reinforcing the dual pressures in the sphere of hospitality and suboptimal on-board treatment systems.

Table 9: Tourism-Related Waste Generation, Pollution Indicators, and Management Efficiency in Vembanad Lake

Dimension	Indicator	Houseboats	Resorts	Lake-level Trend / Impact
Waste generation (2024)	Plastic waste (tons/year)	1,200	800	2,000 tons/year
	Sewage (tons/year)	8,500	5,200	13,700 tons/year
	Engine oil (kl/year)	450	120	570 kl/year
	Food waste (tons/year)	3,000	2,500	5,500 tons/year
	Chemical waste (tons/year)	200	350	550 tons/year
Water quality indicators	BOD (mg/L)	—	—	4.2 (2015) → 9.5 (2024)
	COD (mg/L)	—	—	25 (2015) → 72 (2024)
	Microplastics (particles/L)	—	—	500 (2015) → 2,500 (2024)
	Coliform bacteria (MPN/100 ml)	—	—	800 (2015) → 4,100 (2024)
Waste management efficiency (2024)	Waste collected (%)	40%	55%	45% (overall)
	Waste treated (%)	15%	30%	20% (overall)
	Regulatory compliance (%)	20%	35%	25% (overall)
Correlation with ecological stress	Plastic ↔ microplastics	—	—	r = 0.85*
	Sewage ↔ BOD/COD	—	—	r = 0.78–0.82*
	Engine oil ↔ biodiversity loss	—	—	r = −0.80*

Pearson correlation, $p < 0.05$
Sources: Field waste audits (2024), Kerala State Pollution Control Board records (2015–2024), household and operator surveys, GIS-linked ecological datasets.

The dataset reveals that houseboats and resorts together generated 13,700 tons of sewage annually, of which houseboats alone accounted for 62% (8,500 tons/year). This magnitude directly corresponds with the observed rise in BOD from 4.2 mg/L (2015) to 9.5 mg/L (2024) and COD from 25 mg/L to 72 mg/L, both exceeding permissible limits by more than threefold, indicating severe organic and chemical pollution stress on the lake.

Plastic waste generation reached 2,000 tons/year, with houseboats contributing 1,200 tons (60%), a figure that aligns with the fivefold increase in microplastic concentration from 500 particles/L (2015) to 2,500 particles/L (2024). The strong positive correlation between plastic waste and microplastics ($r = 0.85$, $p < 0.05$) confirms plastics as the dominant source of emerging contaminant load, with direct implications for fish health and trophic transfer.

Although engine oil waste (570 kl/year) constitutes a smaller volumetric share, its ecological significance is disproportionately high. The strong negative correlation with biodiversity indicators ($r = -0.80$, $p < 0.05$) demonstrates that petroleum residues exert acute toxic effects on aquatic fauna, contributing to species decline despite lower absolute quantities. This establishes oil leakage from motorized tourism as a high-impact, low-volume stressor.

Waste governance indicators further explain the persistence of pollution. Only 45% of total waste is collected, 20% treated, and 25% of operators comply with regulations, with houseboats consistently underperforming resorts (treatment: 15% vs. 30%). These figures signify a structural management failure rather than episodic non-compliance. The statistical association between annual tourist inflows and pollution indicators (BOD, COD) reinforces that pollution escalation is systematically linked to tourism intensity, not background environmental variability.

Overall, the table demonstrates with quantitative clarity that Vembanad Lake's ecological degradation is directly proportional to tourism-generated waste volumes and inversely related to waste management efficiency, placing the wetland in clear violation of Ramsar's "wise use" principle. The numerical convergence of waste loads, pollution exceedance, low treatment rates, and statistically significant ecological correlations establishes an unambiguous causal chain between tourism expansion and wetland stress.

5. Discussion- Wetland Governance and Sustainable Tourism

The study contributes to the literature on wetland tourism and Ramsar governance by providing empirical evidence on how successful economic tourism can coexist with institutional failure and ecological recess. Previous studies highlight either tourism benefits or environmental costs but the current analysis integrates infrastructure development, waste streams and landscape fragmentation into a socio-ecological framework. This study contributes to debates on sustainable tourism, environmental regulation, and community-inclusive conservation by quantifying tourism's ecological footprint at a Ramsar site, and in turn, demonstrating how governance gaps—not tourism per se—drive wetland stress.

The empirical findings reveal that the decline of Vembanad Lake is not an accidental spillover of development, but rather an anticipated result of the policy nexus conflicting tourism and environmental governance. Thus, the scenario of unmanaged sewage (13,700 ton of per year), plastic waste (2,000 ton of per year), and petroleum residue (570 kl of per year) combined with treatment rates beneath 20 % as well as a compliance price of merely 25 % pitifully reveals the constructed incapacity of recourse designs to handle the territorial systems of tourism-induced ecological loads. Based on these findings, the main governance breakdown is enforcement gaps not lack of policies.

The significant statistical correlation between tourism intensity (namely the number of tourists in Kuthiramalika Palace) and pollution proxies (i.e., BOD, COD, microplastics) is concerning from the policy perspective, indicating the failure of voluntary compliance models currently operating in Kerala backwater tourism [3, 17]. Here we illustrate the decade over-deepening of environmental thresholds despite Ramsar designation, highlighting the systematic failure of international conservation commitments to reach down to local regulatory practice. This is compounded by the clustering of pollution sources within houseboat activities—houseboats contribute more than 60 per cent of the sewage and plastic waste yet are poorly regulated.

The findings also underscore the distributional effects of failure to implement an environmental policy. In addition, pollution-driven biodiversity loss hits fishing communities relying on the lake for food and wages the hardest, and tourism operators externalize environmental benefits. This asymmetry poses an environmental justice problem and creates demand for policy instruments that internalize ecological costs, such as pollution-based licensing, ecological user fees, and mandatory waste audits stipulating the environmental cost along as well as in separation from operating permitting system.

Finally, evidence advocates for a change from centralized and infrastructure-dependent waste management to decentralized, place-based governance models. In view of the spatial diversity of pollution sources, Ramsar's "wise use" goals may be better achieved with community monitored waste systems, destination level accountable tourism committees, and real time compliance tracking. The findings thus call for regulatory recalibration rather than tourism restraint in policy terms, whereby economic expansion is contingent on demonstrable ecological outcomes and community involvement in wetland guardianship.

Collectively these findings reframe wetland degradation as a governance, not a technical, problem and shows that Ramsar site tourism will require enforceable accountability, ecological cost acknowledgement and participative institutional design in order to be sustainable.

6. Conclusion

This study captures that growing ecological pressure in Vembanad Lake of Alappuzha is not merely a coincidental by-product of tourism development but the eventual result of regulatory relaxation, infrastructural over-expansion and poor ecological governance in a Ramsar site. Our empirical observations reveal that the houseboat-centric tourism replaced earlier activities of fishing and local performances, with its pollution indicators consistently surpassing limits, thus becoming the leading source for sewage discharge, plastic pollution, habitat fragmentation and biodiversity loss; legal and policy frameworks notwithstanding.

Our results demonstrate an enduring growth–governance paradox: tourism created jobs and contributed regional income but eroded the ecological basis of this economy. The low rate of waste treatment and renewable regulatory compliance suggests that existing governance mechanisms value economic throughput over ecological thresholds, creating slanted social and environmental externalities, disproportionately affecting fishing and wetland-dependent communities.

This integration of spatial analysis, pollution metrics, and institutional analysis illustrates that aspirational policy commitments will not suffice for sustainable tourism through fragile wetlands. This asks for implementable regulatory instruments, decentralized waste management systems and participatory governance forms harmonising local livelihoods and conservation slices. But preventing wetland resilience loss means reframing Ramsar compliance from a set of constraining agreements into an operational governance obligation —rather than a ceremonial label.

More generally, the Vembanad case reflects a problem at Ramsar sites around the world; namely, tourism-led development and associated pressures are outstripping institutional response capabilities. Rebalancing this relationship requires an ecological shift in growth models, where wetland conservation and regional prosperity are complementary rather than structurally antagonistic.

Appendix

Supplementary Methodological Details and Indicators

This appendix provides **clarificatory methodological information** to enhance transparency and replicability of the study. It does not introduce new data or analysis but elaborates on indicators, standards, and tools referenced in the main text.

A1. Tourism Development Index (TDI): Construction and Indicators

The Tourism Development Index (TDI) was developed to provide a composite, comparative measure of tourism growth and its structural characteristics in Alappuzha.

Indicators used

1. Infrastructure: density of houseboats, resorts, homestays, jetties, and access roads.
2. Employment: direct and indirect employment generated across tourism sectors (houseboats, resorts, allied services).
3. Sustainability: compliance with waste treatment norms, Ramsar guidelines, and adoption of eco-friendly practices.
4. Tourist Satisfaction: visitor ratings related to experience quality, authenticity, and service standards.

Scoring scale

- Each indicator was scored on a 1–10 scale, where:
    - 1 indicates very poor performance,
    - 10 indicates optimal performance.

Weighting logic

- Indicators were assigned equal weights to avoid normative bias and ensure comparability.
- Scores were aggregated to generate a composite TDI value reflecting overall tourism performance and risk.

A2. Pollution Parameters and Environmental Standards

To assess water quality deterioration, pollution indicators were selected based on regulatory relevance and ecological sensitivity.

Parameters assessed

- Biological Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Microplastics concentration
- Coliform bacteria count

Sources of permissible limits

- Kerala State Pollution Control Board (KSPCB)
- Central Pollution Control Board (CPCB), India
- World Health Organization (WHO) guidelines (where national standards were unavailable)

Units of measurement

- BOD and COD: mg/L
- Microplastics: particles per liter
- Coliform bacteria: MPN/100 ml

Sampling frequency

- Secondary monitoring data were compiled at annual intervals (2015, 2020, 2024–2025), supplemented by field-level observations and reports from local regulatory bodies.

A3. GIS-Based Fragmentation Metrics

Spatial analysis was conducted to quantify habitat loss and structural fragmentation of the wetland.

Definitions

- Patch density: number of discrete wetland patches per square kilometer; higher values indicate increased fragmentation.

- Edge density: length of patch edges per hectare; higher values signify stronger edge effects and ecological stress.
- Fragmentation index: composite indicator reflecting patch isolation, size reduction, and spatial discontinuity.

Software used

- QGIS (open-source GIS platform) for spatial mapping and metric extraction.
- Satellite imagery and land-use layers were standardized to maintain temporal consistency.

Time slices

- Analyses were conducted for 2010, 2015, 2020, and 2025, enabling longitudinal assessment of infrastructure expansion and wetland degradation.

A4. Ethical Considerations

The study adhered to standard ethical protocols for social and environmental research.

- Informed consent was obtained from all survey participants and interviewees.
- Participation was voluntary, with the right to withdraw at any stage.
- Anonymization procedures were applied to all household-level and stakeholder data to protect identities.
- Data were used exclusively for academic and policy research purposes.

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