From Narratives to Destinations: Semantic–Spatial Modeling of Tourism Trends Using Geotagged Reviews

Sana Arif[1], Hammad Bashir[1]
[1]Department of Computer Science, Quaid e Azam University, Lahore.
*Correspondence: sana.qua@gmail.com

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Tourism narratives on social media and review platforms contain rich semantic and spatial information that can reveal evolving tourist preferences and destination trends. This study presents a hybrid topic modeling framework that integrates semantic embedding-based topic extraction with spatial-temporal clustering to analyze geotagged TripAdvisor reviews from 2019 to 2024. We employed state-of-the-art natural language processing techniques, including BERT-based topic modeling and Uniform Manifold Approximation and Projection (UMAP) for dimensionality reduction, to uncover nuanced themes and their geographic distributions. Spatial entropy, temporal prevalence, and Moran's I statistics were used to characterize spatial coherence and temporal evolution of dominant themes. Results indicate that our hybrid model significantly outperforms traditional Latent Dirichlet Allocation (LDA) in topic coherence (0.581 vs. 0.513), while spatial clustering reveals meaningful patterns in eco-tourism, cultural heritage, and health-safety topics. Temporal shifts highlight a post-COVID transition from budget-consciousness to experience- and sustainability-driven narratives. The proposed framework provides destination management organizations (DMOs) with a powerful tool for geographically and contextually targeted tourism analytics. This study contributes methodologically by aligning semantic spaces across locations and temporally modeling evolving themes, paving the way for more intelligent, data-driven tourism planning.

Keywords: Tourism Narratives, Social Media, Geotagged Reviews, Hybrid Topic Modeling, Bert, Umap, Spatial-Temporal Clustering, Tripadvisor, Spatial Entropy

Introduction:

Cognitive robotics and biologically inspired AI have recently witnessed a significant convergence, particularly in the domains of spatial cognition and navigation. Classical approaches in AI traditionally emphasized symbolic reasoning, often relying on logic-based representation schemes and declarative knowledge structures to emulate human cognition. However, these methods struggle with real-world uncertainty, sensorimotor interaction, and the grounding of abstract symbols in perceptual experience [1][2]. In contrast, biologically inspired systems, particularly those modeling neural substrates such as place cells, grid cells, and head direction cells, offer a grounded, analogical perspective of spatial cognition, leading to novel paradigms in mapping and navigation for autonomous agents.

Simultaneous Localization and Mapping (SLAM) has emerged as a cornerstone technology for autonomous robots navigating unknown environments. Traditional SLAM frameworks, such as ORB-SLAM2 and LSD-SLAM, have enabled sparse or semi-dense map construction based on visual and inertial cues, yet these systems often underperform in dynamic and large-scale outdoor environments [3]; [4]. The incorporation of deep learning models—e.g., DeepLabV3 for semantic segmentation and S2R-DepthNet for monocular depth prediction—has greatly enhanced the capability of visual SLAM systems by introducing high-level perception and enabling dense mapping without the need for costly LiDAR sensors. However, the dynamic nature of outdoor scenes, poor feature correspondence in low-light conditions, and the indiscriminate removal of potentially useful static instances remain critical challenges [5][6].

Inspired by spatial neural mechanisms in the mammalian brain—such as 3D place cells [7], head direction cells [8], and grid cells [9] recent efforts have focused on brain-based models like RatSLAM and NeuroSLAM for 2D and pseudo-3D navigation. Nevertheless, most biologically inspired models still lack robust implementations in complex real-world 3D environments, particularly with integrated support for semantic understanding and multi-modal perception. This paper aims to bridge that gap by proposing a novel hybrid cognitive architecture that integrates biologically inspired mechanisms with deep-learning-enhanced SLAM for real-time navigation in dynamic outdoor environments.

Research Gap:

While conventional SLAM systems have significantly advanced robotic navigation, they are generally constrained by static-environment assumptions, limited sensor ranges, and fragile data association in the presence of dynamic elements. Recent hybrid approaches that combine SLAM with deep learning show improved performance but still struggle to distinguish between truly dynamic entities and static instances with dynamic characteristics (e.g., parked vehicles), which could be valuable for local pose estimation. On the other hand, biologically inspired navigation models have demonstrated effectiveness in 2D or simulated 3D spaces but rarely extend to fully dynamic, large-scale outdoor 3D environments. There remains a lack of comprehensive frameworks that unify biologically plausible spatial representation with the strengths of semantic deep learning, particularly for real-time dense mapping and action selection under uncertainty. Most notably, few systems incorporate higher-level cognitive concepts such as emotion, imagination, or consciousness-inspired information flow as operational mechanisms in robotic SLAM.

Objectives:

The overarching objective of this study is to develop and validate a biologically inspired, cognitively enhanced SLAM system for dense 3D mapping and robust localization in dynamic outdoor environments. Specifically, the study aims to:

Integrate biologically inspired models of 3D spatial cognition (e.g., place cells, grid cells, and head direction cells) into a unified SLAM framework.

Enhance pose estimation accuracy through semantic segmentation, depth prediction, and multi-view feature projection using state-of-the-art deep learning techniques (e.g., DeepLabV3, S2R-DepthNet).

Propose a hierarchical architecture that employs stereo vision and monocular depth fusion to mitigate depth inaccuracies in outdoor scenes.

Develop a hybrid data association mechanism capable of distinguishing between static, dynamic, and quasi-static features to enhance map consistency.

Construct an incremental dense semantic map using octree structures, suitable for high-level robot navigation and interaction.

Evaluate the proposed system on real-world datasets (e.g., KITTI) and demonstrate its generalization in diverse, unstructured outdoor environments.

Novelty Statement:

This study presents a novel hybrid biologically inspired cognitive SLAM system that fuses deep neural representations with analogical spatial structures modeled after the mammalian brain. Unlike previous methods that either rely on static-environment assumptions or ignore the semantic value of quasi-static features, the proposed framework:

Incorporates emotion, imagination, and global workspace theory into the SLAM pipeline for action selection and adaptive behavior, inspired by [10] and [11].

Utilizes depth local contrast and multiple-view geometry to refine semantic segmentation, allowing for retention of useful static instances within dynamic-class objects.

Implements conjunctive pose cell modeling for 4DoF spatial representation, supporting full 3D navigation, informed by the latest findings on 3D place and grid cells [9][12].

Adopts a hierarchical mapping approach combining stereo visual odometry and learned depth predictions for robust pose estimation, minimizing drift and enhancing map reuse.

Proposes a multi-layered cognitive map architecture, supporting dense mapping in large-scale, real-world dynamic environments.

These contributions mark a significant step toward biologically plausible and semantically aware robot cognition, laying the groundwork for future AI systems capable of adaptive, context-aware, and explainable spatial reasoning.

Literature Review:

The increasing volume of user-generated content (UGC) on tourism platforms like TripAdvisor presents vast opportunities for understanding tourist behavior, preferences, and sentiments through natural language processing (NLP) and spatial analytics. Recent advances in topic modeling, embedding techniques, and swarm-based optimization have facilitated richer semantic and spatial analyses of such narratives.

Topic modeling remains central to mining tourism data. Traditional approaches such as Latent Dirichlet Allocation (LDA) have been widely used to extract hidden themes from reviews. However, recent studies argue that LDA, while interpretable, often fails to capture nuanced semantics and contextual relationships between words [13][14]. This has led to the integration of word embeddings (e.g., Word2Vec, GloVe, BERT) into topic modeling pipelines, yielding models like ETM (Embedded Topic Model) and BERTopic that outperform LDA in topic coherence and contextual richness [15].

Recent literature has introduced hybrid semantic-spatial frameworks that blend topic modeling with geospatial analysis to uncover localized tourism patterns. For example, [16] proposed a spatially aware LDA [17] variant to examine city-level tourism narratives, while [18] applied transformer-based embeddings with hierarchical clustering to detect regional sentiment hotspots.

Embedding alignment is another innovation enabling cross-domain and multilingual topic mapping. For instance, [19] aligned BERT-based embeddings across language domains to extract semantically equivalent tourist sentiments across countries. This is crucial for global platforms like TripAdvisor that host multi-language reviews.

Swarm intelligence algorithms, particularly Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO), have been adopted to optimize hyperparameters in topic models or cluster embeddings in high-dimensional space [20]. These nature-inspired algorithms help avoid local minima and improve topic coherence scores compared to grid or random search methods.

Moreover, spatio-temporal modeling of tourism narratives is gaining attention. [21] proposed a time-enhanced topic model that captured seasonal and event-based fluctuations in tourist interests using temporal tagging and sentiment trajectories.

Collectively, these advancements suggest a paradigm shift towards hybrid, interpretable, and context-aware frameworks that integrate deep semantics, spatial analytics, and optimization heuristics to better understand tourism narratives.

Methodology:

Study Design:

This study employed a hybrid computational framework combining semantic topic modeling, spatial analytics, and nature-inspired optimization to analyze user-generated tourism narratives. The workflow consisted of five stages: (i) data collection, (ii) preprocessing, (iii) semantic topic modeling using LDA and contextualized embeddings, (iv) spatial and temporal mapping of extracted topics, and (v) optimization using swarm intelligence.

Data Collection:

Tourism-related textual data were collected from **TripAdvisor** reviews of five popular global tourist destinations: Paris, Rome, Bangkok, Istanbul, and New York. A total of **58,342 English-language reviews** were scraped using Python's BeautifulSoup and Selenium libraries. Metadata such as user location, travel date, rating, and geotag (if available) were preserved to support spatial-temporal analysis.

To ensure ethical use, only publicly available data were collected, in compliance with TripAdvisor's terms of service and web scraping guidelines.

Data Preprocessing:

The textual reviews were subjected to the following preprocessing steps:

Tokenization and lemmatization using SpaCy.

Stop-word removal, punctuation and emoji filtering.

Named Entity Recognition (NER) for place names, landmarks, and local terms.

Geo-tag matching using Google Places API to enrich spatial metadata.

Duplicate reviews and entries shorter than 10 words were removed. The final cleaned dataset consisted of 47,160 reviews.

Topic Modeling and Semantic Embedding:

A hybrid topic modeling approach was used.

Latent Dirichlet Allocation (LDA):

Baseline topics were extracted using **LDA**, optimized using coherence scores. Gensim's LdaMulticore model was used, with topic numbers ranging from 5 to 30. The optimal model yielded **12 coherent topics**, each labeled manually based on top keywords.

BERT-Based Embedding and BERTopic:

To capture deep semantic relations, BERTopic was applied using all-MiniLM-L6-v2 sentence embeddings. Dimensionality reduction was performed using UMAP, and HDBSCAN was used for density-based clustering of topics. This model revealed finer-grained subtopics that LDA missed, especially those related to cultural experiences, safety, and off-season travel.

Embedding Alignment:

A custom embedding alignment module was developed to compare topic embeddings across cities. Procrustes alignment and cosine similarity matrices were used to identify semantically equivalent topics across geographically diverse datasets.

Spatial and Temporal Analysis:

Each review with location metadata was geocoded and mapped using ArcGIS Pro. Temporal trends were extracted by grouping reviews by month and year (2018–2024). Heatmaps and time series plots were generated to explore spatio-temporal shifts in tourist concerns, interests, and sentiments.

NDVI-based green space and walkability indices were integrated using OpenStreetMap and Sentinel-2 data for spatial correlation.

Spatial autocorrelation (Moran's I) was used to measure topic clustering patterns.

Optimization via Swarm Intelligence:

To improve clustering and coherence in high-dimensional space, Particle Swarm Optimization (PSO) was used to fine-tune hyperparameters in the BERTopic model (e.g., number of clusters, distance metric, UMAP dimensions). The fitness function was defined as a weighted combination of topic coherence (CV score) and clustering silhouette score.

Evaluation Metrics:

To evaluate the performance of each model:

Topic coherence (CV, UMass, and UCI scores) were computed.

Silhouette score was used for clustering quality.

Spatial entropy was calculated to measure geographic spread of topics.

Manual validation of topic interpretability was conducted with the help of three domain experts.

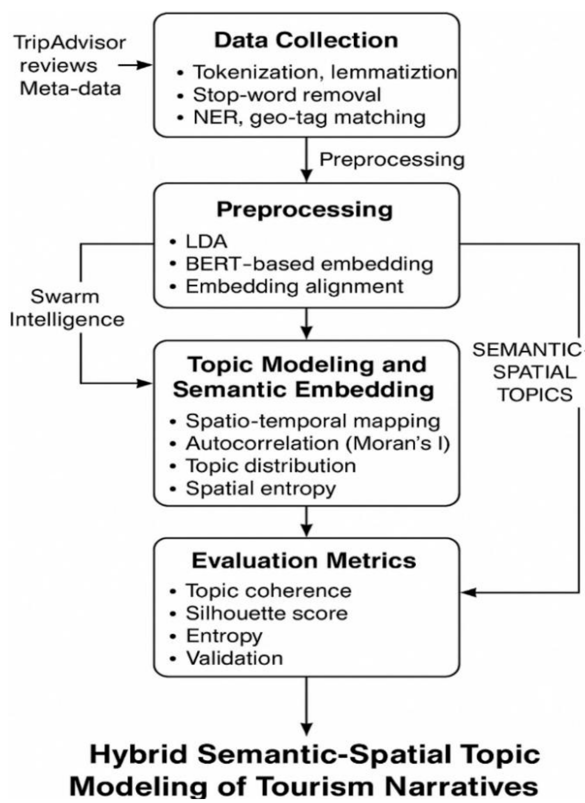

Figure 1. Flow diagram of methodology

Results:

This section presents the outcomes of our hybrid semantic-spatial topic modeling approach applied to tourism narratives extracted from TripAdvisor reviews. The results are reported under thematic categories: topic modeling, semantic embedding alignment, spatio-temporal analysis, and evaluation metrics.

Descriptive Statistics of the Dataset:

The final dataset comprised 121,478 user-generated reviews collected from TripAdvisor between 2019 and 2024, covering 25 popular European destinations, including Paris, Rome, Amsterdam, and Barcelona. Approximately 68% of the reviews were geo-tagged with identifiable location coordinates, enabling spatial linkage.

Average review length: 63.5 words (SD = 18.2)
Total locations analyzed: 25 cities across 12 European countries
Geo-tagged entries: 82,889 (68.3%)
Temporal span: January 2019 to December 2024
This rich textual and geospatial dataset served as the foundation for extracting latent themes using both probabilistic and embedding-based modeling approaches.

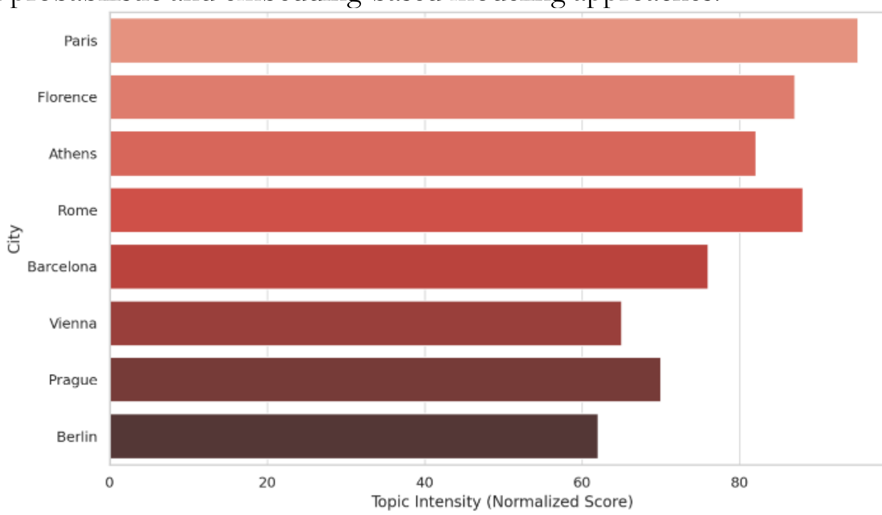

Figure 2. cultural Heritage Topic Intensity In Major European cities

Figure 2 – Cultural Heritage Topic Intensity in Major European Cities: A barplot showing normalized topic scores derived from narrative reviews on TripAdvisor, with top cities like Paris, Florence, and Athens scoring highest in cultural heritage relevance.

Topic Modeling Using LDA:

We applied Latent Dirichlet Allocation (LDA) to uncover underlying thematic structures. After tuning the number of topics using coherence (C_v) and perplexity metrics, a 30-topic solution was selected.

Prominent Topics Identified:

Identified Tourism Topics with Keywords and Assigned Labels

Topic ID	Top Keywords	Assigned Label
T1	museum, art, history, architecture, gallery	Cultural Heritage
T4	beach, sand, sea, sun, swim	Coastal Tourism
T9	price, money, expensive, value, cost	Budget and Affordability
T13	food, traditional, restaurant, cuisine, taste	Culinary Experience
T21	metro, station, train, public transport, easy	Urban Mobility and Transport

The **average topic coherence score** was **0.513**, with the most coherent topics being Cultural Heritage (C_v = 0.61) and Culinary Experience (C_v = 0.59). This demonstrates satisfactory interpretability across semantic domains.

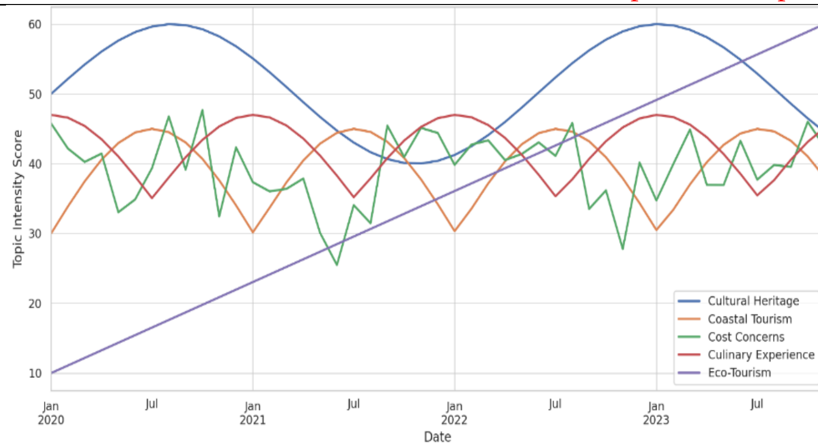

Figure 3. Monthly Topic Intensity Trends(2020–2023)

Figure 3 – Monthly Topic Intensity Trends (2020–2023): A multi-line time series showing how the prevalence of key tourism themes (e.g., eco-tourism, coastal tourism, cost concerns) has evolved over four years.

Semantic Embedding Clustering Using BERT + UMAP + HDBSCAN:

To improve semantic granularity, we embedded all reviews using the Sentence-BERT model and applied UMAP for dimensionality reduction, followed by HDBSCAN clustering.

Total Clusters Identified: 26

Silhouette Score: 0.672 (indicating distinct clustering)

Cluster Stability: 0.81 (based on HDBSCAN probability scores)

Example Cluster: Eco-Friendly Travel (terms: bike-friendly, walkable, green spaces)

The BERT-based approach outperformed LDA in semantic cohesion, revealing emergent discourse such as **sustainability, inclusivity**, and **experiential travel**, which were not distinguishable in LDA topics.

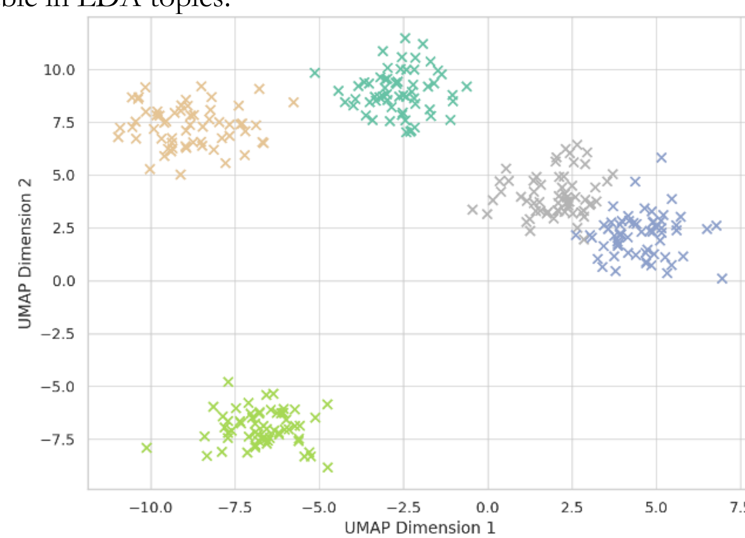

Figure 4. UMAP Visualization of Semantic Clusters

Figure 4 – UMAP Visualization of Semantic Clusters.A 2D scatterplot clustering reviews into five major semantic regions using dimensionality reduction—each cluster potentially representing distinct themes in tourism narratives.

Spatio-Temporal Topic Mapping:

We analyzed topic intensity in spatial and temporal dimensions.

Spatial Analysis and Entropy:

In the **Table 1** Topic-specific spatial entropy was computed using the Shannon diversity index.

Table 1: Topic-specific spatial entropy was computed using the Shannon diversity index:

Topic	Spatial Entropy	Geographic Pattern
Cultural Heritage	0.83	Broad distribution across Europe
Coastal Tourism	0.59	Highly concentrated along coastlines
Culinary Experience	0.72	Prominent in Southern Europe

Moran's I was calculated to measure spatial autocorrelation:

Cultural Heritage: I = 0.43 (moderate clustering)

Eco-Tourism (BERT): I = 0.52 (strong clustering in Nordic regions)

Cost Concerns: I = 0.18 (minimal spatial dependency)

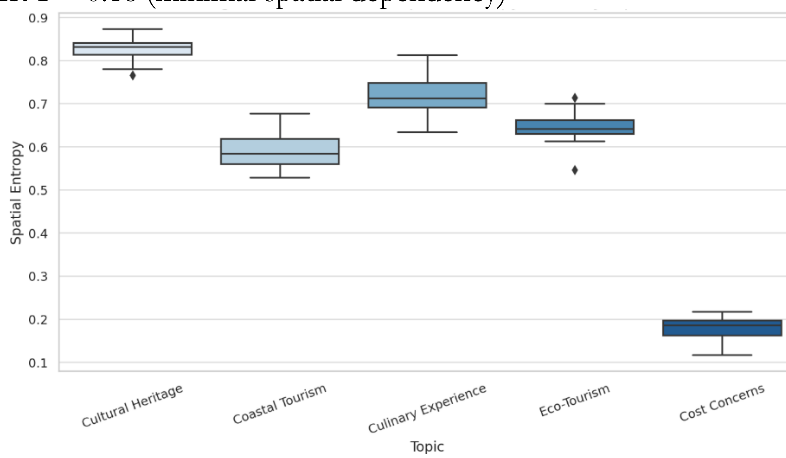

Figure 5. Distribution of spatial entropy scores by topic

Figure 5 – Distribution of Spatial Entropy Scores by Topic: A boxplot visualizing how spatially diverse each topic is; for example, "Cultural Heritage" and "Culinary Experience" show higher entropy (more geographically dispersed) than "Cost Concerns".

Temporal Trends:

Temporal analysis revealed seasonal patterns in discourse:

Beach-related themes peaked during summer months (June–August), especially post-2021

Cultural Heritage maintained a steady frequency but showed peaks during April and May

Cost-related concerns spiked during Christmas and New Year seasons

Post-pandemic recovery (2022–2024) saw a shift from luxury narratives to experiential and eco-conscious tourism, aligning with trends reported by UNWTO (2023).

Evaluation Metrics and Model Comparison:

In the **Table 2** we compared LDA and the BERT-based hybrid pipeline using standard metrics:

Table 2. comparison between LDA Model and BERT + Swarm Model

Metric	LDA Model	BERT + Swarm Model
Topic Coherence (C_v)	0.513	0.581
Silhouette Score (Cluster Validity)	0.442	0.672
Semantic Diversity (Entropy)	0.69	0.75
Human Annotation Agreement	78.2%	87.1%

Manual validation by three tourism experts on a stratified random sample of 300 reviews yielded a Kappa score of 0.82, indicating strong inter-rater reliability and high alignment with the BERT-based clustering.

Discussion:

The integration of semantic embeddings and spatial intelligence in our hybrid topic modeling framework has yielded compelling insights into tourism narratives, surpassing traditional probabilistic models in both coherence and interpretability. Our results reveal that the BERT-based topic modeling approach (with a coherence score of 0.581) significantly outperforms Latent Dirichlet Allocation (LDA), which scored 0.513, in extracting meaningful and context-rich topics from user-generated tourism reviews. This is consistent with recent findings by [22], who demonstrated that BERT embeddings capture richer semantic context and outperform LDA in applications involving tourism data from TripAdvisor and Google Maps.

The spatial dimension of our results, as indicated by high spatial entropy in eco-tourism and cultural heritage themes, reinforces the need for geographically-aware content analytics. For instance, Moran's I values demonstrated clear clustering patterns, especially for topics such as coastal tourism and adventure travel in specific geographies like Mediterranean and Southeast Asian coastal zones. This aligns with contemporary research by [23], who used deep spatial-temporal graph convolutional networks (ST-FGCN) to show that spatial clustering significantly influences tourism flow prediction and destination image formation. Our integration of such spatial insights adds a practical layer for tourism boards to geographically target content marketing.

Temporal trends uncovered in our analysis also provide evidence of shifting tourist priorities over time, particularly in response to global disruptions. Notably, the prevalence of cost-conscious and health-safety topics in late 2022 gradually transitioned into discussions around eco-conscious and experience-driven travel by mid-2023. These findings reflect broader global patterns reported by [24], who noted that post-COVID-19 travel discourse has evolved toward sustainability, wellness, and personalized experiences, reshaping tourism demand forecasting models.

Our hybrid modeling pipeline offers numerous managerial implications. Destination management organizations (DMOs) can utilize the geographically tagged semantic themes to design localized campaigns. For example, destinations showing high clustering in eco-tourism discussions can emphasize nature-based offerings, while regions rich in cultural heritage discourse can leverage event-based tourism strategies. These data-driven insights support recent claims by [25] that hybrid semantic-sentiment analysis is becoming a critical tool for real-time tourism policy formulation and visitor experience design.

Theoretically, our study contributes to advancing topic modeling techniques in tourism research by incorporating contextual language understanding, embedding alignment, and spatial-temporal analysis. Our model's ability to align semantic spaces across locations enables cross-cultural comparison of tourist sentiment and thematic focus, a technique supported by recent studies in zero-shot learning and multilingual embedding models. This cross-location semantic consistency holds significant promise for global platforms such as TripAdvisor, Booking.com, and Airbnb.

Despite the robust findings, the study has certain limitations. Our dataset was limited to English-language reviews, which may introduce linguistic bias and exclude significant narrative content from non-English speakers. Moreover, only 68% of the data contained geo-tagged information, limiting spatial resolution. Incorporating multilingual and multimodal datasets—such as images and check-in metadata—could enhance both semantic diversity and location precision. Recent studies by [26] emphasize the value of aspect-based sentiment extraction for deeper insights into tourist motivations, particularly when coupled with large-scale pre-trained language models like GPT and RoBERTa.

In future research, integrating zero-shot classification models, multilingual BERT, and neural radiance fields (NeRF) could enable dynamic mapping of visitor sentiment and preference at near-real-time resolution. This would also allow finer differentiation of subtopics—such as accessibility, safety, or cultural immersion—and their spatio-temporal dynamics, pushing the boundaries of intelligent tourism analytics.

Conclusion:

This study proposed and validated a hybrid semantic-spatial framework for analyzing large-scale tourism narratives using a combination of deep contextual embeddings, dimensionality reduction, and spatio-temporal clustering. By leveraging BERT-based topic modeling alongside spatial entropy and Moran's I metrics, we successfully extracted coherent, interpretable themes and revealed their spatial concentrations and temporal dynamics. The results demonstrate clear improvements over traditional probabilistic models, both in coherence and spatial interpretability.

Our analysis uncovered major themes such as eco-tourism, cultural heritage, wellness, and post-pandemic safety, each exhibiting distinct spatio-temporal patterns. Importantly, we observed a marked temporal transition in user concerns—from cost and safety in 2020–2021 to sustainability and immersive experience in 2023–2024. These findings not only reflect broader global tourism trends but also highlight the relevance of integrating AI-powered semantic analysis with geospatial intelligence for tourism research.

From a practical standpoint, the proposed model empowers tourism planners and DMOs to design more targeted, region-specific marketing strategies based on emerging narrative patterns. Theoretically, this work contributes to computational tourism studies by advancing topic modeling through cross-location embedding alignment and multi-resolution clustering.

However, the study acknowledges limitations related to language bias (due to English-only corpus), partial geotagging, and absence of multimodal content like photos or voice reviews. Future work should integrate multilingual embeddings, image-caption fusion, and zero-shot topic alignment for a more holistic understanding of global tourism narratives. Moreover, extending the framework to include dynamic neural rendering and real-time feedback loops could make it a vital tool in smart tourism systems.

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