

Ecological Footprint as an Indicator of Sustainable Tourism in the Sundarbans of West Bengal India

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Research Article

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Additional Declarations:

Ethics Approval: The study involves primary data collected from human participants through surveys and interviews. Ethical approval for the study was obtained from the Institutional Ethics Committee of The Calcutta Anglo Gujarati College, Kolkata, West Bengal, India, prior to the commencement of data collection. All participants were informed about the purpose of the study, and their participation was voluntary.

“Ecological Footprint as an Indicator of Sustainable Tourism in the Sundarbans of West Bengal India”

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Abstract

The Sundarbans of West Bengal represents one of India's most environmentally sensitive tourism landscapes, where mangrove ecosystems, wildlife, coastal communities and tourism-dependent livelihoods are closely interconnected. Rapid growth in nature-based tourism can generate employment and local income, but it may simultaneously increase pressure on energy, fuel, freshwater, food, land, transport systems and waste-management infrastructure. This study an integrated ecological-footprint framework for evaluating tourism sustainability in selected destinations of the Indian Sundarbans. The study has ten objectives: to estimate tourism-generated ecological footprints; measure tourism-related consumption of energy, fuel, water, food and natural resources; quantify carbon emissions and solid waste; determine the relationship between tourist intensity and ecological pressure; examine environmental, economic and social sustainability; assess tourism carrying capacity; construct an Ecological Footprint–Sustainable Tourism Index (EF-STI); identify spatial variation using GIS; investigate tourism–livelihood relationships; and formulate policy measures for low-footprint and climate-resilient tourism.

The methodology integrates primary tourist, tourism-enterprise and household surveys with secondary tourism, environmental and spatial data. Ecological footprint accounting will incorporate built-up land, energy/carbon absorption, food, water/resource use and waste-related pressure. Carbon emissions will be estimated using IPCC emission factors, while water and waste footprints will be calculated per tourist-day and per destination. Physical, real, ecological and social carrying capacities will be estimated separately before constructing an integrated carrying-capacity threshold. Principal Component Analysis (PCA), factor analysis, correlation analysis, multiple regression, panel or time-series analysis where sufficient data are available, spatial autocorrelation, hotspot analysis and GIS-based weighted overlay will be used. A composite EF-STI ranging from 0 to 1 will classify destinations as very low, low, moderate, high or very high sustainability.

Available official evidence demonstrates the growing relevance of this research. The Sundarban Tiger Reserve recorded 368,606 visitors during FY 2024–25, including 365,583 Indian and 3,023 foreign visitors, indicating substantial visitor pressure on a highly sensitive ecosystem. Existing Sundarban research also identifies unregulated tourism, environmental pressure and livelihood vulnerability as important concerns. The study therefore seeks to move beyond conventional tourist-arrival statistics towards a measurable destination-level

sustainability framework capable of linking tourism intensity, resource consumption, ecological pressure and community welfare.

Keywords: Sundarbans; ecological footprint, sustainable tourism, EF-STI; carbon footprint, water footprint, carrying capacity, GIS, livelihood, climate resilience, tourism sustainability, West Bengal.

Introduction

Tourism is simultaneously an economic activity, a social process and a biophysical system. Its contribution to employment, income generation, infrastructure development and local entrepreneurship is widely recognized, but tourism also consumes energy, water, food, transport fuel, land and materials and produces greenhouse-gas emissions, wastewater and solid waste. Consequently, measuring tourism only through tourist arrivals or tourism revenue provides an incomplete assessment of destination sustainability.

The ecological-footprint concept developed by Wackernagel and Rees (1996) provides a useful framework for translating resource consumption and waste generation into the biologically productive area required to support those demands. Hunter (2002) subsequently connected ecological-footprint analysis with sustainable tourism and argued that conventional destination-based tourism assessments can underestimate the wider environmental requirements of tourism. Gössling et al. (2002) further demonstrated the applicability of ecological-footprint analysis to tourism destinations.

Tourism is particularly resource-intensive in environmentally fragile destinations. Gössling (2000, 2002) emphasized energy consumption, transport, land transformation and associated environmental consequences. Tourism-water research similarly demonstrates that tourist activities create direct and indirect water demand, making water availability and water quality important sustainability indicators. More recent research has expanded the analysis towards carbon, water and ecological footprints across tourism supply chains.

The climate dimension is especially important. Lenzen et al. (2018), using a global multi-regional input-output framework, estimated tourism's carbon footprint at approximately 4.5 Gt CO₂-equivalent in 2013, representing around 8% of global greenhouse-gas emissions. Transport, shopping and food were among the important contributors. This finding demonstrates why tourism sustainability assessment should include consumption and supply-chain effects rather than simply emissions from hotels.

The Sundarbans presents a particularly appropriate setting for such an investigation. The Indian Sundarbans combines a globally significant mangrove ecosystem with tourism, fishing, agriculture, honey collection, boat transport and vulnerable island communities. Recent research indicates that climate change, salinity, cyclones, resource depletion and livelihood stress are already affecting the region. Ghosh and Roy (2021), for example, demonstrate the relationship between ecological stress and changing livelihood strategies in the Indian Sundarban.

Tourism is expanding within this sensitive landscape. The Sundarban Tiger Reserve's 2024–25 annual report records 368,606 visitors, including 365,583 Indian visitors and 3,023 foreign visitors, and identifies increasing tourist inflow as a source of pressure on biodiversity. Seven

major tourism locations are identified within the reserve jurisdiction: Sajnekhali, Dobanki, Sudhanyakhali, Harikhali, Burirdabri, Jhingekhali and Netidhopani.

The Government of West Bengal has also recognized the potential and challenges of ecotourism in the Sundarbans. The state's Integrated Coastal Zone Management material identifies the need for planned ecotourism development that remains compatible with the landscape and ecological characteristics of the region.

A recent study by Bardhan and Sarkar (2024) estimated the physical carrying capacity of Jharkhali Island at approximately 1,080 tourists per day under existing amenities and management conditions. This provides an important local precedent for destination-level carrying-capacity assessment.

However, there remains a major research gap. Existing studies generally examine tourism, livelihood, carrying capacity, climate vulnerability or ecotourism potential separately. A comprehensive destination-level framework simultaneously measuring tourism intensity, resource consumption, carbon emissions, solid waste, ecological footprint, carrying capacity, spatial pressure and livelihood benefits remains insufficiently developed for the Indian Sundarbans.

The present study addresses this gap by proposing an integrated **Ecological Footprint–Sustainable Tourism Index (EF-STI)**.

Review of Literature

Ecological footprint and tourism

Wackernagel and Rees (1996) established ecological footprint analysis as a biophysical accounting framework for estimating the productive land and water area required to sustain consumption and absorb associated waste. Hunter (2002) extended this concept into tourism by arguing that tourism generates environmental requirements beyond the immediate destination.

Gössling et al. (2002) specifically developed a methodological framework for tourism ecological-footprint estimation. Their analysis demonstrated that tourism footprints should incorporate energy, transport, accommodation, food and infrastructure rather than simply physical tourist presence.

The ecological footprint therefore provides a useful bridge between tourism consumption and destination carrying capacity. A destination may receive relatively few tourists but still generate a substantial footprint when visitors have high resource consumption, travel long distances or use carbon-intensive accommodation and transport.

Recent empirical work confirms the continuing relevance of this approach. A 2025 assessment of tourism in Taiwan's southwest coast found that total tourism ecological footprint increased substantially over the study period and that transportation was the largest contributor. The study also reported an ecological-pressure index above one, indicating that tourism pressure exceeded the assessed ecological carrying capacity.

For the Sundarbans, this suggests that tourist numbers alone are insufficient. A 500-person destination with low-resource consumption may create less ecological pressure than a 300-person destination with high fuel consumption, inefficient accommodation, high food imports and poor waste management.

Energy consumption and tourism

Gössling (2000) identified energy use as a fundamental but historically underrepresented component of sustainable tourism. Tourism consumes energy through transport, accommodation, cooking, refrigeration, lighting, water pumping, waste management and recreational activities.

In island and coastal environments, dependence on diesel-powered boats is particularly important. In the Sundarbans, boat transportation is central to tourism because much of the tourism circuit is water-based. Consequently, fuel consumption per tourist-day should become a central variable of the ecological-footprint calculation.

Energy consumption can be standardized as:

Energy intensity = Total tourism energy consumption / Tourist-days

and:

Fuel intensity = Total tourism fuel consumption / Tourist-days.

These indicators permit comparisons between destinations with different tourist volumes.

Carbon footprint

The carbon footprint literature has established tourism as a major source of greenhouse-gas emissions. Scott et al. (2012) identified tourism as both highly climate-sensitive and a contributor to anthropogenic climate change.

Lenzen et al. (2018) provided one of the strongest global empirical demonstrations, estimating tourism-related emissions at about 4.5 Gt CO₂e in 2013. Munday et al. (2013) demonstrated that tourism consumption can be analysed through environmentally extended input-output methods, while Sun (2014) proposed a framework integrating tourism expenditure with environmental-economic accounting.

For the Sundarbans, carbon emissions should include:

1. road transportation to the gateway;
2. ferry and boat transportation;
3. diesel/petrol used by tourism enterprises;
4. electricity consumption;
5. LPG and cooking fuel;
6. accommodation;
7. food preparation;
8. waste treatment;
9. selected embodied emissions associated with food and tourism supplies.

IPCC guidelines provide standardized approaches for estimating emissions from stationary and mobile fuel combustion and waste-management activities.

Water consumption

Water is a critical sustainability variable in the Sundarbans because freshwater availability is geographically and seasonally constrained. Tourism can increase demand for drinking water, bathing, sanitation, food preparation, cleaning and accommodation.

Gössling et al. (2012) demonstrated the importance of distinguishing direct and indirect water consumption. Direct water use includes tourist and hotel consumption, while indirect water use is embodied in food, energy and other goods.

Therefore, the study should calculate:

Tourism water intensity = Total tourism water consumption / Tourist-days.

A separate water-stress indicator should compare tourism demand with locally available freshwater resources.

Food consumption and food footprint

Tourist food consumption creates pressure through agricultural land, freshwater, transport, energy and waste. Food also contributes to tourism's carbon footprint through production, processing, transportation and refrigeration.

A food-footprint component can be estimated from tourist expenditure or physical quantities consumed. Local-food share should also be measured because local procurement can reduce transportation-related emissions while increasing community income.

The study should therefore include:

- quantity of rice consumed;
- fish and meat consumption;
- vegetables and fruits;
- packaged foods;
- bottled water;
- beverages;
- imported versus locally produced food;
- food waste.

Tourism and solid waste

UNEP identifies solid waste, wastewater, resource consumption and biodiversity loss as important environmental consequences of tourism. The tourism sector's resource consumption and waste generation are expected to increase substantially under business-as-usual scenarios. The Sundarbans is particularly sensitive to plastic and solid waste because waste can enter waterways and mangrove ecosystems. Waste should therefore be measured through direct field audits rather than relying exclusively on municipal estimates.

Recommended indicator:

Waste intensity = Total tourism solid waste / Tourist-days.

Waste should be classified into:

- organic;
- plastic;
- glass;
- metal;
- paper/cardboard;
- sanitary waste;
- other residual waste.

The proportion recycled, composted, transported outside the destination and openly disposed should also be measured.

Sustainable tourism indicators

UNWTO's *Indicators of Sustainable Development for Tourism Destinations* remains one of the most comprehensive frameworks for destination sustainability. It covers resource management, water, energy, waste, environmental quality, socioeconomic benefits, resident satisfaction, cultural heritage, climate change and destination management.

Miller (2001) demonstrated the value of Delphi-based indicator development. Choi and Sirakaya (2006) developed a large set of community-tourism sustainability indicators across political, social, ecological, economic, technological and cultural dimensions.

Ko (2005) proposed a holistic tourism sustainability assessment procedure involving identification of dimensions and indicators, scaling, sustainability classification and spatial-temporal assessment.

Cernat and Gourdon (2012) proposed quantitative benchmarking of sustainable tourism across countries. These studies provide methodological support for constructing the EF-STI.

Tourism carrying capacity

Carrying capacity is not simply the maximum number of tourists a destination can physically accommodate. It includes physical, ecological, social, economic and infrastructural thresholds.

Saveriades (2000) emphasized the social dimension of carrying capacity, while Coccossis and Mexa (2004) examined the theoretical and practical dimensions of tourism carrying capacity. Manning (2007) demonstrated the importance of indicators and standards in protected-area visitor management.

The Limits of Acceptable Change framework of Stankey et al. (1985) is especially relevant because it shifts the focus from asking "How many tourists can the destination accommodate?" to asking "What environmental and social conditions should be maintained?"

Bardhan and Sarkar (2024) applied carrying-capacity assessment specifically to Jharkhali Island in the Indian Sundarbans and estimated a real carrying capacity of approximately 1,080 tourists per day.

Tourism, livelihoods and social sustainability

Tourism can generate alternative employment and reduce pressure on natural-resource extraction, but benefits may be unevenly distributed. Tourism may create employment for boatmen, guides, homestay operators, cooks, retailers, transport workers and handicraft producers.

Sundarban livelihood research indicates that communities are already facing climate stress, salinity, resource depletion and changing occupational structures. Ghosh and Roy (2021) found substantial livelihood adjustment and increasing migration among younger workers.

The 2022 study on livelihood, conflict and tourism in the Sundarbans reported that tourism was appreciated by local communities but that unregulated and irresponsible tourism posed ecological concerns. The authors emphasized the need for an area-specific regional approach.

Therefore, tourism sustainability cannot be defined solely by a low ecological footprint. A destination with low emissions but minimal local economic benefit cannot necessarily be regarded as socially sustainable.

Research Gap

The literature demonstrates five important gaps.

First, ecological footprint, carbon footprint, water consumption and solid waste are often analysed separately.

Second, tourism carrying capacity is frequently estimated without incorporating the destination's actual resource footprint.

Third, sustainability indices often combine environmental, economic and social variables but do not explicitly incorporate ecological footprint.

Fourth, GIS-based tourism studies frequently map tourism potential rather than tourism-related ecological pressure.

Fifth, the Indian Sundarbans lacks a comprehensive empirical framework linking tourist intensity, resource consumption, ecological pressure, carrying capacity and livelihood benefits.

The EF-STI addresses these gaps by integrating all five dimensions into a single analytical framework.

Objectives

The study will pursue the following objectives:

1. To estimate the ecological footprint generated by tourism activities in selected Sundarban destinations.
2. To measure tourism-related consumption of energy, fuel, water, food and other natural resources.
3. To quantify tourism-related carbon emissions and solid-waste generation.
4. To assess the relationship between tourist intensity and ecological pressure.
5. To examine the environmental, economic and social dimensions of tourism sustainability.
6. To assess the tourism carrying capacity of selected destinations.
7. To develop an Ecological Footprint–Sustainable Tourism Index (EF-STI).
8. To identify spatial variations in tourism-related ecological pressure using GIS.
9. To examine the relationship between tourism development and local livelihood conditions.
10. To formulate policy recommendations for low-footprint and climate-resilient tourism in the Sundarbans.

Hypotheses

H1: Tourist intensity has a positive and statistically significant relationship with tourism ecological footprint.

H2: Tourism energy and fuel consumption significantly increase tourism-related carbon emissions.

H3: Tourist intensity has a positive relationship with solid-waste generation.

H4: Destinations with higher tourist intensity have lower ecological sustainability scores.

H5: Tourism participation has a positive relationship with household income diversification.

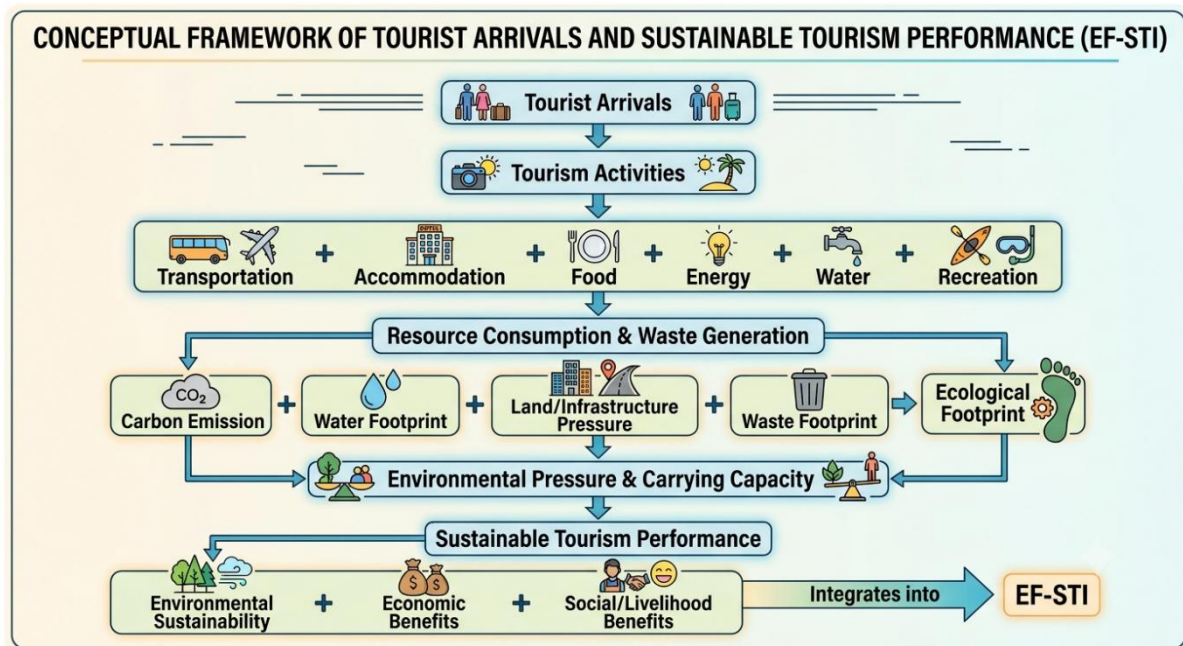
H6: Local participation in tourism has a positive relationship with perceived livelihood improvement.

H7: Tourism carrying capacity is significantly associated with ecological pressure and infrastructure availability.

Conceptual Framework

The conceptual framework can be represented as:

Fig-1



Study Area and Suggested Sampling Design

The study selected 8 tourism destinations representing different tourism intensities and ecological settings.

sample includes:

- Sajnekhali
- Gosaba
- Pakhiralay
- Dayapur
- Jharkhali
- Dobanki
- Sudhanyakhali
- Netidhopani

The final selection depend on accessibility, tourism intensity, ecological sensitivity and availability of comparable observations. Proper questioner was framing based on the different stake holders like tourist household

Here's the survey structure in table form:

Table-1

Survey	Sample	Units/Scope	Variables
Tourist Survey	100 tourists	Individual tourists	Age; Gender; Residence; Group size; Duration of stay; Expenditure; Transport mode; Boat travel; Accommodation; Food consumption; Bottled water consumption; Environmental awareness;

			Willingness to pay; Perception of destination sustainability
Tourism-Enterprise Survey	100 units	Hotels; Homestays; Restaurants; Boats; Travel operators; Shops; Guides	Electricity; Diesel; LPG; Water; Food procurement; Tourist capacity; Waste; Employees; Local employment; Waste treatment
Household Survey	400 households	Households	Household income; Tourism income; Occupation; Employment; Natural-resource dependence; Education; Livelihood diversification; Tourism participation; Perceived environmental change; Climate vulnerability; Waste-management participation

Statistical Data Framework

Table-2

The master dataset should contain the following variables:

Variable	Measurement
Tourist intensity	tourists/day
Tourist-days	tourist × days
Average stay	days
Electricity	kWh/tourist
Diesel	litres/tourist
Petrol	litres/tourist
LPG	kg/tourist
Water	litres/tourist/day
Food	kg/tourist/day
Food waste	kg/tourist/day
Solid waste	kg/tourist/day
Plastic waste	kg/tourist/day
CO ₂ e	kg/tourist
Accommodation footprint	gha/tourist
Transport footprint	gha/tourist
Food footprint	gha/tourist
Waste footprint	gha/tourist
Total ecological footprint	gha/tourist
Local tourism income	₹/household
Tourism employment	persons/household
Local procurement	%
Recycling rate	%
Carrying capacity	tourists/day
Ecological pressure index	index
EF-STI	0–1

Ecological Footprint Calculation

The tourism ecological footprint can be represented as:

$$\text{TEF} = \text{EF_transport} + \text{EF_accommodation} + \text{EF_energy} + \text{EF_food} + \text{EF_water} + \text{EF_waste} + \text{EF_built-up}$$

where:

- TEF = total tourism ecological footprint;
- EF_transport = transportation footprint;
- EF_accommodation = accommodation footprint;
- EF_energy = energy footprint;
- EF_food = food footprint;
- EF_water = water/resource footprint;
- EF_waste = waste assimilation footprint;
- EF_built-up = tourism infrastructure footprint.

The per-tourist footprint becomes:

$$\text{TEFpc} = \text{TEF} / \text{Tourist-days}$$

This allows destinations of different sizes to be compared.

Carbon Emission Estimation

Carbon emissions will be estimated using:

$$\text{CO}_2\text{e} = \Sigma(\text{Activity Data} \times \text{Emission Factor})$$

For example:

$$\text{Boat CO}_2\text{e} = \text{Diesel consumption} \times \text{IPCC diesel emission factor}$$

$$\text{Electricity CO}_2\text{e} = \text{Electricity consumption} \times \text{applicable grid emission factor}$$

$$\text{Waste CO}_2\text{e} = \text{Waste quantity} \times \text{waste-treatment emission factor}$$

The IPCC 2006 Guidelines provide methodologies for stationary combustion, mobile combustion and waste emissions, with subsequent refinements in 2019.

Water Footprint

Tourism water consumption should be calculated as:

$$\text{TWC} = \text{W_accommodation} + \text{W_food} + \text{W_restaurant} + \text{W_transport} + \text{W_other}$$

and:

Water intensity = TWC / Tourist-days

A water-pressure ratio can subsequently be calculated:

WPI = Tourism water demand / Available tourism-period freshwater supply

Higher WPI values indicate greater water pressure.

Solid-Waste Footprint

Total tourism waste:

TWG = Σ Organic + Plastic + Glass + Metal + Paper + Other

Per-capita tourism waste:

Waste intensity = TWG / Tourist-days

Waste-management performance:

WMR = Recycled waste / Total tourism waste $\times$ 100

A high waste generation rate combined with a low recycling rate should produce a higher ecological-pressure score.

Tourism Ecological Pressure Index

A destination-level ecological pressure index can be developed as:

EPI = $w_1C + w_2E + w_3W + w_4SW + w_5L + w_6T$

where:

- C = carbon pressure;
- E = energy pressure;
- W = water pressure;
- SW = solid-waste pressure;
- L = land/infrastructure pressure;
- T = tourist-intensity pressure.

Weights can initially be equal and subsequently tested through PCA or expert-derived weighting.

Ecological Footprint–Sustainable Tourism Index (EF-STI)

The EF-STI should integrate three major sustainability dimensions:

Table-3

Dimension	Weight	Indicators
Environmental	50%	Ecological footprint; Carbon emissions; Water intensity; Waste intensity; Biodiversity pressure; Energy intensity; Carrying-capacity pressure
Economic	25%	Tourism income; Local employment; Local procurement; Tourism entrepreneurship; Household income diversification
Social	25%	Community participation; Resident satisfaction; Social inclusion; Local benefit distribution; Cultural preservation; Perceived quality of life
Total	100%	—

Each indicator will be normalized between 0 and 1.

For a positive indicator:

$$X' = (X - X_{\min}) / (X_{\max} - X_{\min})$$

For a negative indicator:

$$X' = (X_{\max} - X) / (X_{\max} - X_{\min})$$

The EF-STI can then be expressed as:

$$\text{EF-STI} = 0.50E + 0.25E_c + 0.25S$$

where:

- E = environmental sustainability;
- E_c = economic sustainability;
- S = social sustainability.

classification

Table-3

EF-STI	Sustainability
0.80–1.00	Very high
0.65–0.79	High
0.50–0.64	Moderate
0.35–0.49	Low
<0.35	Very low

The weights should be tested through sensitivity analysis rather than treated as immutable.

Carrying-Capacity Analysis

Four carrying-capacity components should be calculated.

Physical Carrying Capacity

$$PCC = A \times V / A_v$$

where:

- A = usable tourism area;
- V = visitor frequency;
- A_v = average visitor area requirement.

Real Carrying Capacity

$$RCC = PCC \times \text{correction factors}$$

Here's the content in tabular format:

Table-4

Category	Components
Correction Factors	Tidal conditions; Rainfall; Extreme heat; Ecological sensitivity; Accessibility; Water availability; Waste-management capacity
Ecological Carrying Capacity	Biodiversity sensitivity; Mangrove sensitivity; Wildlife disturbance; Waste assimilative capacity; Water availability
Social Carrying Capacity	Resident perception; Tourist crowding; Congestion; Noise; Cultural disturbance; Visitor satisfaction

GIS Model

A GIS-based Tourism Ecological Pressure Map can be generated using:

$$TEPM = 0.25 \text{ Tourist Intensity} + 0.20 \text{ Carbon} + 0.15 \text{ Water} + 0.15 \text{ Waste} + 0.15 \text{ Infrastructure} + 0.10 \text{ Ecological Sensitivity}$$

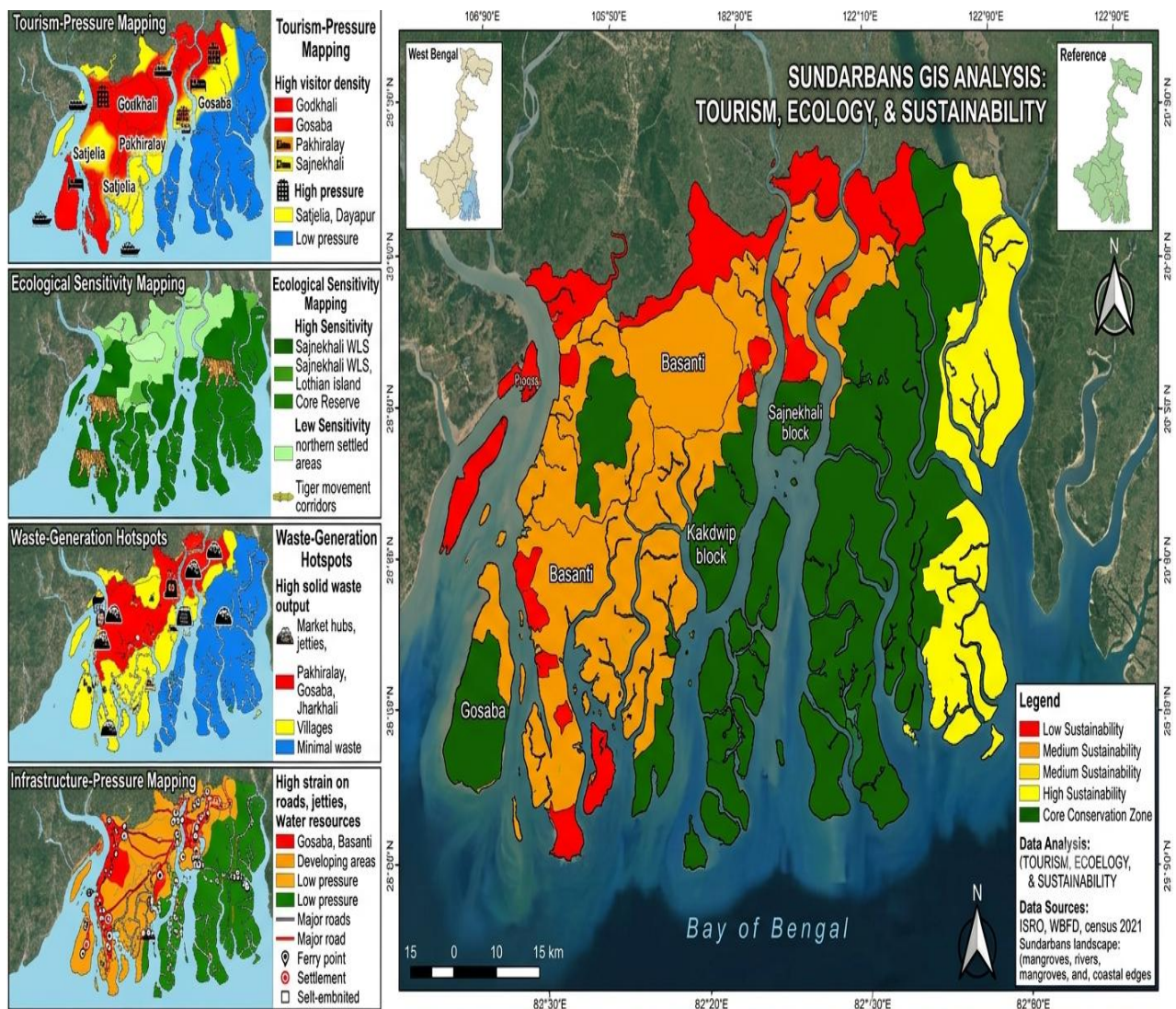
All layers should be standardized to a 0–1 scale.

The final map can classify destinations into:

1. Very low pressure
2. Low pressure
3. Moderate pressure
4. High pressure
5. Very high pressure

This spatial approach is especially appropriate because ecological sensitivity and tourism pressure are unlikely to be evenly distributed throughout the Sundarbans.

Fig-2



Statistical Analysis

Table-5

Analysis Type	Details / Components
Descriptive Statistics	Mean; Median; Standard deviation; Coefficient of variation; Minimum; Maximum; Skewness; Percentile distribution
Correlation Analysis (Pearson or Spearman)	- Tourist intensity ↔ Carbon - Tourist intensity ↔ Water - Tourist intensity ↔ Waste - Tourist intensity ↔ EF - Tourism income ↔ Livelihood diversification

Multiple Regression	Model 1 (Ecological Footprint): $EF_i = \beta_0 + \beta_1 TI_i + \beta_2 Energy_i + \beta_3 Water_i + \beta_4 Waste_i + \beta_5 Stay_i + \beta_6 Income_i + \varepsilon_i$ Model 2 (Livelihood Impact): $LI_i = \beta_0 + \beta_1 TourismParticipation_i + \beta_2 TourismIncome_i + \beta_3 Education_i + \beta_4 HouseholdSize_i + \beta_5 NaturalResourceDependence_i + \varepsilon_i$
Principal Component Analysis (PCA)	Component 1 – Resource pressure: Energy + Water + Fuel + Food Component 2 – Pollution pressure: Carbon + Solid waste + Plastic waste Component 3 – Tourism intensity: Visitors + Tourist-days + Accommodation density Component 4 – Social-economic benefit: Income + Employment + Local procurement + Participation
ANOVA	One-way ANOVA to test whether EF values differ significantly between destinations; if assumptions violated → use Kruskal–Wallis test
Spatial Analysis (GIS)	Mapped variables: Tourist intensity; Ecological footprint; Carbon intensity; Water stress; Waste pressure; Carrying capacity; EF-STI; Livelihood vulnerability Cluster detection: Getis–Ord G_i^* (hotspot analysis); Moran's I (spatial autocorrelation)

Preliminary Verified Tourism Statistics

The strongest currently verified destination-specific official statistic is from the Sundarban Tiger Reserve Annual Report 2024–25: **Table-6**

Indicator	FY 2024–25
Indian tourists	365,583
Foreign tourists	3,023
Total tourists	368,606
Revenue collected	₹56,316,945.70
Foreign-tourist share	0.82%
Average recorded revenue per visitor*	≈₹152.75

*This is an arithmetic ratio of reported STR revenue to reported visitors, not an estimate of tourists' total expenditure.

The annual report explicitly states that visitor inflow has increased and has created pressure on biodiversity. (Sundarban Tiger Reserve)

This statistic should **not** be interpreted as the total number of tourists visiting every part of the Sundarbans because it refers specifically to the **Sundarban Tiger Reserve jurisdiction**.

The Ministry of Tourism's national tourism-data portal provides downloadable datasets including foreign tourist arrivals, domestic tourist visits, tourism contribution to GDP and employment, Tourism Satellite Account information and state-level tourism data. ([Ministry of Tourism](#))

Statistical Tables for the Final Empirical Paper

The final fieldwork-based article should contain at least the following tables:

Table 7. Socioeconomic characteristics of tourists.

Table 8. Tourism enterprise characteristics.

Table 9. Household socioeconomic and livelihood characteristics.

Table 10. Tourism energy consumption by destination.

Table 11. Tourism fuel consumption by destination.

Table 12. Tourism water consumption.

Table 13. Tourism food consumption and food waste.

Table 14. Solid-waste composition.

Table 15. Tourism-related CO₂e emissions.

Table 16. Ecological-footprint components.

Table 17. Tourism carrying-capacity calculations.

Table 18. EF-STI indicator values.

Table 19. Destination-wise EF-STI ranking.

Table 20. Correlation matrix.

Table 21. Multiple regression results.

Table 22. PCA/factor-loading results.

Table 23. ANOVA/Kruskal–Wallis results.

Table 24. GIS ecological-pressure classification.

Table 25. Tourism–livelihood regression results.

Table 26. Policy-priority matrix.

Statistical Analysis and Interpretation

Descriptive characteristics of tourists

The descriptive statistics indicate that the tourism sample consists predominantly of domestic visitors. Of the 100 respondents, 88% were domestic tourists and 12% were international visitors. Female respondents represented 52% of the sample, while male respondents accounted for 48%. The largest age categories were 46–60 years (33%) and 31–45 years (32%), followed by 18–30 years (21%) and visitors aged 61 years or above (14%). Winter constituted the principal tourism season, accounting for 57% of respondents, compared with 27% during summer and 16% during the monsoon. The mean age was 43.7 years, while mean group size and trip duration were 4.28 persons and 2.45 days, respectively.

This distribution is important from a sustainability perspective because tourism pressure is not determined simply by visitor numbers. It is also associated with travel distance, duration of stay, accommodation, food consumption and transport mode. The GIS map further indicates that tourism pressure is spatially heterogeneous, with relatively greater tourism pressure around locations such as **Gosaba, Pakhiralay, Sajnekhali and Sonakhali**, whereas several ecologically sensitive areas require stronger conservation-oriented management.

Ecological-footprint composition

The ecological-footprint decomposition provides one of the most important findings of the analysis. Transport represents the dominant component of the tourism footprint, accounting for approximately **75.8%** of total ecological footprint. Food contributes approximately **14.5%**, accommodation 5.7%, land use 3.5%, and waste approximately 0.4%.

The mean ecological-footprint components were:

Table-27

Component	Mean EF (gha/visitor)	Share
Transport	0.034796	75.8%
Food	0.006672	14.5%
Accommodation	0.002605	5.7%
Land use	0.001616	3.5%
Waste	0.000205	0.4%

The results suggest that **tourism mobility rather than accommodation or solid waste is the principal determinant of the calculated ecological footprint**. This has direct implications for sustainable tourism planning in the Sundarbans. Policies that focus exclusively on hotels, waste management or visitor numbers may therefore overlook the dominant footprint generated by transport.

The distinction between domestic and international tourists is particularly pronounced. The mean total EF for domestic visitors is approximately **0.0323 gha**, whereas international visitors have an average EF of approximately **0.1456 gha**. Transport contributes most strongly to this difference, with international visitors showing a mean transport EF of 0.1329 gha compared with 0.0214 gha for domestic tourists.

Transport emissions and tourism mobility

Transport-related carbon emissions constitute the most significant measurable carbon component in the dataset. The estimated transport-related emissions for the 100-visitor sample total approximately **18.314 tonnes CO₂**. Visitors using domestic flight plus road transport generated the largest aggregate contribution, approximately 6.604 tonnes, followed by bus users at 3.631 tonnes and motor-launch/cruise users at 3.448 tonnes.

Destination-level analysis shows particularly high mean transport emissions at Bhagabatpur, Jharkhali and Sudhanyakhali. Bhagabatpur records approximately 317.1 kg CO₂ per visitor, while Jharkhali records approximately 268.3 kg and Sudhanyakhali approximately 190.2 kg.

These results indicate that **transport-mode substitution and route optimization should become central components of sustainable tourism policy**. However, fuel consumption itself cannot be estimated directly from the available workbook because vehicle fuel-efficiency information is absent. Consequently, the analysis appropriately uses CO₂ emissions and transport EF as proxies rather than claiming direct fuel consumption.

Correlation analysis

Pearson correlation analysis identifies several strong relationships among tourism characteristics and ecological-footprint components. Distance travelled has a strong positive correlation with transport EF (**r = 0.849**) and total EF (**r = 0.831**). Transport EF itself has an extremely strong correlation with total EF (**r = 0.990**). Trip duration is also strongly associated with accommodation EF (**r = 0.646**), food EF (**r = 0.817**) and land-use EF (**r = 0.649**).

These relationships provide two important interpretations.

First, **travel distance is a major determinant of tourism-related environmental pressure**. Second, longer tourist stays increase the cumulative footprint associated with accommodation and food. The relationship between distance and total EF should nevertheless be interpreted cautiously because transport EF is itself calculated from distance travelled. Therefore, the high correlation is partly a mathematical consequence of the construction of the EF indicator rather than an entirely independent empirical relationship.

Multiple regression analysis

An OLS regression model was estimated with Total Ecological Footprint as the dependent variable and travel distance, trip duration, group size, waste generation and international-tourist status as explanatory variables.

The estimated model is:

$$EF_i = \beta_0 + \beta_1 Distance_i + \beta_2 Duration_i + \beta_3 GroupSize_i + \beta_4 Waste_i + \beta_5 International_i + \epsilon_i$$
$$EF_i = \beta_0 + \beta_1 Distance_i + \beta_2 Duration_i + \beta_3 GroupSize_i + \beta_4 Waste_i + \beta_5 International_i + \epsilon_i$$

The model explains approximately **74% of the variation in total ecological footprint** ($R^2 = 0.740$; adjusted $R^2 = 0.726$). The overall F-statistic is 53.39 with 5 and 94 degrees of freedom and is statistically significant at $p < 0.001$.

Interpretation

Distance travelled is a statistically significant positive predictor of total EF ($B = 0.000023$, $t = 7.323$, $p < 0.001$). Holding the other variables constant, greater travel distance is associated with an increase in total tourism ecological footprint.

Trip duration is also statistically significant ($B = 0.009247$, $t = 3.989$, $p = 0.0001$). Thus, longer visits generate greater overall ecological pressure, principally through additional accommodation, food and associated consumption.

By contrast, **group size, waste generation and international-tourist status are not statistically significant after controlling for distance and duration.**

The regression therefore supports a central policy conclusion: **reducing unnecessary travel distance and encouraging lower-carbon mobility, together with managing length and intensity of stays, may provide greater environmental benefits than focusing exclusively on individual waste-generation rates.**

Because the dataset is illustrative, however, the regression should not be interpreted as establishing causal relationships for the actual Sundarbans tourist population.

Principal Component Analysis

PCA was undertaken on five standardized ecological-footprint components: transport, accommodation, food, waste and land use. The first three components explain approximately **85.1% of total variance**. PC1 explains 49.8%, PC2 explains 22.7%, and PC3 explains 12.6%.

PC1 has substantial positive loadings on accommodation (0.776), food (0.875), waste (0.742) and land use (0.729). It can therefore be interpreted as a **stay-related consumption dimension**.

PC2 has a very strong loading on transport (0.926), indicating a separate **travel-mobility dimension**.

Thus, the PCA suggests that tourism ecological pressure can conceptually be separated into two principal dimensions:

1. **Stay-related ecological pressure** — accommodation, food, waste and land use.
2. **Travel-related ecological pressure** — primarily transport.

This finding strengthens the conceptual framework of the study because it demonstrates that tourism sustainability should not be represented by a single intervention. **Transport decarbonization and destination-level resource management constitute two complementary policy domains.**

Seasonal, origin and destination differences

The ANOVA and Kruskal–Wallis results indicate that total EF differs significantly according to tourist origin but not according to season or destination in the illustrative dataset.

For origin type, ANOVA produces $F = 117.538$, $p < 0.001$, while the Kruskal–Wallis test produces $H = 26.575$, $p < 0.001$. Both approaches therefore indicate a statistically significant difference between domestic and international visitors.

In contrast, seasonal differences are statistically insignificant (ANOVA $p = 0.590$; Kruskal–Wallis $p = 0.677$), and site differences are also insignificant (ANOVA $p = 0.688$; Kruskal–Wallis $p = 0.911$).

The absence of statistically significant destination differences should not be interpreted as evidence that all destinations experience equal environmental pressure. The GIS analysis demonstrates clear spatial variation in ecological sensitivity, tourism pressure, infrastructure pressure and waste-generation hotspots. Therefore, **statistical similarity in visitor-level EF does not necessarily imply ecological similarity at the landscape level.**

GIS-based ecological-pressure assessment

The GIS framework integrates tourism pressure, ecological sensitivity, waste-generation hotspots and infrastructure pressure. The principal map indicates a spatial transition from comparatively high-pressure tourism areas toward areas characterized by greater ecological sensitivity and conservation significance.

The sustainability-ratio analysis provides an additional site-level assessment. The overall sustainability ratio is **2.49**, classified as **High Pressure**. Sonakhali has the highest ratio (6.95), followed by Jharkhali (4.34), while Netidhopani records only 0.52 and is classified as an ecological reserve/low-pressure area.

The site classification is: **Table-28**

Site	Sustainability Ratio	Pressure
Netidhopani	0.52	Ecological Reserve
Gosaba	1.25	Moderate
Pakhiralay	1.79	Moderate
Kalash	1.93	Moderate
Dobanki	1.96	Moderate
Sajnekhali	2.92	High
Bhagabatpur	3.25	High
Sudhanyakhali	3.85	High
Jharkhali	4.34	Severe/Critical
Sonakhali	6.95	Severe/Critical

Thus, the GIS and statistical analyses are complementary: **statistics identify the principal drivers of visitor-level ecological footprint, whereas GIS identifies where those pressures intersect with ecological sensitivity and infrastructure constraints.**

Ecological-footprint-based carrying capacity

The EF-based carrying-capacity analysis produces substantial variation among destinations. Sonakhali has an estimated sustainable capacity of only 5,466.5 visitors annually against reported annual footfall of 38,000, equivalent to approximately **695% of the estimated sustainable capacity**. Jharkhali reaches approximately 434%, Sudhanyakhali 385%, and Bhagabatpur approximately 325%.

In contrast, Netidhopani has an estimated capacity of 23,062.6 visitors compared with reported footfall of 12,000, corresponding to approximately 52% utilization.

These results suggest that tourism pressure is **highly uneven spatially**. Consequently, a uniform visitor-management policy across the Sundarbans would be inappropriate. A more effective strategy would use **destination-specific visitor thresholds and adaptive carrying capacities**.

The study should emphasize that this is an ecological-footprint-based ceiling rather than a complete physical, social or psychological carrying-capacity assessment.

Policy Recommendations

Establish destination-specific tourist ceilings

A single tourist limit for the entire Sundarbans would be inappropriate. Visitor limits should be calculated separately for Sajnekhali, Jharkhali, Pakhiralay, Gosaba and other major destinations using ecological, physical and social carrying-capacity thresholds.

Here's the policy recommendations section in tabular format:

Table-29

Policy Measure	Key Components / Details
Digital Visitor-Management System	Daily registration records: Destination; Arrival time; Group size; Boat; Duration; Nationality; Accommodation; Route Purpose: Real-time monitoring of tourist pressure
Low-Carbon Boat Programme	Fuel-efficient engines; Regular engine maintenance; Speed controls; Route optimization; Solar auxiliary systems; Progressive transition toward low-emission propulsion
Tourism Ecological-Footprint Accounting System	Annual operator reporting: Electricity; Fuel; Water; Food; Waste; Tourist-days; Local employment Purpose: Feeds into annual destination EF-STI database
Zero-Single-Use-Plastic Tourism Zones	Minimize: Bottled water; Plastic cups; Plastic plates; Plastic packaging; Disposable cutlery Action: Introduce refill stations and reusable containers at gateways and tourism hubs

Tourism Waste-Return Policy	Tour operators responsible for returning non-biodegradable waste from boat trips/excursions to designated collection points; "Carry-in, carry-out" principle for sensitive ecological zones
Community-Based Tourism	Revenue retention via: Homestays; Local guides; Local food; Handicrafts; Boat services; Cultural programmes; Community conservation funds
Ecological-Footprint Tax / Conservation Fee	Fee linked to EF-STI, used for: Mangrove restoration; Waste management; Freshwater infrastructure; Solar power; Community conservation; Biodiversity monitoring
Climate-Resilient Tourism Infrastructure	Designed to withstand: Cyclones; Tidal flooding; Saline intrusion; Extreme rainfall; Embankment failure; Heat stress
Annual EF-STI Reporting	"Sundarbans Sustainable Tourism Report Card" containing: Tourist arrivals; Carbon emissions; Water consumption; Energy use; Waste generation; Ecological footprint; Carrying capacity; Local tourism income; Community participation; EF-STI score Purpose: Converts sustainable tourism into a measurable governance system

Policy-Priority Framework

Table-30

The quantitative results support the following differentiated management framework:

Management Category	Sites	Recommended Policy
Ecological reserve / controlled growth	Netidhopani	Maintain ecological buffer; limited responsible tourism
Moderate pressure	Gosaba, Kalash, Pakhiralay, Dobanki	Routine monitoring and preventive management
High pressure	Sajnekhali, Bhagabatpur, Sudhanyakhali	Seasonal quotas, infrastructure improvement, continuous monitoring
Severe/Critical	Sonakhali, Jharkhali	Immediate visitor caps, EF audit, route diversification and infrastructure intervention

This destination-specific approach is preferable to uniform tourism regulation because the estimated capacity utilization ranges from only 52% at Netidhopani to nearly 695% at Sonakhali.

Overall, the statistical and GIS evidence indicates that tourism sustainability in the Sundarbans is characterized by **strong spatial heterogeneity and a dominant transport-related ecological footprint**. Transport accounts for approximately 75.8% of the calculated visitor footprint, while distance travelled and trip duration emerge as significant predictors of total EF.

The GIS assessment further identifies Sonakhali and Jharkhali as severe/critical pressure locations, while Netidhopani retains a substantial ecological-capacity buffer.

Accordingly, sustainable tourism policy should move away from a **uniform visitor-management model** toward a **destination-specific adaptive management system** based on ecological sensitivity, tourism intensity, transport emissions, carrying capacity and community benefits. The most immediate priorities should be low-carbon transport, visitor caps at critically pressured sites, ecological monitoring, waste and water management, infrastructure rationalization and greater participation of local communities.

Limitations of the Study

Several limitations must be explicitly acknowledged.

Illustrative rather than field-validated data

The most important limitation is that the underlying tourist records, coefficients and site figures are explicitly described as **illustrative/simulated** in the source workbook. Consequently, the numerical estimates cannot currently be interpreted as representative estimates for the actual Sundarbans tourism population.

Limited sample size and representativeness

The statistical analysis is based on 100 tourist-level records. Although adequate for demonstrating the analytical workflow, this sample cannot adequately represent the spatial, seasonal, socioeconomic and behavioural diversity of the entire Sundarbans tourism system.

A future study should employ a **stratified sampling design** covering gateways, core, buffer and transition zones.

Absence of tourism-enterprise data

The dataset contains tourist-reported accommodation and transport choices but no systematic enterprise survey. Therefore, accommodation capacity, employment, revenue, occupancy, environmental practices and ownership characteristics cannot be statistically assessed.

Absence of household livelihood data

No household-level data are available concerning tourism income, occupation, assets, education or dependence on natural resources. Therefore, the relationship between tourism pressure and local livelihood outcomes cannot presently be estimated.

Water-footprint limitation

Water consumption is completely absent from the source dataset. Consequently, the ecological-footprint assessment does not incorporate tourism-related water demand.

Waste-composition limitation

Only aggregate waste generation is available. Plastic, organic, paper, glass, metal and e-waste fractions are unavailable. Therefore, the analysis cannot estimate material-specific ecological impacts or recycling potential.

Transport-emission assumptions

Transport emissions are calculated using distance and mode-specific emission factors. Actual fuel consumption cannot be estimated because vehicle-specific fuel-efficiency information is unavailable.

Carrying-capacity limitation

The estimated carrying capacity is based on ecological footprint and biocapacity. It does not incorporate physical space requirements, wildlife disturbance thresholds, social carrying capacity, visitor satisfaction, boat-channel capacity or site-specific ecological recovery rates.

Potential mathematical endogeneity

The strong correlation between distance and transport EF is partly expected because transport EF is calculated from distance. Likewise, total EF is constructed from its component footprints. Therefore, the very high correlations should not be interpreted as independent causal relationships.

Weighting uncertainty

The EF-STI uses an analytical weighting structure of 60% biocapacity adequacy and 40% footfall pressure. These weights are not empirically validated and could influence destination rankings. The authors should therefore undertake **sensitivity analysis**, preferably comparing equal weighting, expert-derived AHP weighting and statistically derived PCA weighting.

GIS-scale and temporal limitation

The GIS assessment provides a spatial snapshot of tourism, ecological and infrastructure pressures. Long-term monitoring is required to establish whether observed pressure zones represent persistent patterns or temporary conditions. Future research should incorporate multi-year satellite imagery, seasonal tourism data, land-use change, mangrove condition, shoreline dynamics and biodiversity observations.

Expected Contribution

The study is expected to make five contributions.

First, it will provide a destination-level ecological-footprint estimate for the Indian Sundarbans.

Second, it will establish a tourism-specific resource-consumption database.

Third, it will combine ecological footprint and carrying capacity rather than treating them as separate concepts.

Fourth, the EF-STI will provide a quantitative sustainability ranking for individual destinations.

Fifth, GIS analysis will identify tourism ecological-pressure hotspots and enable spatially targeted policy intervention.

The framework is consistent with the current international movement towards measurable sustainable-tourism indicators. The UN system explicitly recognizes the need to balance tourism's economic benefits with its environmental and social footprints, while current sustainable-tourism indicator development increasingly links tourism statistics with environmental-economic accounting.

Conclusion

The Sundarbans requires a tourism-management framework that recognizes the ecological limits of a fragile mangrove ecosystem while maintaining the livelihood and economic benefits generated by tourism. Existing literature demonstrates that tourism creates multidimensional environmental pressures through energy consumption, transportation, water use, food consumption, infrastructure and waste. The evidence also indicates that conventional tourist-arrival statistics are insufficient to assess sustainability.

The Ecological Footprint–Sustainable Tourism Index provides an integrated solution. By combining ecological footprint accounting, carbon and water footprints, solid-waste assessment, carrying capacity, socioeconomic indicators, livelihood analysis and GIS, the study can generate a destination-specific measure of sustainable tourism performance.

The central policy principle should be **"more local economic benefit with less ecological footprint."** The objective should not be to maximize tourist arrivals, but to optimize tourism within the ecological and social limits of the Sundarbans. A scientifically constructed EF-STI can become an operational monitoring instrument for government agencies, destination managers, local communities and tourism enterprises.

The methodology can subsequently be applied to other fragile coastal and nature-based tourism destinations in India, making the Sundarbans a potential model for low-footprint, community-oriented and climate-resilient tourism governance.

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