

GeoDFNet: a point-of-interest classification algorithm with dual fusion of geospatial local neighborhood features

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ABSTRACT

Current Point of Interest (POI) classification models predominantly depend on textual data for feature modeling, often failing to resolve ambiguities in POI naming conventions. To overcome this limitation, we propose a Geospatial local neighborhood Dual Fusion Network (GeoDFNet), which synergizes multimodal features through a hierarchical fusion framework. By leveraging geographic similarity principles, GeoDFNet first constructs POI-centric local neighborhoods by encoding spatial relationships and aggregating surrounding geographic features *via* graph attention networks (GAT). In parallel, a Transformer encoder extracts latent semantic representations from textual metadata. The model employs a multi-head attention mechanism coupled with a dual-phase fusion strategy to dynamically calibrate the contributions of text and geospatial features. Experimental results on three real-world datasets (Shanghai POI, Beijing AutoNavi, and Guangdong OpenStreetMap) demonstrate that GeoDFNet achieves significantly higher classification accuracy compared to baseline models. Notably, on the Shanghai dataset, GeoDFNet attained an overall accuracy of 98.60%, substantially outperforming all textual baselines (*e.g.*, Text Convolutional Neural Networks (TextCNN): 91.13%, Text Recurrent Neural Networks (TextRNN): 83.54%, Transformer: 86.64%). These experimental results confirm that the proposed model achieves robust performance and effectively mitigates the ambiguity issue in POI names.

Subjects Algorithms and Analysis of Algorithms, Artificial Intelligence, Data Mining and Machine Learning, Spatial and Geographic Information Systems, Neural Networks

Keywords Point-of-interest classification, Deep learning, Graph neural networks, Transformer, Multimodal fusion

INTRODUCTION

With the rapid advancement of Internet technology and artificial intelligence, location-based services (LBS) have witnessed a significant proliferation of applications, encompassing path navigation and location recommendation systems (Zhao, Ma & Zhang, 2018; Zheng *et al.*, 2021; Yang & Dong, 2022). Point of interest (POI), defined as geographic entities of public interest that can be abstractly represented as point features,

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refers to facilities such as parks, community centers, and bookstores, among others (Psyllidis *et al.*, 2022). The availability of time-sensitive and high-precision POI data, particularly categorical information, serves as the foundational dataset for delivering high-quality LBS and constitutes a critical source for urban planning research. Examples include urban functional regions identification (Jing *et al.*, 2022; Yan *et al.*, 2023), trajectory prediction (Zeng *et al.*, 2022; Li *et al.*, 2024; Feng *et al.*, 2025), and user-centric location recommendation systems (Halder *et al.*, 2022; Liu *et al.*, 2023; Alatiyyah, 2025). However, the manual handling of massive POI data updates frequently results in missing attributes, including categorical information, due to the sheer data volume. Consequently, the development of automated, efficient, and real-time POI classification methods has become critical to ensuring data quality and maintaining the integrity of POI databases.

The name attribute serves as a critical semantic attribute and fundamental basis for POI automatic classification. Current research approaches largely concentrate on extracting and analyzing textual features from POI names, subsequently computing semantic similarity (Tan *et al.*, 2013, 2023) between POI names and predefined category labels (Luo *et al.*, 2012). With the advancement of machine learning techniques, advanced models including Word2Vec and bidirectional encoder representations from transformers (BERT) have been employed to generate vector representations of POI names. These representations are subsequently integrated into traditional machine learning classifiers (*e.g.*, support vector machines and random forests) or advanced deep learning architectures (*e.g.*, region-based convolutional neural networks (R-CNN), TextCNN, and enhanced sequential inference model (ESIM)) to enable automated POI classification (Li, 2022; Li *et al.*, 2022b; Luo, Yan & Luo, 2022; Li *et al.*, 2022a). Beyond relying solely on name attributes, recent studies have expanded the classification framework by incorporating heterogeneous data sources, including social media data (Wan & Wang, 2018), address information (Jiahao, 2020), large-scale internet data (Zhou *et al.*, 2020) and behavioral trajectory data (Liu *et al.*, 2024a). The integration of large language models (LLMs) has further improved classification performance by leveraging their robust reasoning and contextual comprehension capabilities (Liu *et al.*, 2024a). Additionally, POI tag features (Zhang *et al.*, 2024) have been utilized to augment semantic representations, thereby enhancing classification accuracy. Existing POI classification methods predominantly rely on textual information and achieve satisfactory performance for conventional POI names. However, text-based approaches are constrained by inherent semantic ambiguities in POI names. Existing POI classification methods predominantly rely on textual information and achieve satisfactory performance for conventional POI names. However, they exhibit significant limitations when handling ambiguous POI names due to the semantic vagueness inherent in text-based approaches. To quantify the prevalence of this issue, we conducted a manual validation on a random sample of 1,500 instances drawn from a large-scale dataset of over 200,000 entries. The results indicate that approximately 14.27% of POI names exhibit semantic ambiguities leading to misclassification. For instance, establishments such as “Centennial Dragon Robe”, “Akang Story”, and “Hi Meow” are frequently misclassified into shopping or life service categories,

despite their actual classification under catering services. Similarly, locations like “Eden”, “South Park”, “Bansong Garden”, and “Canal Bay” are often erroneously categorized as scenic spots rather than commercial-residential complexes. These frequent misclassifications underscore the substantive gap in current textual methods regarding contextual and semantic disambiguation.

In POI datasets, beyond explicit textual attributes (*e.g.*, names, addresses), geospatial relationships constitute critical implicit features within localized neighborhoods. The Third Law of Geography—empirically formalized as the more similar geographic configurations of two points (areas), the more similar the values (processes) of the target variable at these two points (areas) (*Zhu et al., 2018*)—manifests through observable patterns as evidenced by the common presence of snack bars and stationery stores in the vicinity of schools across diverse locations.

This principle establishes that topologically analogous environments engender congruent entity characteristics. Harnessing neighborhood relationships thus overcomes limitations of text-reliant methods by encoding contextual knowledge unobtainable from lexical features alone. The fusion of textual-semantic and geospatial features has been widely adopted in interdisciplinary research. For instance, researchers have leveraged NLP and spatial analysis techniques to extract and analyze disaster-related content from social media (*Sit, Koylu & Demir, 2019; Gulnerman & Karaman, 2020; Scheele, Yu & Huang, 2021*). Others have integrated text mining and spatial accessibility models to optimize travel route planning (*Zhou et al., 2024*) and elucidate the spatiotemporal dynamics of residents’ daily activities (*Liu et al., 2021*). Additionally, spatial-textual analytics have been applied to crime prediction (*Saraiva et al., 2022*), urban functional zone recognition (*Almatar et al., 2020; Zhang et al., 2021*), and POI recommendation systems (*Wang et al., 2023*).

However, within POI classification specifically, the synergistic fusion of textual semantics and geospatial context remains underexplored. While existing studies successfully integrate text and spatial data, they predominantly address broader scales (*e.g.*, urban zones, disaster areas) or divergent objectives (*e.g.*, route optimization, recommendation systems, event detection). Crucially, these approaches typically fail to explicitly leverage the fine-grained discriminative capacity inherent in a target POI’s immediate geospatial neighborhood for resolving textual ambiguities. Most methodologies either treat spatial context as coarse-grained statistical aggregations (*Zheng et al., 2014*) or employ it in isolation (*Qin et al., 2023*), rather than deeply embedding localized neighborhood semantics to directly interpret and disambiguate the target POI’s attributes within a unified modeling framework. Addressing this gap, in this study, spatial proximity is utilized to construct a semantically rich local geospatial neighborhood by aggregating spatially proximate clusters around target POIs. This neighborhood feature is then embedded into the classification framework to augment inference accuracy by providing contextual synergy. For example, during the classification of the establishment “Centennial Dragon Robe”, its local geospatial neighborhood exhibits high similarity to POIs in the catering service category, thereby providing crucial discriminative evidence—beyond what its ambiguous name alone offers—for its correct categorization as

a restaurant. This methodology underscores the efficacy of deeply integrating localized geospatial neighborhood context specifically for resolving POI classification ambiguities.

We propose an automatic POI classification method that integrates geospatial neighborhood embeddings and textual semantic features through a multimodal fusion framework. We introduce the Geo-neighborhood Dual Fusion Network (GeoDFNet), a hybrid model combining text classification, graph neural networks, and cross-modal fusion. The proposed framework follows a multistage computational pipeline: First, geospatial neighborhoods are derived through spatial proximity modeling, where neighborhood signals are propagated from spatially adjacent nodes *via* graph attention networks (GAT) (Velikovi et al., 2017). Second, hierarchical semantic extraction is performed on POI name texts using the Transformer encoder architecture (Vaswani et al., 2017). Finally, the model performs classification *via* a cross-modal fusion module that dynamically aligns geospatial and textual representations. To validate the methodology, experiments are conducted on large-scale POI datasets from Beijing, Guangdong, and Shanghai. Empirical evaluations demonstrate that GeoDFNet surpasses baseline models across accuracy, *F1*-score, and robustness metrics. The results highlight that geospatial neighborhood integration substantially enhances classification performance, offering a generalizable solution to mitigate semantic ambiguity in real-world POI applications.

To summarize, the contributions of our work are listed as follows:

- (1) Leveraging the Third Law of Geography, we establish a knowledge framework for spatial topological relationships among geographic entities, enabling the construction of geospatial local neighborhoods. These localized spatial representations are effectively incorporated into the model training process through graph-structured data and GNNs, achieving enhanced capture of local spatial patterns within POI datasets.
- (2) We propose GeoDFNet, a novel dual-fusion network for POI classification that integrates both feature-level and decision-level fusion, unlike conventional single-strategy approaches. The T-G Feature Fusion (T-GFF) module merges textual and geospatial features, while the Enhanced Geospatial Neighborhood (EGN) module incorporates spatial topology at the decision level. Ablation studies confirm the necessity of both modules: removing T-GFF or EGN significantly reduces *F1*-score (to 97.04% and 96.81%, respectively) and increases performance instability, compared to the full model (97.65% *F1*). This synergistic dual-fusion mechanism captures fine-grained feature interactions and high-level spatial context, yielding more accurate and robust predictions.
- (3) We conducted extensive validation using real-world geospatial datasets across multiple regions and heterogeneous data sources. The experimental results demonstrate both the effectiveness and robustness of our proposed model, with comprehensive testing in cross-regional scenarios confirming its superior performance in geographical information processing tasks.

RELATED WORK

The third law of geography

Geospatial similarity, manifested through the widely recognized Third Law of Geography ([Zhu et al., 2018](#)), establishes that ‘geographic entities in analogous spatial environments exhibit congruent characteristics’, with universality and generalizability empirically confirmed ([Zhu et al., 2020](#)). This implies consistent attribute manifestation among entities within homogeneous geospatial neighborhoods, regardless of location. We operationalize this principle through categorical neighborhood congruence: By quantifying adjacent POI similarity as a neighborhood proxy, cross-location analogy emerges when proximate entities show categorical alignment. This defines analogous neighborhoods implying intrinsic anchor POI similarity, transforming geographical principles into computable features for neighborhood topology integration in POI classification.

Graph neural networks

The inherent graph structure of geospatial data—where POIs constitute nodes and spatial relationships (e.g., proximity, adjacency) form edges—establishes graph neural networks (GNNs) as a natural paradigm for modeling POI dependencies. Foundational architectures including graph convolutional networks (GCN) ([Kipf & Welling, 2016](#)), GraphSAGE ([Hamilton, Ying & Leskovec, 2017](#)), and GAT enable direct operation on irregular spatial topologies, adaptively capturing neighborhood dependencies essential for resolving POI ambiguities (e.g., classifying stationery stores adjacent to schools vs. commercial zones, or distinguishing medical facilities proximate to pharmacies from retail clusters). This capability originates from core GNN principles: The message-passing mechanism models neighborhood influence dynamics wherein POI semantics are contextually refined by local environments, while permutation invariance guarantees robustness to irregular geospatial point patterns—fulfilling fundamental requirements for geographic knowledge discovery.

Multimodal fusion

Multimodal fusion entails joint modeling of complementary attributes across heterogeneous data streams. While current research predominantly integrates vision-language modalities (e.g., images, text) ([Zhou et al., 2023](#); [Xu et al., 2023](#)), this study pioneers geospatial-textual fusion to bridge neighborhood topology and POI name semantics. Inspired by cross-modal reinforcement paradigms—demonstrated in [Liu et al.’s \(2024b\)](#) fusion of remote sensing and trajectory data for road-aware POI identification—we develop a dual-stream framework: Geospatial embeddings encode Neighborhood attributes through spatial aggregation while textual embeddings capture lexical patterns. By dynamically harmonizing spatial neighborhood and textual semantics, the model capitalizes on their discriminative synergies, enabling spatial clusters to resolve textual ambiguities (e.g., ‘Dragon’ in restaurant vs. apparel contexts) and lexical cues to interpret spatial anomalies, significantly enhancing classification robustness across urban morphologies.

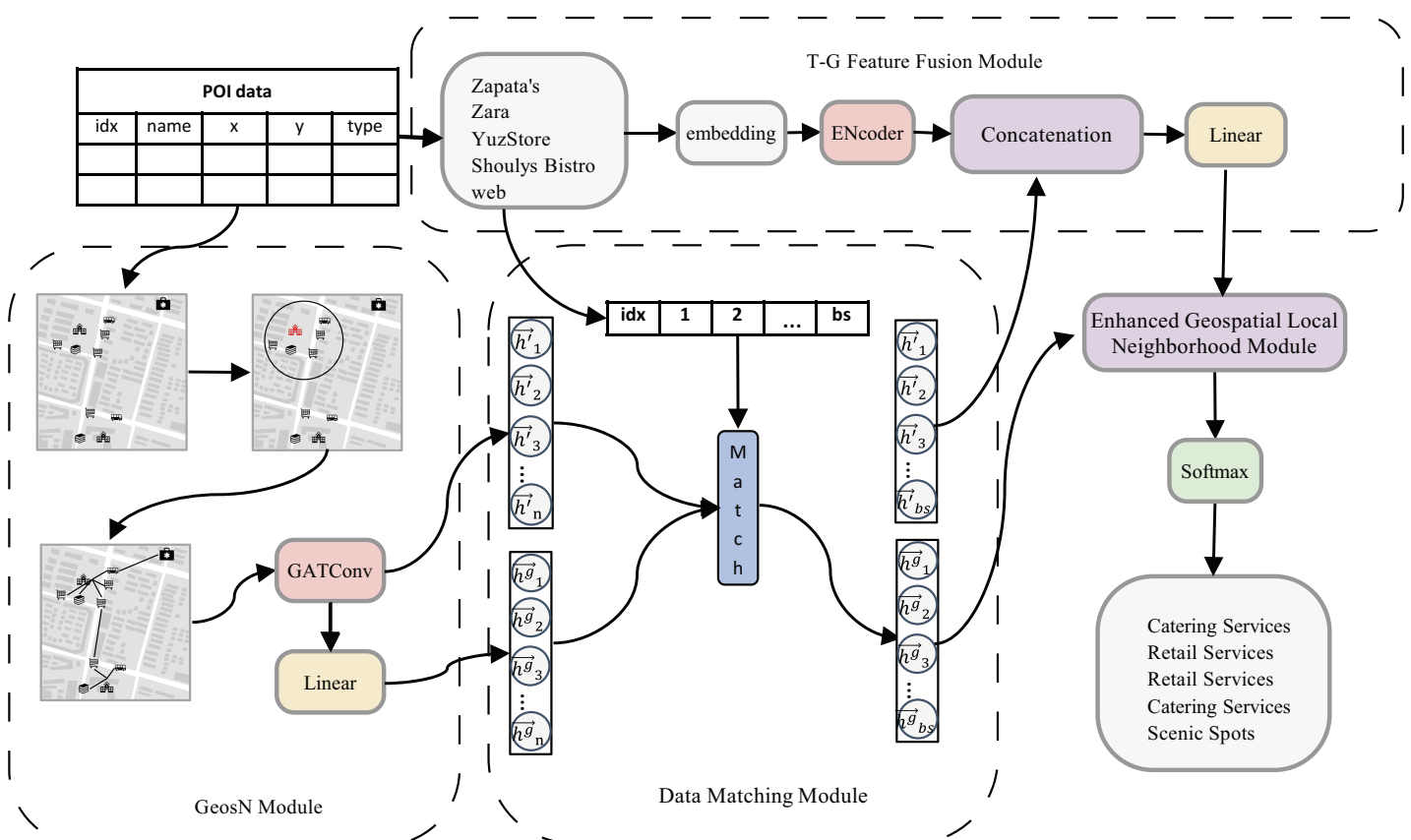


Figure 1 Overall framework diagram.

Full-size DOI: 10.7717/peerj-cs.3323/fig-1

METHODS

Overall architecture

The architecture of the proposed GeoDFNet model is illustrated in Fig. 1, which consists of four principal components: the Geospatial Neighborhood (GeosN) module, Data Matching module, Textual-Geographical Feature Fusion (T-G Feature Fusion) module, and Enhanced Geospatial Local Neighborhood module. This hierarchical design integrates geospatial neighborhood understanding with cross-modal feature interaction, followed by localized neighborhood refinement to enhance geographical representation learning.

GeosN module: This module harnesses the message propagation and neighborhood aggregation paradigm of graph neural networks. Specifically, it incorporates a first-layer of GAT with disabled self-loop connections to mitigate feature contamination from the target POI. By excluding the target node's ego features during aggregation, the module ensures that geospatial representations are exclusively neighbor by spatially adjacent nodes. A multi-head attention mechanism is employed to adaptively recalibrate attention weights across neighbors, thereby capturing the comprehensive local geospatial neighborhood features. Finally, a linear transformation layer projects these features into a latent space, producing refined local geospatial neighborhood embeddings for downstream classification.

Data Matching Module: The GeosN module generates embeddings for all nodes; however, computational constraints necessitate batch-wise processing of textual features during training iterations, as handling the full dataset exceeds hardware capacity. This batch partitioning creates a mismatch between the quantity of textual features and geospatial local neighborhood features within individual batches. To address this discrepancy, the Data Matching module selectively aligns the geospatial local neighborhood features of corresponding POI nodes with their textual counterparts in the current batch. Specifically, this module matches both the complete and compressed geospatial local neighborhood features of geographic entities present in the batch, ensuring cross-modal consistency. The implementation employs a dual-indexing mechanism and feature similarity thresholds to dynamically establish correspondences, thereby mitigating computational overhead while preserving critical spatial-textual relationships for downstream fusion processes.

T-G Feature Fusion module: This module synthesizes spatial-semantic representations by integrating textual semantic embeddings and geospatial neighborhood embeddings. The Transformer encoder processes textual information from POI names to generate semantic embeddings, while the Data Matching Module provides task-aligned geospatial neighborhood features. By orchestrating cross-modal fusion between these modalities, the module leverages their discriminative synergies to construct a joint latent representation. This fusion mechanism enables joint modeling of semantic and spatial dependencies, significantly improving classification accuracy through enriched neighborhood.

Enhanced Geospatial Local Neighborhood module: In the text-geospatial local neighborhood features generated by the T-G Feature Fusion module, the contribution of text features significantly outweighs that of geospatial local neighborhood features. To address this imbalance, the Geospatial Local Neighborhood Enhancement module utilizes the compressed geospatial local neighborhood features from the GeosN module, which are filtered and aligned by the Data Matching module. These external features are then integrated through a decision fusion approach, effectively enhancing the representation of geospatial neighborhood. This process ensures a more balanced and robust feature set, strengthening the model's ability to leverage spatial information for improved classification performance.

Finally, the fusion matrix, enriched with enhanced features, serves as the input to the Softmax layer. The subsequent section provides a detailed description of the model architecture and its components.

GeosN module

The geospatial local neighborhood module, based on graph neural networks, constructs a graph representation where real geographic entities serve as nodes, and the adjacency relationships between these entities form the edges of the graph. This module maps the geospatial neighborhood of the target POI into a high-dimensional vector space. By leveraging the message-passing and aggregation mechanism of graph neural networks, it effectively captures the geographic environment in accordance with the principle of geographical similarity. This process results in the formation of

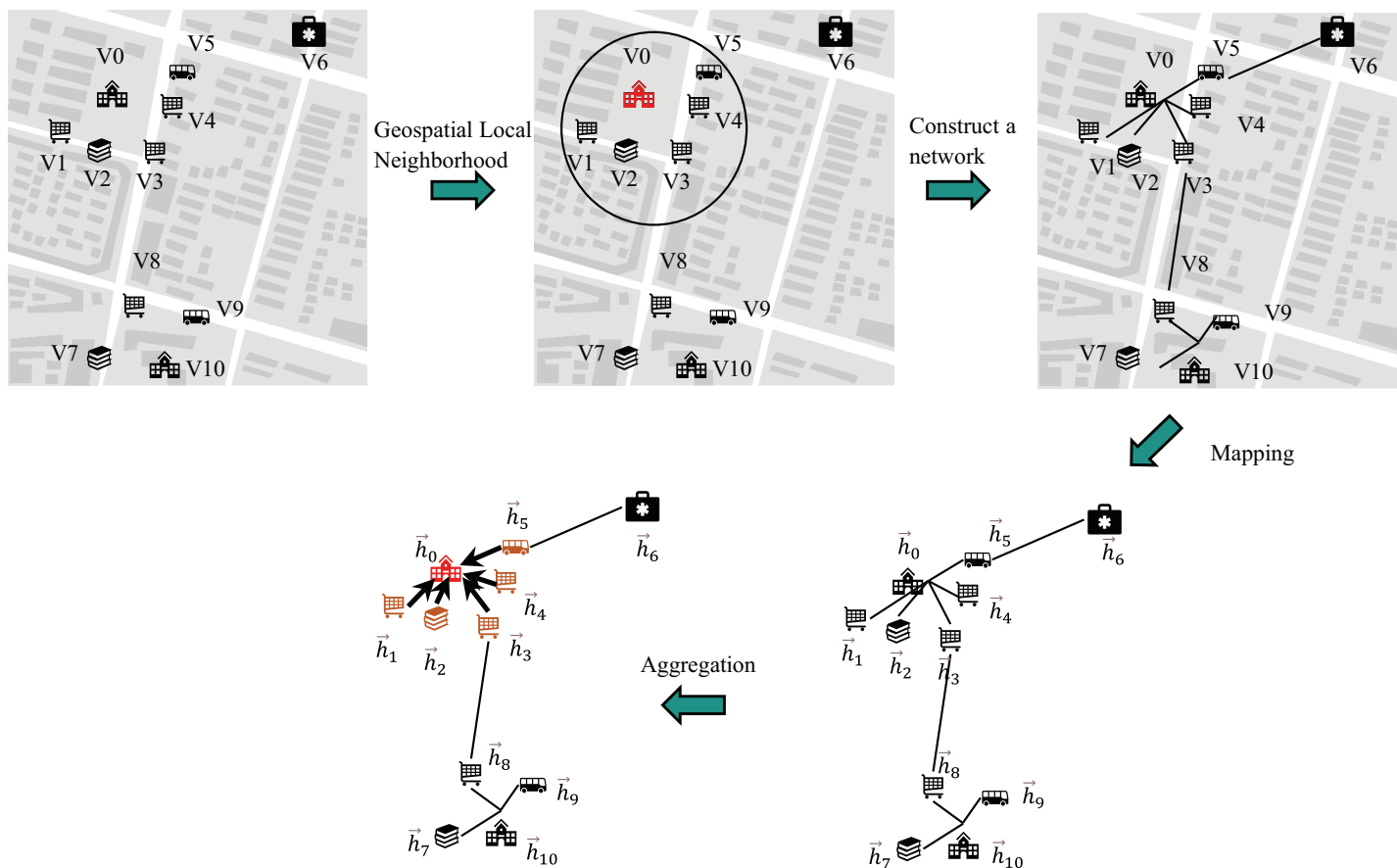


Figure 2 Messaging vs. aggregation.

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comprehensive local neighborhood features that encapsulate the spatial neighborhood of the target POI.

In this module, the GAT framework is employed to derive the geospatial local neighborhood feature vector representation. The aggregated features within its spatial domain are illustrated in Fig. 2.

In Fig. 2, the nodes V0, V1, V2, V3, V4 and V5 represent specific geographic entities, including a school, snack bars, a bookstore, and a bus station, respectively. Meanwhile, the nodes V6, V7, V8, V9 and V10 correspond to other geographic elements within the local spatial neighborhood.

The input to the GAT can be formally expressed as Eq. (1):

$$h = \{\vec{h}_1, \vec{h}_2, \dots, \vec{h}_n\}, \vec{h}_i \in \mathbb{R}^F. \quad (1)$$

In Eq. (1), n denotes the number of nodes in the graph, which corresponds to the number of POIs, while F represents the initial feature dimension of each node.

A multi-head graph attention layer implemented without self-loops (as visualized in Fig. 3) aggregates contextual features from each node's neighborhood. This process transforms the initial input features h into higher-order knowledge representations h' , designated as the complete geospatial local neighborhood features. This design

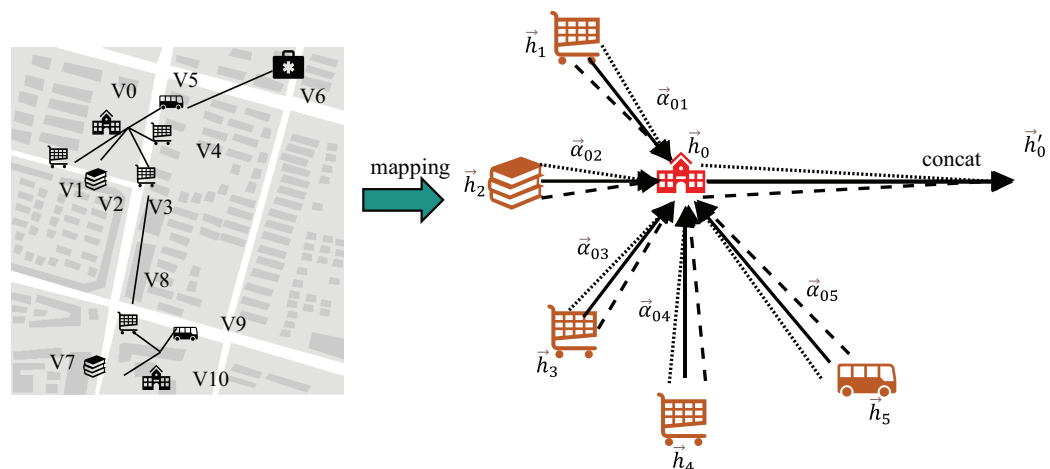


Figure 3 Multiple attention and no self-loop.

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intentionally omits self-loop operations, distinguishing it from conventional GAT implementations.

$$h' = \text{GAT}_{no_self}(h). \quad (2)$$

$$h' = \{\vec{h}'_1, \vec{h}'_2, \dots, \vec{h}'_n\}. \quad (3)$$

In Eqs. (2) and (3), GAT_{no_self} denotes the graph attention operation excluding self-loops, \vec{h}'_i represents the complete geospatial local neighborhood feature for node i .

Finally, the aggregated local neighborhood features of all geospatial regions are compressed to the same dimension as the number of classifications through linear layers, and the probability distribution h^g of geospatial local neighborhood features is obtained, that is, to compress the local neighborhood features of the geospatial space.

$$h^g = \text{linear}(h') = \{\vec{h}^g_1, \vec{h}^g_2, \dots, \vec{h}^g_n\}. \quad (4)$$

Data matching module

During the construction of textual and graph datasets for POIs, each POI entity is assigned a unique identifier to synchronize its textual descriptors and graph node representations. For a training batch with textual inputs $T = [T_1, T_2, \dots, T_{bs}]$, where bs denotes the batch size, the module first extracts the unique POI identifiers idx within the current batch. These identifiers are then cross-referenced with the node indices in the geospatial embeddings h' and h^g generated by the GeosN module. The aligned features are aggregated using a tensor stacking operation, yielding the batch-specific complete geospatial local neighborhood features G' and compressed counterparts G^g . These aligned features serve as inputs to the T-G Fusion module and Enhanced Geospatial Local Neighborhood module, enabling joint optimization of cross-modal interactions as defined in Eqs. (5)–(7).

$$idx = \text{Index}(T) \quad (5)$$

$$G' = \text{stack}(\text{Match}(idx, h')) = \{\vec{h}'_1, \vec{h}'_2, \dots, \vec{h}'_{bs}\} \quad (6)$$

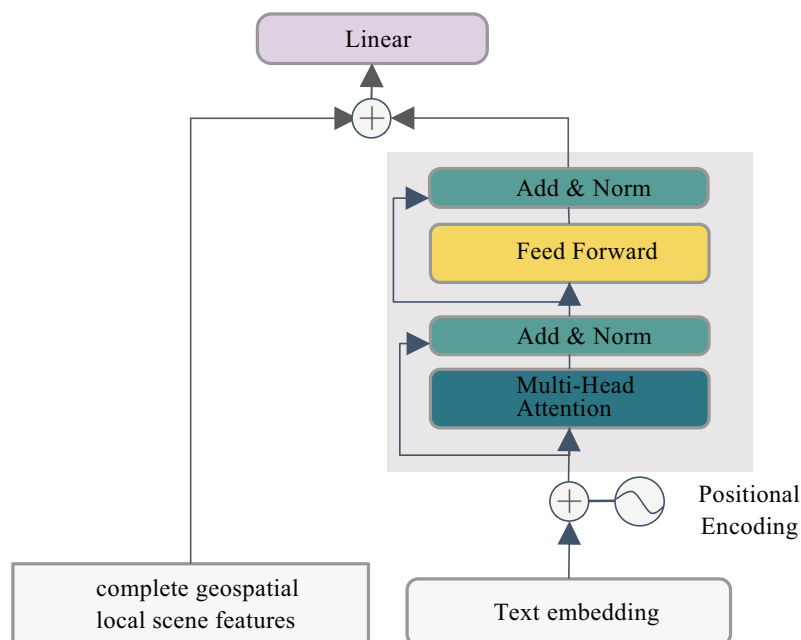


Figure 4 Synergistic text-geo integration.

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$$G^g = \text{stack}(\text{Match}(\text{idx}, h^g)) = \{\vec{h}_1^g, \vec{h}_2^g, \dots, \vec{h}_{bs}^g\}. \quad (7)$$

Here, the Index operation selects the identifier of the target sample T within the current mini-batch, while the T operation retrieves the corresponding encoded tensors from the heterogeneous feature spaces h' and h^g , ensuring cross-modal alignment.

T-G feature fusion module

In this research, the Transformer Encoder architecture is employed to process text embeddings and positional encoding through stacked self-attention layers and feedforward neural networks. A multi-head attention mechanism is utilized to integrate the extracted feature vectors for text classification tasks. However, this approach fails to account for spatial dependencies in POI classification, resulting in incomplete feature representation. To mitigate this limitation, we propose a hybrid framework that synergistically combines textual features with local geospatial neighborhood features. This integration significantly enhances the semantic characterization of POIs, with the detailed architectural design illustrated in Fig. 4.

For the T-G Feature Fusion module, the textual input batch processed in each training iteration is mathematically formulated as:

$$\begin{aligned} T &= [T_1, T_2, \dots, T_{bs}] \\ &= [[t_{11}, t_{12}, \dots, t_{1c}], \dots, [t_{bs1}, t_{bs2}, \dots, t_{bsc}]] \\ &= [X_1, X_2, \dots, X_{bs}] \\ &= [[e_{11}, e_{12}, \dots, e_{1c}], \dots, [e_{bs1}, e_{bs2}, \dots, e_{bsc}]]. \end{aligned} \quad (8)$$

The local neighborhood features, aggregated through graph convolutional operations to encapsulate integrated geospatial neighborhood information, are mathematically formulated as:

$$G' = \{\vec{h}'_1, \vec{h}'_2, \dots, \vec{h}'_{bs}\}. \quad (9)$$

The resultant fused feature embeddings, generated through the Transformer Encoder's multi-head attention mechanisms and subsequent multi-modal feature fusion layers, are formally expressed as:

$$T^{tg} = [X_1^{tg}, X_2^{tg}, \dots, X_{bs}^{tg}]. \quad (10)$$

For a textual sample $T_i = [t_{i1}, t_{i2}, \dots, t_{ic}]$ with sequence length c , each token t_{ij} is encoded into a vector $e_{ij} \in \mathbb{R}^d$ via word embedding and positional encoding, forming the tokenized matrix $X_i = [e_{i1}, e_{i2}, \dots, e_{ic}] \in \mathbb{R}^{c \times d}$. Generate X_i^t by passing X_i through the Transformer Encoder.

$$X_i^t = \text{Encoder}(X_i). \quad (11)$$

Cross-modal feature fusion:

$$X_i^{tg} = \text{linear}\left(\text{Concat}\left(X_i^t, \vec{h}'_i\right)\right). \quad (12)$$

Here, \vec{h}'_i denotes the geospatial local neighborhood feature of the i -th POI. By concatenating the POI name text feature X_i^t with its corresponding geospatial local neighborhood feature \vec{h}'_i along the feature dimension, all modalities are projected into a shared latent space to ensure cross-modal compatibility and meaningful interaction, while preserving modality-specific characteristics and preventing critical unimodal information loss. A linear layer then compresses the concatenated features to match the dimensionality of the classification task, generating the fused text- neighborhood joint representation X_i^{tg} .

Enhanced geospatial local neighborhood module

To reinforce the geospatial local neighborhood, the outputs of the T-G Fusion module (X_i^{tg}) and the GeosN module (\vec{h}^g_i) are integrated via a decision fusion strategy. The fused features are then fed into a Softmax layer for final classification.

For a batch of size bs , the textual-geospatial features are aggregated:

$$T^{tg} = [X_1^{tg}, X_2^{tg}, \dots, X_{bs}^{tg}]. \quad (13)$$

And the complete geospatial local neighborhood features are represented:

$$G^g = \{\vec{h}^g_1, \vec{h}^g_2, \dots, \vec{h}^g_{bs}\}. \quad (14)$$

The element-wise summation in the decision fusion strategy is adopted to fuse multimodal features, generating the input f for the classification layer. This approach preserves the raw modality-specific information, T^{tg} and G^g , while enabling effective cross-modal relational learning. The linear combination ensures compatibility between heterogeneous

Table 1 GeosN module hyperparameters.

Parameter	Parameter size
GAT network layer	in_channels=300, out_channels=16, heads=4, add_self_loops=False
Linear layer	in_channels=64, out_channels=14
Activate the function	relu

Table 2 T-G feature fusion module hyperparameters.

Parameter	Parameter size
Transformer network layer	QKV_size=32, heads=4, Number of layers =2, pad_size=32, dim_model=300, hidden=512, last_hidden=256
Linear layer	in_channels=9664, out_channels=14
Activate the function	relu

representations and retains critical unimodal characteristics, thereby enhancing the discriminative power of the fused feature f .

$$f = T^{tg} + G^g. \quad (15)$$

Here, the summation is performed element-wise to amplify geospatial neighborhood salience. The fused feature f is normalized *via* a Softmax layer to generate the final POI classification probabilities:

$$P(y|f) = \text{Softmax}(W_c f + b_c) \quad (16)$$

where W_c and b_c are the classification head's weight matrix and bias term, respectively.

Experiment

Experimental setup

All experiments were conducted on a Windows 10 workstation equipped with an Intel Core i7-9750H CPU, 16 GB DDR4 RAM, and an NVIDIA GeForce RTX 2080 GPU (8 GB GDDR6 VRAM). The implementation utilizes Python 3.9.19 with PyTorch 2.2.2 (CUDA 12.1 acceleration) for deep learning operations.

Experimental parameters are categorized into two groups: primary model hyperparameters and model training parameters. The primary hyperparameter configurations are detailed in [Tables 1](#) and [2](#), while the training parameters are specified in [Table 3](#). To ensure reliability, each experiment was repeated 10 times using different random seeds. The mean and standard deviation of the results from these repeated experiments are reported.

Dataset

To comprehensively validate the feasibility and superiority of the proposed method, we constructed three heterogeneous POI datasets derived from distinct data sources and geographical regions:

Shanghai POI dataset: The dataset is derived from the Shanghai subset of the POI data for key Chinese cities, available on the Geographic Data Sharing Infrastructure, global resources

Table 3 Training parameters.

Parameter	Parameter size
Training rounds	5
Batch size	2,048
Optimizer	Adam
Learning rate	0.001

Table 4 Details of the Shanghai POI dataset.

Category	Number	Category	Number
Catering services	26,749	Science, education and cultural services	18,349
Scenic spots	1,512	Business residences	18,889
Public utilities	2,113	Daily life services	15,530
Corporate entities	61,050	Sports and leisure services	10,145
Retail services	2,313	Healthcare services	7,405
Transportation facilities	25,623	Government Institutions and social organizations	13,616
Financial and insurance services	8,774	Accommodation services	5,954

data cloud (<http://www.gis5g.com/>). It encompasses selected administrative districts under Shanghai's jurisdiction, covering a total of 14 distinct categories. The dataset comprises 218,022 POIs, with detailed category distributions provided in Table 4.

AutoNavi Beijing POI dataset: The dataset originates from the Peking University Open Research Data Platform (opendata.pku.edu.cn), specifically comprising POI data for Beijing. It includes a total of 22 categories and 12,397 POIs, providing a comprehensive representation of geographic entities within the region.

OSM Guangdong POI dataset: The dataset is sourced from the OpenStreetMap website (www.openstreetmap.org), specifically focusing on Guangdong Province. After data selection and filtering, it comprises 93 categories and 29,265 POIs, offering a diverse and extensive representation of geographic entities within the region.

For the three datasets, the POI latitude and longitude information, category information, and name information are utilized for data processing.

Graph dataset construction: we uniformly use the WGS 84 (EPSG:4326) geographic coordinate system. Using the latitude and longitude information, each node is connected to its five nearest neighbors ($k = 5$) to form the graph dataset. In this representation, nodes correspond to POI points, node features represent POI categories, and edges denote the adjacency relationships between POIs.

Text dataset construction: POI names constitute the textual classification dataset, with each entry assigned a category label. Unique identifiers maintain cross-modal consistency between graph data and text records. Text preprocessing involves character-level tokenization that preserves original casing and punctuation, followed by vocabulary control limiting tokens to 10,000 maximum frequencies (infrequent characters mapped to <UNK>). Sequences are normalized to fixed lengths through <PAD> padding and truncation, with randomly initialized embeddings fine-tuned during training. This

Table 5 Dataset information.

	Shanghai POI dataset	AutoNavi Beijing POI dataset	OSM Guangdong POI dataset
Dataset volume	218,022	12,397	29,265
Graph node population	218,022	12,397	29,265
Graph edge population	1,090,110	61,985	146,325
Textual <i>Corpus</i> count	218,022	12,397	29,265
Dataset volume	218,022	12,397	29,265
Training set			
Original partition size	109,011	6,198	14,632
Enhanced size	98,129	5,948	7,007
Training set partition size	65,406	3,719	8,780
Validation set partition size	43,605	2,480	5,853

pipeline ensures identifier alignment while transforming raw names into standardized character sequences for joint text-graph modeling.

Dataset splitting: A shared mask partitions both graph and text datasets into training (50%), validation (30%), and test (20%) sets. To address class imbalance, we implement dynamic resampling *via* quartile analysis: class stratification is performed using Q1, median, and Q3 distribution thresholds; minority classes below Q1 are oversampled to match the median size, while majority classes exceeding Q3 are undersampled to the Q3 level. Comprehensive dataset statistics are detailed in [Table 5](#).

Evaluation metrics

To assess model performance, we employ four standard metrics: precision (P), accuracy, recall (R), and the F1-score, defined as follows:

$$P = \frac{TP}{TP + FP} \times 100\% \quad (17)$$

$$accuracy = \frac{TP + TN}{TP + FN + FP + TN} \quad (18)$$

$$R = \frac{TP}{TP + FN} \times 100\% \quad (19)$$

$$F1 = \frac{2 \times P \times R}{P + R} \quad (20)$$

where TP (True Positives) denotes correctly predicted positive samples, FN (False Negatives) positive samples misclassified as negative, FP (False Positives) negative samples misclassified as positive, and TN (True Negatives) correctly predicted negative samples.

The proposed GeoDFNet model employs a weighted cross-entropy loss function during training, utilizing class-specific weights to mitigate class imbalance effects. This loss function measures the discrepancy between predicted class probabilities and ground-truth labels, with heightened penalties for misclassifying rare classes. The mathematical formulation of this weighted loss is given in [Eq. \(21\)](#):

$$LOSS = - \sum_{c=1}^C w_c y_c \log(\hat{y}_c) \quad (21)$$

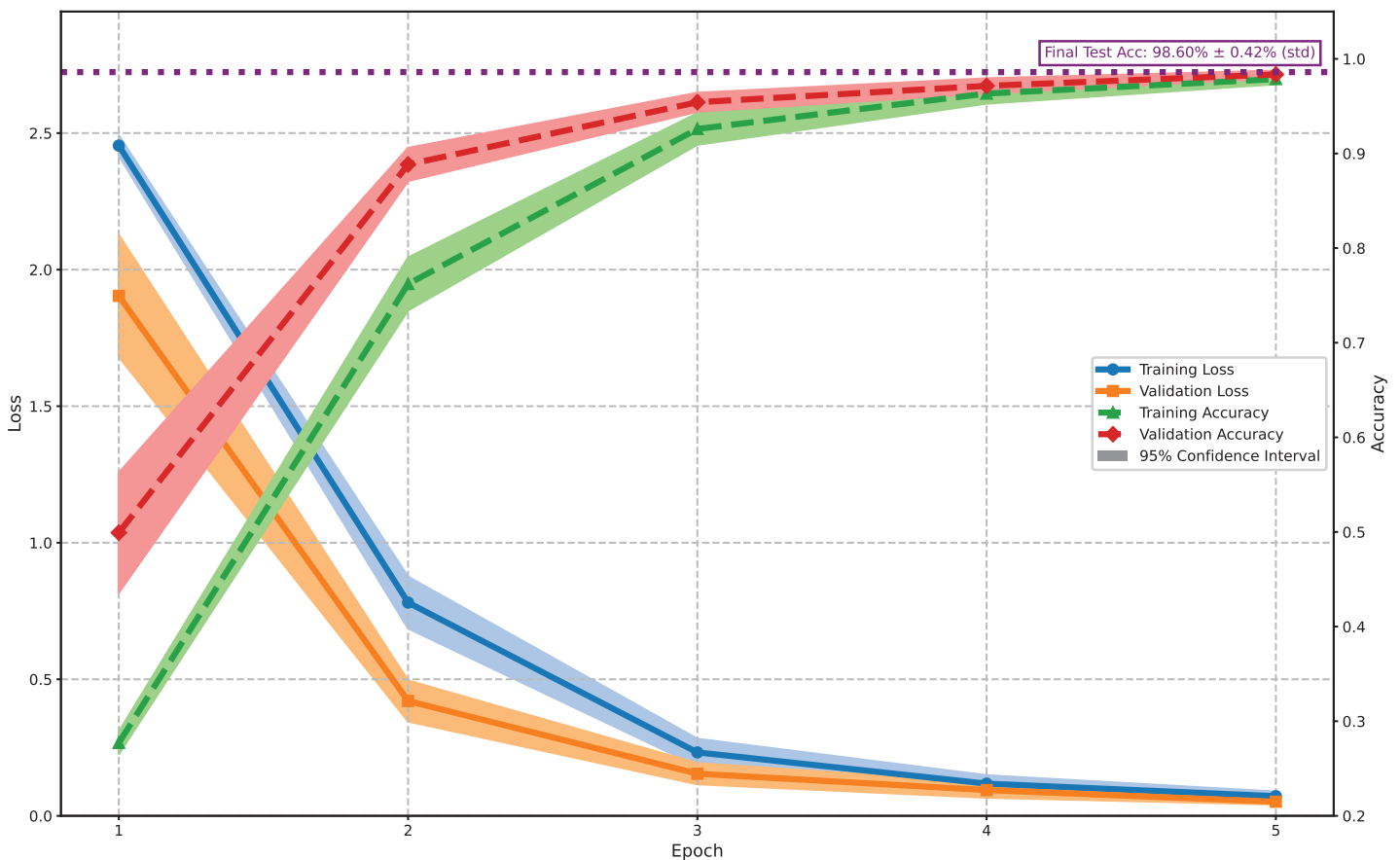


Figure 5 Model training and validation performance (mean of 10 runs \pm 95% CI).

Full-size DOI: 10.7717/peerj-cs.3323/fig-5

where C denotes the number of classes, y_c represents the ground-truth indicator for class c , and \hat{y}_c is the predicted probability for class c .

RESULT

Figure 5 illustrates the training and validation performance of the proposed model on the Shanghai POI dataset. Solid lines represent mean values from 10 independent runs, with shaded areas indicating 95% confidence intervals. Notably, training loss exceeds validation loss and training accuracy remains lower than validation accuracy throughout the process—a phenomenon attributed to the data-level resampling and algorithm-level weighting strategies employed to enhance generalization. These techniques deliberately increase training difficulty, leading to more robust feature learning. The narrow confidence intervals (e.g., validation accuracy: 98.31% [97.98%, 98.64%]; test accuracy: 98.60% [98.32%, 98.88%]) indicate stable and consistent learning across runs. The model achieves a final validation accuracy of 98.31% and test accuracy of 98.60%, demonstrating its effectiveness and robustness for Shanghai POI classification.

Experimental results demonstrate that the model achieved an overall classification accuracy of $98.60 \pm 0.45\%$ in POI categorization using multimodal data. Strong performance was observed across most categories, with macro-average precision, recall,

Table 6 Accuracy, recall, F1 value, test set samples.

Category	P (%)	R (%)	F1 (%)	Sample of the test set
Catering services	99.50 ± 0.39	99.34 ± 0.71	99.42 ± 0.53	5,200
Scenic spots	88.42 ± 14.37	95.03 ± 4.46	91.10 ± 9.08	310
Public utilities	94.58 ± 3.22	99.25 ± 0.36	96.83 ± 1.61	441
Corporate entities	99.63 ± 0.34	98.28 ± 1.50	98.94 ± 0.80	12,244
Retail services	97.59 ± 2.56	97.04 ± 2.32	97.30 ± 2.06	449
Transportation facilities	99.54 ± 0.24	99.71 ± 0.10	99.63 ± 0.13	5,135
Financial and insurance services	97.86 ± 1.39	98.89 ± 0.46	98.37 ± 0.86	1,798
Science, education and cultural services	98.24 ± 1.57	98.23 ± 1.45	98.23 ± 1.19	3,763
Business residences	99.43 ± 0.55	97.61 ± 1.34	98.51 ± 0.93	3,786
Daily life services	98.88 ± 1.02	99.03 ± 0.83	98.95 ± 0.80	3,086
Sports and leisure services	94.31 ± 6.80	97.33 ± 2.11	95.67 ± 3.73	2,108
Healthcare services	97.88 ± 2.68	98.44 ± 1.13	98.15 ± 1.83	1,471
Government institutions and social organizations	98.03 ± 1.51	99.47 ± 0.33	98.74 ± 0.82	2,604
Accommodation services	96.01 ± 2.25	98.52 ± 1.19	97.23 ± 1.21	1,210
Accuracy			98.60 ± 0.45	43,605
Macro-average	97.14 ± 1.10	98.30 ± 0.66	97.65 ± 0.85	43,605

and F1-scores of $97.14 \pm 1.10\%$, $98.30 \pm 0.66\%$, and $97.65 \pm 0.85\%$ respectively. As detailed in Table 6, the model excels in common POI types (e.g., Transportation Facilities: $99.63 \pm 0.13\%$ F1; Corporate Entities: $98.94 \pm 0.80\%$ F1), but exhibits higher variability in rare categories such as Scenic Spots ($91.10 \pm 9.08\%$ F1). These results validate the model's ability to leverage cross-modal features while highlighting opportunities to improve robustness for underrepresented classes.

Comparative experiments

We compare our GeoDFNet with the following baselines:

TextCNN (Kim, 2014): This model leverages a convolutional neural network (CNN) architecture, employing multiple convolutional layers with varying kernel sizes to capture key information at different granularities within the text. By extracting local features of varying lengths, TextCNN effectively encodes textual semantics for downstream tasks.

TextRNN (Liu, Qiu & Huang, 2016): This model is built on a recurrent neural network (RNN) architecture, which captures sequential information in text by incorporating recurrent connections. These connections enable the network to retain and process contextual information across sequences, making it effective for modeling dependencies in textual data.

TextDPCNN (Johnson & Zhang, 2017): This model is based on convolutional neural networks (CNNs) and enhances the extraction of long-range dependencies in text through the use of downsampling, isometric convolutions, and network deepening. These techniques enable the model to effectively capture both local and global textual patterns, improving its ability to process and understand complex textual structures.

TextRCNN ([Lai et al., 2015](#)): This model combines a recurrent convolutional neural network architecture with bidirectional RNNs and pooling layers to effectively capture contextual information and represent textual semantics with greater accuracy. By integrating recurrent and convolutional mechanisms, TextRCNN leverages both sequential and local features, enhancing its ability to model complex textual relationships.

TextRNN_ATTENTION ([Zhou et al., 2016](#)): This model employs a bidirectional LSTM network enhanced with an attention mechanism to identify and emphasize the most critical semantic information within sentences for relational classification tasks. By leveraging attention, the model dynamically focuses on the most relevant parts of the input, improving its ability to capture contextual dependencies and semantic nuances.

Transformer: This model utilizes a self-attention mechanism to process the entire input sequence simultaneously, enabling it to capture global dependencies and relationships within the data. By focusing on the interactions between all elements of the sequence, the Transformer effectively performs classification tasks while maintaining a high level of contextual understanding.

Comprehensive evaluation on the Shanghai POI dataset in [Table 7](#) confirms GeoDFNet's consistent superiority over six text-based baselines, with pronounced performance disparities in semantically ambiguous categories. While low-ambiguity categories like Public Utilities—where explicit lexical cues (*e.g.*, 'public toilet') enable near-perfect baseline accuracy (TextCNN $F1 = 99.68\% \pm 0.12$)—high-ambiguity categories reveal critical gaps: GeoDFNet achieved $99.42\% \pm 0.53$ $F1$ in Catering Services (*vs.* best baseline $92.86\% \pm 0.21$), $91.10\% \pm 8.59$ in Scenic Spots (*vs.* $61.49\% \pm 0.92$), and $97.20\% \pm 2.02$ in Retail Services (*vs.* $63.78\% \pm 2.12$). This divergence stems from GeoDFNet's operationalization of geospatial similarity principles, where lexically unclassifiable names (*e.g.*, 'Centennial Dragon Robe') are accurately categorized through spatial neighborhood integration.

Critically, GeoDFNet outperformed all baselines in every run (10/10). Wilcoxon signed-rank tests on the accuracy data in [Table 8](#) confirmed statistically significant superiority ($p = 0.001953$ for all comparisons), with consistently higher terminal $F1$ -scores and training accuracy. These results robustly validate the method's efficacy in advancing POI classification.

Ablation experiments

To validate the contributions of the T-GFF and EGN modules in GeoDFNet, we conducted rigorous ablation studies by systematically isolating components. The T-GFF module performs multimodal feature-level fusion integrating textual and geospatial representations, while the EGN module executes decision-level fusion incorporating spatial neighborhood topology. Through sequential removal of these modules ([Table 9](#)), we precisely quantify their individual impacts on POI classification performance, establishing causal relationships between architectural components and model efficacy.

Table 7 The accuracy, recall, F1 value, and test set samples of each model.

Model	Category	Metric (%)			
		P	R	F1	Accuracy
TextCNN	Catering services	94.37 ± 1.21	91.42 ± 1.00	92.86 ± 0.21	91.13 ± 0.17
	Scenic spots	53.39 ± 1.42	72.55 ± 1.09	61.49 ± 0.92	
	Public utilities	99.37 ± 0.23	100.00 ± 0.00	99.68 ± 0.12	
	Corporate entities	97.54 ± 0.17	88.34 ± 0.40	92.71 ± 0.17	
	Retail services	54.62 ± 3.41	76.84 ± 0.87	63.78 ± 2.12	
	Transportation facilities	99.56 ± 0.08	99.68 ± 0.03	99.62 ± 0.04	
	Financial and insurance services	85.62 ± 0.64	97.39 ± 0.28	91.12 ± 0.26	
	Science, education and cultural services	89.39 ± 0.76	89.81 ± 0.70	89.59 ± 0.21	
	Business residences	88.13 ± 1.43	89.11 ± 1.01	88.60 ± 0.30	
	Daily life services	87.71 ± 1.31	89.25 ± 0.86	88.46 ± 0.36	
	Sports and leisure services	77.47 ± 2.55	88.38 ± 0.96	82.53 ± 1.05	
	Healthcare services	83.87 ± 2.21	90.60 ± 0.90	87.08 ± 0.81	
	Government institutions and social organizations	88.92 ± 0.78	94.56 ± 0.43	91.65 ± 0.24	
	Accommodation services	88.31 ± 1.19	92.74 ± 0.91	90.46 ± 0.36	
	Accommodation services	88.31 ± 1.19	92.74 ± 0.91	90.46 ± 0.36	
TextRNN	Catering services	93.10 ± 5.09	79.18 ± 4.21	85.52 ± 3.93	83.54 ± 3.10
	Scenic spots	31.47 ± 12.68	61.81 ± 3.28	40.14 ± 11.34	
	Public utilities	97.73 ± 2.49	98.87 ± 3.27	98.29 ± 2.73	
	Corporate entities	96.32 ± 0.91	82.29 ± 3.49	88.71 ± 1.94	
	Retail services	30.29 ± 8.18	67.08 ± 5.39	41.00 ± 6.95	
	Transportation facilities	99.34 ± 0.66	99.18 ± 0.28	99.26 ± 0.35	
	Financial and insurance services	79.77 ± 3.77	95.70 ± 1.17	86.95 ± 1.97	
	Science, education and cultural services	82.25 ± 5.40	81.47 ± 3.69	81.79 ± 3.93	
	Business residences	82.88 ± 5.25	77.86 ± 7.30	79.89 ± 3.01	
	Daily life services	75.22 ± 7.06	79.30 ± 5.69	77.01 ± 5.29	
	Sports and leisure services	61.88 ± 8.91	72.63 ± 10.04	66.46 ± 7.86	
	Healthcare services	65.80 ± 12.79	80.35 ± 10.32	72.21 ± 12.05	
	Government institutions and social organizations	82.63 ± 5.32	89.18 ± 2.70	85.65 ± 2.80	
	Accommodation services	70.19 ± 14.65	82.28 ± 18.70	75.23 ± 15.81	
	Accommodation services	70.19 ± 14.65	82.28 ± 18.70	75.23 ± 15.81	
TextDPCNN	Catering services	93.79 ± 1.23	91.08 ± 1.15	92.40 ± 0.31	90.69 ± 0.23
	Scenic spots	61.71 ± 8.89	64.90 ± 4.56	62.62 ± 2.80	
	Public utilities	99.75 ± 0.29	99.84 ± 0.19	99.80 ± 0.13	
	Corporate entities	96.28 ± 0.50	89.17 ± 0.66	92.58 ± 0.21	
	Retail services	58.24 ± 5.54	73.92 ± 1.56	64.96 ± 2.78	
	Transportation facilities	99.64 ± 0.10	99.65 ± 0.07	99.65 ± 0.04	
	Financial and insurance services	86.95 ± 2.75	95.39 ± 1.65	90.93 ± 0.90	
	Science, education and cultural services	89.36 ± 1.76	88.48 ± 1.87	88.88 ± 0.37	
	Business residences	87.84 ± 2.35	88.31 ± 1.70	88.03 ± 0.47	
	Daily life services	84.39 ± 4.69	89.03 ± 2.07	86.53 ± 1.68	
	Sports and leisure services	79.17 ± 3.47	85.90 ± 1.69	82.32 ± 1.30	
	Healthcare services	80.00 ± 4.86	90.08 ± 2.60	84.59 ± 1.71	

Table 7 (continued)

Model	Category	Metric (%)			
		P	R	F1	Accuracy
<u>TextRCNN</u>	Government institutions and social organizations	89.51 ± 1.58	93.30 ± 1.01	91.35 ± 0.47	90.12 ± 0.16
	Accommodation services	86.97 ± 3.17	91.06 ± 1.88	88.90 ± 1.08	
	Catering services	94.23 ± 1.58	89.63 ± 1.48	91.85 ± 0.20	
	Scenic spots	45.70 ± 4.45	69.16 ± 2.45	54.83 ± 2.51	
	Public utilities	99.12 ± 0.33	99.55 ± 0.21	99.34 ± 0.19	
	Corporate entities	96.65 ± 0.60	88.28 ± 0.77	92.27 ± 0.19	
	Retail services	51.87 ± 8.88	73.79 ± 2.72	60.35 ± 5.49	
	Transportation facilities	99.57 ± 0.07	99.67 ± 0.05	99.62 ± 0.04	
	Financial and insurance services	86.07 ± 1.68	95.87 ± 1.13	90.69 ± 0.51	
	Science, education and cultural services	88.64 ± 1.64	88.31 ± 1.27	88.45 ± 0.33	
	Business residences	87.29 ± 2.21	86.81 ± 2.06	87.00 ± 0.35	
	Daily life services	86.05 ± 2.85	88.02 ± 1.73	86.97 ± 0.68	
	Sports and leisure services	75.73 ± 2.82	86.91 ± 1.51	80.88 ± 1.15	
	Healthcare services	80.58 ± 2.39	89.72 ± 0.99	84.88 ± 0.99	
TextRNN_ ATTENTION	Government institutions and social organizations	90.22 ± 1.82	92.69 ± 1.38	91.41 ± 0.48	87.53 ± 0.70
	Accommodation services	83.91 ± 4.36	91.79 ± 1.84	87.57 ± 1.63	
	Catering services	94.95 ± 0.88	85.14 ± 2.05	89.76 ± 0.81	
	Scenic spots	38.79 ± 3.31	66.39 ± 3.71	48.83 ± 2.48	
	Public utilities	98.36 ± 1.52	99.37 ± 0.35	98.85 ± 0.68	
	Corporate entities	97.14 ± 0.50	84.75 ± 0.83	90.52 ± 0.29	
	Retail services	36.09 ± 6.11	74.63 ± 1.58	48.33 ± 5.44	
	Transportation facilities	99.56 ± 0.14	99.18 ± 0.20	99.37 ± 0.09	
	Financial and insurance services	80.22 ± 2.30	96.42 ± 0.68	87.55 ± 1.16	
	Science, education and cultural services	85.60 ± 2.72	85.85 ± 2.21	85.67 ± 0.98	
	Business Residences	86.34 ± 2.36	82.79 ± 2.13	84.49 ± 0.97	
	Daily life services	83.72 ± 3.19	84.26 ± 2.91	83.91 ± 1.43	
	Sports and leisure services	69.15 ± 5.40	85.10 ± 2.53	76.14 ± 3.07	
	Healthcare Services	79.65 ± 3.10	86.99 ± 1.59	83.11 ± 1.44	
Transformer	Government Institutions and social organizations	84.75 ± 2.41	92.45 ± 0.66	88.42 ± 1.09	86.64 ± 0.53
	Accommodation services	76.64 ± 2.32	91.81 ± 1.08	83.52 ± 1.35	
	Catering services	88.83 ± 3.95	88.46 ± 2.01	88.55 ± 1.10	
	Scenic spots	44.60 ± 10.00	65.23 ± 5.92	51.88 ± 5.57	
	Public utilities	92.93 ± 4.65	98.84 ± 0.31	95.74 ± 2.46	
	Corporate entities	96.13 ± 0.92	83.76 ± 1.49	89.51 ± 0.55	
	Retail services	46.60 ± 11.11	70.11 ± 4.25	54.93 ± 6.67	
	Transportation facilities	98.87 ± 0.32	99.00 ± 0.33	98.93 ± 0.15	
	Financial and insurance services	79.03 ± 3.45	95.29 ± 1.43	86.34 ± 1.55	
	Science, education and cultural services	82.76 ± 2.12	85.26 ± 1.33	83.96 ± 0.72	
	Business residences	88.45 ± 3.38	80.26 ± 4.20	84.01 ± 1.13	
	Daily life services	81.32 ± 3.78	83.24 ± 2.69	82.16 ± 1.02	

(Continued)

Table 7 (continued)

Model	Category	Metric (%)			
		P	R	F1	Accuracy
GeoDFNet	Sports and leisure services	73.59 ± 5.65	78.10 ± 4.34	75.48 ± 1.25	98.60 ± 0.45
	Healthcare services	76.55 ± 5.35	84.19 ± 2.87	80.00 ± 1.78	
	Government institutions and social organizations	82.25 ± 3.74	90.74 ± 2.07	86.20 ± 1.21	
	Accommodation services	74.99 ± 4.83	91.94 ± 1.28	82.49 ± 2.56	
	Catering services	99.50 ± 0.39	99.34 ± 0.71	99.42 ± 0.53	
	Scenic spots	88.42 ± 14.37	95.03 ± 4.46	91.10 ± 9.08	
	Public utilities	94.58 ± 3.22	99.25 ± 0.36	96.83 ± 1.61	
	Corporate entities	99.63 ± 0.34	98.28 ± 1.50	98.94 ± 0.80	
	Retail services	97.59 ± 2.56	97.04 ± 2.32	97.30 ± 2.06	
	Transportation facilities	99.54 ± 0.24	99.71 ± 0.10	99.63 ± 0.13	
	Financial and insurance services	97.86 ± 1.39	98.89 ± 0.46	98.37 ± 0.86	
	Science, education and cultural services	98.24 ± 1.57	98.23 ± 1.45	98.23 ± 1.19	
	Business residences	99.43 ± 0.55	97.61 ± 1.34	98.51 ± 0.93	
	Daily life services	98.88 ± 1.02	99.03 ± 0.83	98.95 ± 0.80	
	Sports and leisure services	94.31 ± 6.80	97.33 ± 2.11	95.67 ± 3.73	
	Healthcare services	97.88 ± 2.68	98.44 ± 1.13	98.15 ± 1.83	
	Government institutions and social organizations	98.03 ± 1.51	99.47 ± 0.33	98.74 ± 0.82	
	Accommodation services	96.01 ± 2.25	98.52 ± 1.19	97.23 ± 1.21	

Table 8 Statistical significance of performance differences between models.

	GeoDFnet	Transformer	TextDPCNN	TextRNN	TextRCNN	TextCNN	TextRNN_ATTENTION
GeoDFnet	–	–	–	–	–	–	–
Transformer	1.95E–03	–	–	–	–	–	–
TextDPCNN	1.95E–03	1.95E–03	–	–	–	–	–
TextRNN	1.95E–03	3.91E–03	1.95E–03	–	–	–	–
TextRCNN	1.95E–03	1.95E–03	3.91E–03	1.95E–03	–	–	–
TextCNN	1.95E–03	1.95E–03	1.95E–03	1.95E–03	1.95E–03	–	–
TextRNN_ATTENTION	1.95E–03	5.86E–03	1.95E–03	1.95E–03	1.95E–03	1.95E–03	–

T-G feature fusion module evaluation

To isolate the contribution of the T-GFF module, we compared the full GeoDFNet model against a variant where the T-GFF module was removed (denoted as GeoDFNet w/o T-GFF, which retains only decision-level fusion). The results demonstrate that removing this feature-level fusion causes a significant performance drop: the *F1*-score decreases to 97.04% (± 1.69) and accuracy falls to 98.01% (± 1.08) from the full model's 97.65% (± 0.85) *F1* and 98.60% (± 0.45) accuracy. This decline confirms the critical role of T-GFF in effectively integrating spatial-textual features at the feature level, which is essential for the model's understanding of POI characteristics.

Table 9 Ablation study on the dual-fusion architecture (feature-level vs. decision-level).

Model	Metric (%)			
	P	R	F1	Accuracy
GeoDFNet (w/o T-GFF) (decision-level fusion)	96.44 ± 2.02	97.74 ± 1.27	97.04 ± 1.69	98.01 ± 1.08
GeoDFNet (w/o EGN) (feature-level fusion)	96.19 ± 2.50	97.63 ± 1.20	96.81 ± 1.93	98.12 ± 1.24
GeoDFNet	97.14 ± 1.10	98.30 ± 0.66	97.65 ± 0.85	98.60 ± 0.45

Table 10 k-value sensitivity analysis.

k-value	Metric (%)			
	P	R	F1	Accuracy
2	97.52 ± 1.36	98.50 ± 0.71	97.97 ± 1.05	98.69 ± 0.82
3	96.36 ± 1.79	97.80 ± 0.75	96.99 ± 1.33	98.19 ± 1.03
4	96.72 ± 2.04	97.80 ± 1.47	97.19 ± 1.80	98.21 ± 1.33
5	97.14 ± 1.10	98.30 ± 0.66	97.65 ± 0.85	98.60 ± 0.45
6	97.15 ± 2.31	98.37 ± 1.08	97.70 ± 1.75	98.45 ± 1.20
7	96.44 ± 1.83	97.80 ± 0.79	97.03 ± 1.35	98.06 ± 0.93
8	96.54 ± 1.76	97.89 ± 1.07	97.16 ± 1.44	98.33 ± 0.94
9	96.61 ± 1.55	97.95 ± 1.00	97.22 ± 1.28	98.38 ± 0.81
10	97.21 ± 1.12	98.08 ± 0.70	97.60 ± 0.90	98.40 ± 0.79

Enhanced geospatial local neighborhood module evaluation

To examine the contribution of the EGN module, we compared the full model against a variant where the EGN module was removed (denoted as GeoDFNet w/o EGN, which retains only feature-level fusion). Removing this decision-level fusion module also leads to a substantial performance degradation: the *F1*-score drops to 96.81% (± 1.93) and accuracy reduces to 98.12% (± 1.24). This result clearly demonstrates the effectiveness of the EGN module in leveraging spatial topology, which is vital for capturing the influence of spatial neighborhood features on category characteristics.

Synergistic effect

The significant performance decline observed in both ablated models—not only in overall accuracy and *F1* but also in *P* and *R*—underscores that the T-GFF and EGN modules are both indispensable components of GeoDFNet. The full model's superior and more stable performance (as evidenced by lower standard deviations) arises from the synergistic effect of these complementary fusion strategies: T-GFF's feature-level integration working in concert with EGN's decision-level refinement.

k-value sensitivity analysis

We conducted a parametric sensitivity analysis to evaluate the impact of the number of neighboring points, *k*, used in constructing the geographic dataset. As summarized in the

Table 11 Cross-dataset generalization performance across models.

Model	AutoNavi Beijing POI dataset				OSM Guangdong POI dataset			
	P (%)	R (%)	F1 (%)	Accuracy (%)	P (%)	R (%)	F1 (%)	Accuracy (%)
TextCNN	78.25 ± 0.46	80.62 ± 0.47	78.91 ± 0.42	81.54 ± 0.36	50.75 ± 1.16	60.18 ± 0.68	52.99 ± 0.86	61.12 ± 0.72
TextRNN	46.92 ± 2.52	48.84 ± 3.28	45.19 ± 2.90	45.48 ± 2.86	31.86 ± 0.59	41.11 ± 0.95	33.03 ± 0.61	45.03 ± 1.22
TextDPCNN	72.62 ± 1.82	72.21 ± 0.83	71.09 ± 1.58	72.85 ± 2.25	40.83 ± 1.57	44.78 ± 1.26	38.69 ± 1.21	49.13 ± 1.78
TextRCNN	73.55 ± 1.27	75.69 ± 1.03	74.05 ± 1.04	76.31 ± 0.61	44.88 ± 1.01	54.64 ± 0.72	46.79 ± 0.70	56.39 ± 0.42
TextRNN_ ATTENTION	62.34 ± 2.62	63.89 ± 3.66	61.64 ± 3.27	63.36 ± 3.52	31.71 ± 2.68	40.86 ± 3.59	32.39 ± 2.82	42.83 ± 2.76
Transformer	70.69 ± 0.81	73.21 ± 0.68	71.17 ± 0.72	73.58 ± 0.75	37.30 ± 1.29	45.77 ± 2.01	37.97 ± 1.79	49.77 ± 2.10
GeoDFNet	93.47 ± 1.59	93.77 ± 1.15	92.99 ± 1.60	95.70 ± 2.25	69.22 ± 8.64	74.34 ± 6.54	69.71 ± 7.79	82.76 ± 6.41

Table 10, model performance is sensitive to the choice of k , with optimal results achieved at $k = 5$ across all metrics: precision ($97.14 \pm 1.10\%$), recall ($98.30 \pm 0.66\%$), $F1$ -score ($97.65 \pm 0.85\%$), and accuracy ($98.60 \pm 0.45\%$). This configuration also exhibited the smallest standard deviations, indicating superior stability and robustness.

Performance improved as k increased from 2 to 5, suggesting that incorporating more spatial context enhances feature representation and contextual understanding. However, beyond $k = 5$, all metrics gradually declined, implying that excessively large neighborhoods may introduce noise or redundant information, thereby reducing model efficacy. These results highlight the critical role of selecting an appropriate spatial scale to balance contextual information and discriminative power.

Generalization experiments

To comprehensively evaluate the generalization capability of the GeoDFNet model and validate its applicability across different regions and datasets, a series of experiments were conducted to assess its adaptability and robustness in handling diverse semantic structures and regional characteristics. Additional POI public datasets, including the AutoNavi Beijing POI dataset and the OSM Guangdong POI dataset, were introduced to perform generalization performance experiments.

During model training, each dataset was partitioned into training, validation, and test sets at a ratio of 5:3:2 to ensure consistency in model training and evaluation. Given the varying sizes of the datasets, an appropriate number of training epochs was selected for each dataset, while other hyperparameters remained consistent with the experimental settings described earlier to ensure comparability of results. The model's classification performance was evaluated using two key metrics: accuracy and $F1$ -score.

The classification performance of each model on datasets from different regions and sources is summarized in Table 11. The results demonstrate that the proposed GeoDFNet model achieves strong performance across diverse datasets, highlighting its generalization ability and robustness. The reason why the AutoNavi Beijing POI dataset results are higher than the OSM Guangdong POI Dataset results is that the OSM Guangdong POI dataset has relatively fewer samples and more labels.

DISCUSSION

The proposed GeoDFNet effectively addresses POI semantic ambiguity through a novel dual-fusion architecture, achieving state-of-the-art performance with a test accuracy of $98.60 \pm 0.45\%$ and a macro F1-score of $97.65 \pm 0.85\%$ on the Shanghai POI dataset. The model demonstrates particular strength in resolving lexically ambiguous cases—exemplified by its accurate classification of “Centennial Dragon Robe” as a catering service rather than a clothing store or tea shop—where conventional text-based models exhibit significant limitations. This capability is realized through the operationalization of geographic similarity principles *via* two specialized modules: T-GFF and EGN. The T-GFF module enables robust multimodal feature-level fusion by integrating textual representations with geospatial neighborhood information, while the EGN module performs decision-level fusion through spatial neighborhood aggregation. Ablation studies confirm that both modules contribute critically and synergistically to overall performance, with removal of either component resulting in statistically significant performance degradation (F1-score declining to $97.04 \pm 1.69\%$ without T-GFF and $96.81 \pm 1.93\%$ without EGN).

Nevertheless, the model’s performance remains constrained by several limitations. It exhibits sensitivity to class imbalance, as evidenced by higher performance variance for infrequent categories (e.g., Scenic Spots with an F1-score of $91.10 \pm 9.08\%$). Moreover, performance depends on selecting an optimal spatial neighborhood scale ($k = 5$); expanding beyond this scale leads to degradation. Additionally, the model does not fully leverage other available multimodal data, such as imagery and temporal dynamics.

These limitations delineate clear pathways for future improvement. Incorporating advanced techniques such as contrastive learning could enhance representation learning for rare categories, while reinforcement learning might dynamically optimize sampling strategies or reward correct classification of infrequent classes. Furthermore, developing adaptive mechanisms to automatically determine suitable spatial context scales across diverse urban environments would improve robustness and generalizability. Ultimately, extending the model into a fully multimodal framework—integrating visual, textual, and temporal cues—could enable a more comprehensive understanding of POI characteristics and support finer-grained urban semantic analysis.

CONCLUSIONS

To address the challenge of insufficient utilization of POI features in POI classification tasks, proposes a dual fusion network model that integrates geospatial local neighborhood features to enhance the accuracy of POI classification. The main conclusions are as follows:

- (1) The geographic similarity theory can be effectively represented using graph neural networks, enabling the formation of local neighborhood features and the construction of a geospatial local neighborhood knowledge graph. The proposed model successfully captures and interprets relevant geospatial local neighborhood knowledge, significantly improving classification performance through the use of this knowledge graph.

- (2) By incorporating a dual fusion operation of geospatial local neighborhood features into the Transformer network, the model provides relevant geospatial neighborhood for each POI name. This approach facilitates the comprehensive utilization and learning of POI feature information, enhancing the model's ability to uncover intrinsic characteristics within POI data.
- (3) Extensive experiments on multiple real-world public datasets demonstrate that the GeoDFNet model achieves state-of-the-art performance in both classification accuracy and *F1*-score across POI datasets from diverse regions and structures. The model exhibits high learning efficiency and strong generalization capabilities, validating its effectiveness and robustness.

Given that the dataset employed in this study originates from real-world observations and utilizes coarse-grained categorical features, significant class imbalance emerges when analyzing fine-grained subcategories, thereby limiting the potential for granular urban studies. Furthermore, the POI dataset contains multimodal information including user reviews, visual documentation, and temporal check-in patterns that remain underutilized in our current framework. To address these limitations, future research directions will focus on three key aspects:

- (1) developing integrated datasets with balanced hierarchical categorization.
- (2) implementing multi-modal fusion architectures that synthesize textual, visual, and temporal signals.
- (3) optimizing computational frameworks through architectural innovations and parallelization strategies.

These enhancements will enable more sophisticated analysis of POI characteristics across multiple dimensions, supporting finer-grained urban computing applications while maintaining computational efficiency in large-scale spatial analyses.

ADDITIONAL INFORMATION AND DECLARATIONS

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Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Yuao Wang conceived and designed the experiments, performed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Yongbin Tan conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Yuxing Xu performed the experiments, prepared figures and/or tables, and approved the final draft.
- Xingzhen Zhang analyzed the data, prepared figures and/or tables, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The code is available in the [Supplemental Files](#) and at figshare:

- wang, yuao (2025). POI_Data_Processing_Documentation. figshare. Dataset. <https://doi.org/10.6084/m9.figshare.30304261.v2>.

The Shanghai POI dataset is available at: <http://www.gis5g.com/data/cssj?id=517>.

The AutoNavi Beijing POI dataset is available at the Peking University Open Research Data Platform:

- <https://opendata.pku.edu.cn/dataset.xhtml?persistentId=doi:10.18170/DVN/WSXCNM>.

- State Information Center, 2017, "Map POI (Point of Interest) data", <https://doi.org/10.18170/DVN/WSXCNM>, Peking University Open Research Data Platform, V2

- The dataset is hosted in a restricted-access repository. To download it, users must register for a free account on the platform. A detailed step-by-step guide with annotated screenshots that walks researchers through the registration and data download procedure is available via Figshare: <https://doi.org/10.6084/m9.figshare.30304261>.

The OSM Guangdong POI dataset is available at: <https://download.geofabrik.de/asia/china/guangdong.html>.

Supplemental Information

Supplemental information for this article can be found online at <http://dx.doi.org/10.7717/peerj-cs.3323#supplemental-information>.

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