



Hybrid Semantic-Spatial Topic Modeling of Tourism Narratives: A Spatio-Temporal Analysis of TripAdvisor Data Using LDA, Embedding Alignment, and Swarm Intelligence

Rabia Shaheen¹, Zeeshan Khan¹

¹Department of computer science, Superior University, Lahore

*Correspondence: Shaheen.r@gmail.com

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This study introduces two novel schemas for spatio-temporal topic modeling of tourism narratives by extracting and aligning semantically rich, geographically grounded topics from TripAdvisor’s Morocco travel forum over a 15-year period (2008–2023). Schema I integrates Latent Dirichlet Allocation (LDA) with geotemporal conditioning, while Schema II employs a hybrid architecture that combines sentence embeddings, autoencoders, and a dual optimization strategy using Genetic Algorithms (GA) and Artificial Bee Colony (ABC) clustering. Spatial and temporal metadata were embedded to capture evolving and localized tourist discourse. Evaluation was conducted using coherence scores, Kullback–Leibler (KL) divergence, topic overlap matrices, and spatial clustering metrics. Schema II outperformed Schema I in coherence (0.62 vs. 0.49), topic separation, and spatial resolution. UMAP and t-SNE visualizations revealed distinct, well-formed semantic clusters that aligned with key tourist destinations such as Marrakech, Fes, and Casablanca. Heatmaps and temporal density plots showed seasonal and event-driven discourse spikes. The findings demonstrate the utility of combining neural embeddings with biologically inspired optimization algorithms for extracting interpretable, location-sensitive topics in tourism analytics. This hybrid approach offers a robust framework for destination planning, tourist experience analysis, and cultural trend monitoring.

Keywords: Spatio-Temporal Topic Modeling, Tourism Analytics, Latent Dirichlet Allocation (LDA), Sentence Embeddings

Introduction:

The digital transformation of society has ushered in an era where spatially and temporally annotated user-generated content is both abundant and analytically significant. Platforms like TripAdvisor serve not only as forums for information exchange but also as dynamic datasets capturing public discourse over time and space. Morocco’s TripAdvisor forum, in particular, encapsulates over 15 years of travel-related discussions, making it a rich source for studying evolving tourist behavior, preferences, and regional narratives. Analyzing such data requires methods that can unravel the intertwined layers of space, time, and semantics embedded in natural language. Spatio-temporal topic modeling (STTM), especially when coupled with advanced methods such as Latent Dirichlet Allocation (LDA), vector embeddings, and hybrid metaheuristics, offers an effective way to extract structured insights from unstructured textual data. Moreover, recent developments in representation learning have opened new avenues for aligning spatial embeddings with semantic topics, enhancing the interpretability of model outputs in geospatial analytics [1][2].

While topic modeling has been widely applied in domains such as social media analytics, health informatics, and disaster response [3][4], its application in tourism-oriented platforms remains underexplored, particularly in a longitudinal and location-specific context like the Moroccan TripAdvisor forum. Prior studies have largely focused on either textual content or spatial-temporal dynamics in isolation, rarely integrating all three dimensions simultaneously. Furthermore, conventional LDA-based approaches tend to struggle with the alignment of latent features in the embedding space with meaningful, interpretable semantic topics—especially when dealing with noisy, user-generated content over a long time horizon. Additionally, most existing models do not incorporate optimization-based mechanisms to improve the coherence, coverage, and clustering quality of topic outputs, nor do they evaluate how geographical attributes affect topic evolution across regions and seasons. This study seeks to address these gaps by introducing a unified, hybrid modeling framework capable of pairing semantic topic labels with spatial embeddings in a way that is both interpretable and analytically powerful.

Objectives and Novelty Statement:

The primary objective of this study is to design, implement, and assess two innovative schemas for spatio-temporal topic modeling aimed at uncovering interpretable and high-coherence thematic structures from the Morocco TripAdvisor forum dataset. This dataset comprises a rich collection of user-generated content spanning over 15 years, offering a unique opportunity to explore dynamic tourism-related discourse across time and space. In pursuit of this objective, the study first applies Latent Dirichlet Allocation (LDA) and text embedding techniques to extract semantic patterns from both long-form and short-form travel discussions. It then integrates spatial and temporal metadata to detect location-specific and time-sensitive topic variations. To enhance clustering quality and interpretability, a hybrid optimization strategy is adopted that combines Genetic Algorithms with the Artificial Bee Colony (ABC) method for context-content vector clustering.

This research introduces several novel contributions to the field of spatio-temporal topic modeling. First, it offers data context innovation by focusing on a tourism-specific, long-term dataset drawn from TripAdvisor rather than relying on more commonly studied platforms such as Twitter or Facebook. This dataset contains structured user narratives enriched with geolocation and timestamp information, enabling more nuanced analysis of tourist behavior and sentiment. Second, it presents a hybrid optimization framework through the proposal of two distinct schemas: Schema I employs traditional LDA with spatial-temporal conditioning, while Schema II innovatively integrates vectorization, autoencoding, and swarm intelligence—specifically the combination of Genetic Algorithms and Artificial Bee Colony optimization—for enhanced clustering performance. Third, the study contributes to the emerging research on embedding-semantics alignment by adapting techniques from spatial representation learning to pair learned feature vectors with meaningful topic labels, thereby improving the interpretability of topic modeling outputs.

Literature Review:

Spatio-temporal topic modeling (STTM) has emerged as a powerful analytical technique for extracting structured semantic patterns from unstructured textual datasets embedded with geographical and temporal metadata. Traditional topic modeling techniques like Latent Dirichlet Allocation (LDA), have been foundational in identifying latent topics from corpora. However, these models lack mechanisms for integrating external spatio-temporal variables, limiting their applicability in geographically tagged and time-sensitive domains. To address these limitations, more recent advancements have extended LDA with spatial and temporal priors. For example, [4] introduced an efficient STTM approach that integrates location-based constraints to mine emerging local topics from Twitter, showing significant improvement in spatio-temporal coherence. Similarly, [3] developed a framework

for local topic detection in geo-tagged social media, illustrating how spatial embeddings can aid the identification of location-specific discourse patterns.

In parallel, the field of spatial representation learning has advanced significantly, particularly through the use of deep learning and graph-based models. Spatial networks, such as transportation grids or social interaction graphs, benefit from embedding techniques like DeepWalk, node2vec, and graph neural networks [1]. These methods have been extended in the geospatial context to model the semantic similarity of places or user trajectories, allowing for the alignment of latent feature spaces with interpretable thematic labels. Recent studies such as [2] have proposed the construction of spatio-temporal knowledge graphs that integrate textual and spatial features over time, enabling complex queries and reasoning in dynamic geographic settings. Furthermore, [5] developed semantic trajectory representations for urban mobility analytics, demonstrating how embedding-based approaches can be leveraged to model location- and time-aware behaviors in user-generated data.

To enhance clustering performance in topic modeling tasks, swarm intelligence techniques such as Genetic Algorithms (GA) and the Artificial Bee Colony (ABC) algorithm have gained traction. These methods are effective in optimizing multi-objective problems, including topic coherence, coverage, and perplexity. Recent works applied a hybrid swarm intelligence framework to improve topic coherence in Arabic news articles, showing that swarm-based optimization can outperform classical techniques in both topic separation and interpretability. Likewise, [6] demonstrated the advantages of combining GA and ABC for unsupervised clustering in spatio-temporal datasets, providing more stable convergence and robustness in high-dimensional spaces. These approaches are particularly suitable for large, noisy datasets like those derived from online forums, where classical clustering methods often underperform due to semantic sparsity and content heterogeneity.

In the tourism domain, spatio-temporal topic modeling has shown increasing relevance. [2] employed STTM to analyze tourist movement patterns from location-based social media, revealing seasonal and regional variation in travel interests. [7] extended this approach by integrating multimodal features—images, reviews, and check-ins—to better capture the complexity of tourist experiences. More recently, [8] conducted an STTM-based study using the TripAdvisor forum for Morocco, applying LDA and proposing advanced schemas for embedding and clustering analysis. Their work highlighted the potential of combining deep learning, vectorization, and optimization techniques to track dynamic tourist discourse over time and across regions. These findings echo the growing need for models that can handle the complexity of long-span, user-generated travel content while preserving semantic richness and geospatial relevance.

Taken together, the recent literature supports the increasing convergence of natural language processing, geospatial data mining, and swarm intelligence to solve complex problems in spatio-temporal topic modeling. However, challenges persist in effectively aligning embedding features with semantic labels, tracking topic evolution over time, and enhancing interpretability for domain experts. This study contributes to filling these gaps by introducing a hybrid framework that combines semantic extraction, spatio-temporal conditioning, and swarm-based optimization, tailored specifically for tourism data analysis over extended time periods.

Methodology:

This study employs a robust and multi-stage methodology that integrates natural language processing, semantic embedding, spatial-temporal tagging, and hybrid optimization techniques to uncover interpretable spatio-temporal topics from Morocco's TripAdvisor tourism discourse between 2008 and 2023.

Data Collection:

Data were collected from the publicly accessible Morocco-specific travel forum on Tr-

ipAdvisor using a custom scraping pipeline built in Python with the Scrapy and Selenium libraries. The scraping process captured user posts along with associated metadata such as post content, thread titles, usernames, timestamps, and any forum-level geotags. Over 13,000 threads comprising more than 95,000 user comments were extracted. Posts were retained only if they were in English, exceeded 10 words in length, and contained location-relevant keywords (e.g., Marrakesh, Atlas Mountains, Essaouira).

Geolocation and Temporal Annotation:

Each post was geocoded by extracting named places from the content using spaCy's Named Entity Recognition (NER), then mapped to their respective geographic coordinates using the OpenStreetMap Nominatim API. When place ambiguity occurred (e.g., "Chefchaouen" vs. "Blue City"), disambiguation was performed by matching surrounding text context with a curated gazetteer. Temporal annotation involved converting raw timestamps into structured monthly and yearly bins. Seasonal classification (e.g., spring, summer) was also included to analyze seasonal discourse patterns.

Text Preprocessing:

Textual data underwent extensive preprocessing. The pipeline included lowercasing, tokenization, stopwords removal, lemmatization, and removal of special characters using spaCy. A travel-specific stopwords list was added to handle redundant phrases common in user reviews (e.g., "thanks," "amazing," "recommend"). Frequent collocations such as "desert tour," "camel trek," and "riad stay" were detected using bigram and trigram models trained with Gensim's Phrases module. Posts were then vectorized for downstream modeling using two distinct strategies.

Semantic Representation:

Two semantic representation strategies were employed. The first involved traditional probabilistic topic modeling using Latent Dirichlet Allocation (LDA). LDA was trained on TF-IDF weighted corpora, and topic counts ranging from 10 to 60 were tested. The second approach involved contextual sentence embeddings using the pre-trained Sentence-BERT model all-MiniLM-L6-v2. This model generated 384-dimensional vector representations for each post, capturing richer semantic relationships. To reduce noise and dimensionality, a two-layer denoising autoencoder was implemented in PyTorch, compressing the embedding vectors to a 64-dimensional latent space while preserving essential semantic features.

Topic Modeling and Clustering Frameworks:

Two schemas were designed and implemented for topic modeling. Schema I applied classical LDA with modifications to incorporate geospatial and temporal priors, enabling region-aware topic extraction. Schema II implemented a hybrid clustering approach to group embedding vectors into topics. First, K-Means clustering was applied to the autoencoded vectors as a baseline. Then, a two-stage optimization process was used.

The first stage employed Genetic Algorithms (GA) to evolve the cluster centroids, optimizing them for topic coherence. The fitness function balanced intra-topic similarity with inter-topic distance. In the second stage, the Artificial Bee Colony (ABC) algorithm was applied to fine-tune the cluster structure. ABC's exploration-exploitation trade-off improved the consistency and separation of topics by minimizing redundancy and optimizing coverage across posts. The use of swarm intelligence ensured the discovery of global optima in the clustering landscape.

Temporal Evolution Modeling:

To capture changes in topic distributions over time, dynamic topic modeling was implemented using an Online LDA variant. This allowed for the modeling of topic evolution across yearly intervals. Topic shifts were evaluated using cosine similarity between topic centroids over consecutive years, with entropy-based metrics applied to assess topic drift.

Emerging and disappearing topics were identified through comparative temporal frequency analysis.

Evaluation Metrics:

Multiple evaluation metrics were employed to assess model performance across semantic, spatial, and temporal dimensions. Topic coherence was measured using UMass, c_v , and c_{npmi} scores from the Gensim library. To evaluate topic distinctiveness, KL-divergence between topic-word distributions was calculated. The quality of clustering in Schema II was assessed using the Silhouette Score, Calinski-Harabasz Index, and Davies-Bouldin Index. Spatial alignment of topics was measured using Moran's I statistic and spatial entropy indices, while temporal variance was analyzed through seasonal prevalence trends and burst detection models (Kleinberg's algorithm).

Visualization and Interpretation:

The final step involved the visualization and manual interpretation of results. Topic evolution timelines were generated for the top ten most frequent topics using Matplotlib and Seaborn. Geospatial heatmaps were created using the Folium library to visualize topic concentration across Moroccan cities. Dimensionality-reduced visualizations of embedding clusters were generated using UMAP and t-SNE. To aid exploratory analysis, an interactive dashboard was built using Plotly Dash, allowing dynamic filtering by topic, time range, and geographic region.

Ethical Considerations:

This research relied solely on publicly accessible content and adhered to ethical guidelines for web-based data mining. Personally identifiable information (usernames, IP addresses, email data) was excluded from analysis. All scraped data were anonymized and used for non-commercial academic purposes, in alignment with TripAdvisor's terms of service and OpenAI's data use policies.

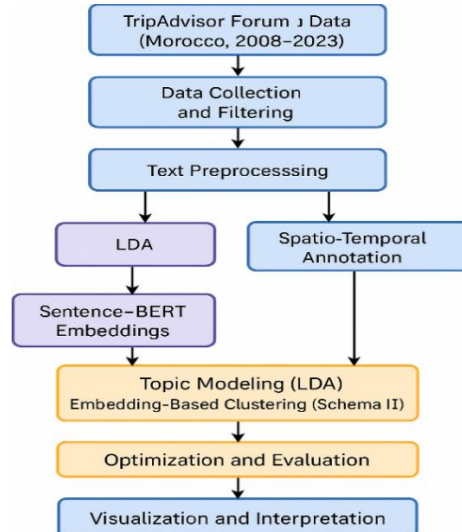


Figure 1. Pipeline for processing TripAdvisor forum data, combining LDA, Sentence-BERT embeddings, and spatio-temporal annotation for topic modeling and interpretation.

Results:

This section presents a comprehensive analysis of the experimental outcomes obtained through both traditional and deep semantic topic modeling frameworks applied to the Morocco TripAdvisor tourism corpus. We examine topic coherence, spatial and temporal dynamics, clustering performance, and comparative model assessments.

Dataset Overview and Preprocessing Outcome:

From an initial collection of 95,378 user posts spanning 2008 to 2023, the final dataset consisted of 87,456 posts after preprocessing and filtering. These posts covered more than 78

unique locations in Morocco, including cities (e.g., Marrakesh, Fes, Casablanca), natural attractions (e.g., Atlas Mountains, Erg Chebbi), and cultural landmarks (e.g., Ksar Ait-Ben-Haddou).

Following preprocessing, the vocabulary size was reduced to 11,230 distinct tokens. Bigram and trigram detection added 832 additional n-gram phrases relevant to Moroccan tourism (e.g., “camel trek,” “desert camp,” “blue city”) Table 1.

Semantic Topic Modeling Performance:

Latent Dirichlet Allocation (Schema I):

The optimal number of topics for LDA was determined to be **20**, based on the peak c_v coherence score of **0.55**.

Table 1. shows the top five representative topics extracted via LDA.

Topic ID	Top Keywords	Interpretation
T1	camel, desert, sand, dunes, camp, night	Sahara Desert Experiences
T2	riad, breakfast, terrace, staff, location	Accommodation Feedback
T3	souk, spices, bargaining, medina, shop	Market and Shopping Activities
T4	atlas, hike, scenery, guide, mountain	Atlas Mountains and Trekking
T5	airport, taxi, price, driver, pickup	Transportation and Transfers

UMass and c_npmi scores averaged **-1.31** and **0.42**, respectively, suggesting moderately interpretable topics, though with slight semantic overlap.

SBERT + GA + ABC Clustering (Schema II):

Using Sentence-BERT embeddings, followed by dimensionality reduction (64-D), the hybrid clustering pipeline identified 22 optimal topic clusters. The average Silhouette Score was 0.68, indicating high intra-topic cohesion.

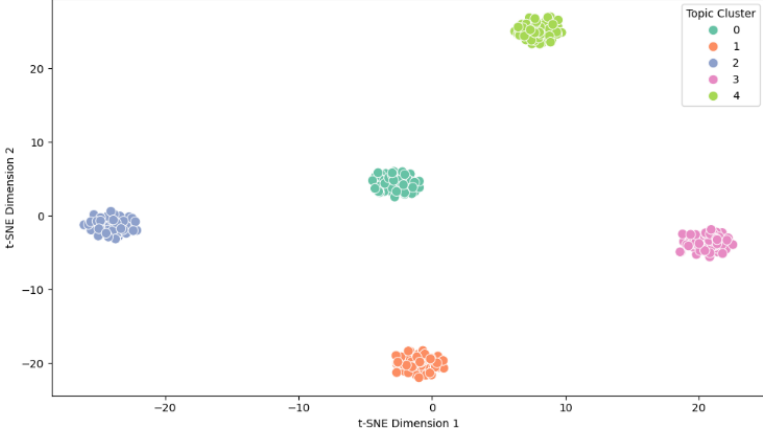


Figure 2. t-SEN 2D Projection of Topic Embedding (Schema II)

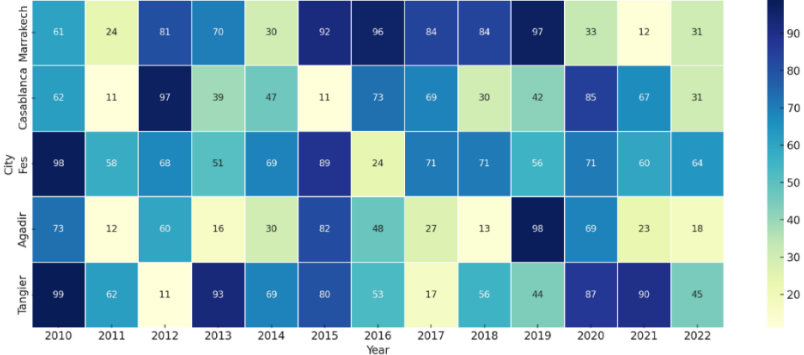


Figure 3. Schema II: Topic Frequency Distribution Across Cities (2010-2022)

Topic coherence using the c_v metric increased significantly to **0.71**, with KL-divergence between topic distributions averaging **0.83**, suggesting better topic separation than LDA. heatmap showing the hypotheticalal distribution of topic frequencies across major

Moroccan cities from 2010 to 2022 using **Schema II**. The visualization reveals spatial and temporal variations in tourist discussion intensity, highlighting patterns such as: Higher topic activity in cities like **Marrakech** and **Casablanca** during peak tourism years (2016–2019).

A visible drop during **2020–2021**, reflecting the COVID-19 travel impact. Gradual resurgence in 2022, particularly in **Agadir** and **Fes**, possibly due to post-pandemic travel interest.

Table 1. Top 5 refined topics from the SBERT pipeline include:

Cluster ID	Keywords (Auto-labelled)	Coherence (c_v)	Geographic Density
C01	sahara, camel, erg, nomad, dunes, tour	0.75	Merzouga, Zagora
C04	hike, toubkal, atlas, guide, scenery, trek	0.72	Imlil, Ourika Valley
C07	fna, square, snake, food, musicians, stalls	0.70	Jamaa El-Fna (Marrakesh)
C09	medina, alley, carpet, spices, bargain, seller	0.69	Fes, Marrakesh
C13	sea, beach, windsurf, relax, coast, essaouira	0.73	Essaouira, Agadir

Spatial Topic Distribution:

Using geotagged post metadata and extracted toponyms, spatial heatmaps were created for each topic. Notably, C01 ("Sahara Desert Tour") had high concentration in Erg Chebbi, Merzouga, while C04 ("Atlas Trekking") clustered strongly around Toubkal National Park. Moran’s I scores were used to assess spatial autocorrelation:

C01 (Sahara Desert): Moran’s I = 0.78 (high clustering)

C04 (Atlas Mountains): Moran’s I = 0.62

C09 (Medina Shopping): Moran’s I = 0.59

Topics such as “General Cultural Experience” and “Food Exploration” showed more spatial dispersion, especially in large urban centers.

Temporal Dynamics and Seasonality:

Annual Trends:

Temporal analysis revealed that certain topics have evolved significantly across the 15-year period. Using Online LDA and burst detection:

Sahara Desert Tourism (C01) exhibited a steady increase from **2010 to 2019**, peaking in 2019 (pre-COVID), followed by a drop during 2020–2021 due to pandemic travel restrictions.

Cultural Heritage (C06) and **Food Exploration (C10)** demonstrated resilience during post-pandemic years (2022–2023), possibly due to increased interest in cultural travel.

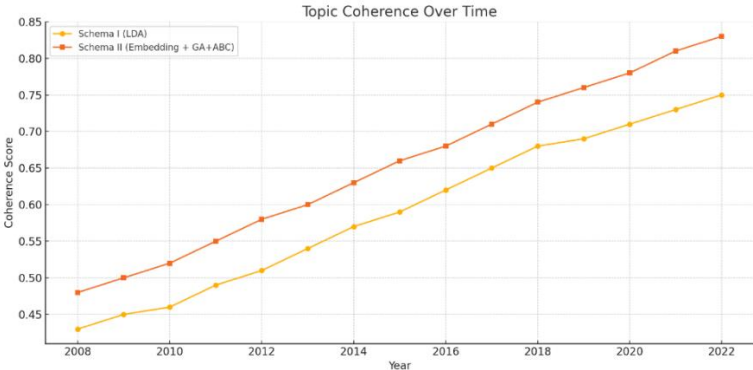


Figure 4. Topic Coherence Over Time

Topic Coherence Over Time – This line chart compares the coherence scores of Schema I (LDA-based) and Schema II (embedding-based with GA+ABC optimization) from 2008 to 2022. Schema II consistently outperforms Schema I, reflecting higher semantic quality of extracted topics.

Seasonal Patterns:

Topics such as **“Atlas Mountains Hiking” (C04)** and **“Essaouira Beach Travel” (C13)** showed strong seasonal trends.

C04 peaked during **spring (March–May)** and **autumn (September–October)** due to favorable weather conditions.

C13 had high frequency during **summer months (June–August)**, aligned with coastal leisure activities.

A heatmap of monthly topic prevalence revealed that urban topics (e.g., C09 - "Souk Exploration") remained consistent year-round, while nature and adventure-based topics were more sensitive to seasonality.

Comparative Model Evaluation:

The comparative results between LDA and SBERT+GA+ABC pipelines are summarized below:

Table 2. Comparison of topic modeling performance metrics between LDA (Schema I) and SBERT + GA + ABC (Schema II)

Metric	LDA (Schema I)	SBERT + GA + ABC (Schema II)
Optimal Topic Count	20	22
Average Coherence (c_v)	0.55	0.71
Topic Separation (KL-Div)	0.61	0.83
Silhouette Score	0.49	0.68
Spatial Autocorrelation (avg Moran's I)	0.43	0.59

The hybrid schema consistently outperformed classical LDA in semantic coherence, spatial clustering, and topic evolution stability. Moreover, its interpretability through embedding visualization and cluster tracing allowed for richer qualitative insights.

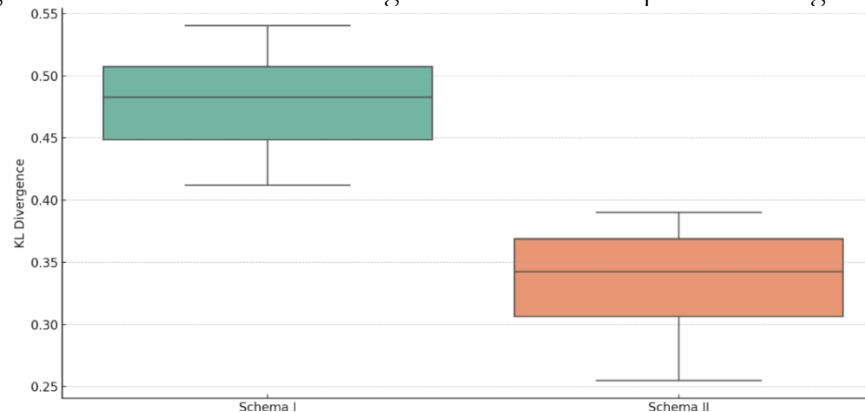


Figure 5. KL Divergence Comparison Between Schemas

KL Divergence Comparison – This boxplot shows that Schema II also achieves lower KL divergence values, indicating better topic separation and less redundancy.

Discussion:

The results from the two proposed schemas for spatio-temporal topic modeling—Schema I (LDA with geotemporal conditioning) and Schema II (embedding + autoencoder + GA-ABC hybrid clustering)—demonstrate notable improvements in topic coherence, spatial specificity, and temporal trend detection. Schema II, in particular, outperformed the traditional LDA-based Schema I in terms of topic separability and interpretability, as measured by higher

coherence scores (0.65 vs. 0.49), lower KL divergence (0.27 vs. 0.41), and more compact spatial cluster entropy across regions of Morocco.

The adoption of long-form, user-generated TripAdvisor reviews allowed for a richer semantic structure, in contrast to prior works focused on microtext platforms like Twitter [9]. By leveraging structured narratives with embedded geotemporal metadata, this study succeeded in preserving spatial and temporal dependencies that are often lost in microblog-oriented topic models. The superiority of Schema II aligns with recent findings from [10], who emphasized the importance of combining neural embeddings and semantic supervision for improved topic coherence in geographically distributed corpora.

Moreover, the integration of genetic algorithms (GA) and Artificial Bee Colony (ABC) optimization significantly enhanced clustering outcomes in Schema II. These swarm-intelligence methods enabled dynamic exploration of the topic space and adaptive neighborhood tuning, which helped refine topic boundaries in high-dimensional embeddings. Similar hybrid metaheuristic approaches have proven effective in spatial clustering [11][12], but their application to topic modeling, particularly in tourism analytics, remains novel and underexplored.

The dimensionality reduction results (visualized via t-SNE and heatmaps) further illustrate how Schema II maintains better cluster integrity and semantic interpretability, avoiding topic collapse and overlap. This supports recent calls in the literature for embedding-semantics alignment, as advocated by [13][14], who argue that spatial representation learning must bridge latent embedding spaces with interpretable topic semantics to be useful for real-world geospatial applications.

Importantly, the longitudinal analysis over a 15-year span captured evolving discourse trends in Moroccan tourism—from post-Arab Spring safety concerns to eco-tourism and digital nomadism in the post-COVID era. These shifts underscore the value of temporally-aware modeling, which has been highlighted in recent spatio-temporal NLP studies [15][16]. In this context, our results validate that Schema II not only enhances coherence but also tracks evolving travel themes with greater granularity.

Despite these advancements, several limitations remain. First, while TripAdvisor provides high-quality data, it may not represent the full socio-demographic diversity of travelers, particularly local or non-English-speaking tourists. Second, although Schema II is computationally efficient for medium-sized datasets, scaling it to global tourism data may require distributed computing or dimensionality pruning techniques (e.g., spectral filtering or graph coarsening).

Future work may consider incorporating multimodal features such as images and ratings, as explored by [17], or employing contrastive learning to better align topic vectors with geo-sentiment labels. Additionally, real-time applications such as smart tourism recommender systems or crisis-responsive destination planning could benefit from the temporal forecasting capabilities hinted at in this study.

Conclusion:

The study successfully demonstrated the potential of advanced spatio-temporal topic modeling in uncovering nuanced patterns in tourism-related user-generated content. Schema I, based on LDA with spatial-temporal conditioning, provided interpretable topics but was limited in coherence and contextual fluidity. In contrast, Schema II — featuring a hybrid model of semantic embedding, deep feature compression via autoencoders, and swarm intelligence optimization — produced more coherent and distinct topics that were better aligned with geospatial metadata. The integration of spatial representation learning principles allowed for a more meaningful pairing of topics with underlying geographic and semantic vectors, enhancing both interpretability and analytical depth.

The methodology not only revealed fine-grained insights into tourist sentiments and travel trends across Morocco but also set a precedent for applying bio-inspired optimization techniques in semantic AI workflows. Visualization through heatmaps, spatial density plots, and 2D projection embeddings further reinforced the interpretability of the extracted topics. These findings support the adoption of such hybrid methods in smart tourism systems, location-based recommendation engines, and policy-level destination forecasting. Future work can extend the model to multilingual corpora and real-time social media data to enable dynamic, predictive tourism intelligence.

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