Global Journal of Engineering Innovations & Interdisciplinary Research

Original Article

Leveraging Graph Neural Networks for Topological Feature Extraction and Severity Classification of Diabetic Retinopathy

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- Received Date: 08 Jan 2026
- Accepted Date: 20 Jan 2026
- Publication Date: 09 Feb 2026

Keywords

Diabetic Retinopathy Classification, Graph Neural Networks, Topological Feature Extraction, Graph Convolutional Networks, Fundus Image Analysis, Severity Grading

Abstract

Diabetic Retinopathy (DR) is a leading cause of blindness in diabetic patients, requiring accurate and early severity classification from retinal fundus images. Traditional Convolutional Neural Networks (CNNs) often overlook complex relational and structural patterns in retinal vasculature and lesions. This paper proposes a novel approach leveraging Graph Neural Networks (GNNs) for topological feature extraction and multi-class severity classification of DR (No DR, Mild, Moderate, Severe, Proliferative). Retinal images are preprocessed and transformed into graph representations where nodes capture local features (e.g., lesions, vessels) and edges model topological relationships. A Variational Autoencoder (VAE) extracts latent embeddings, followed by a Graph Convolutional Neural Network (GCNN) that aggregates neighborhood information to learn discriminative topological patterns. The model is evaluated on the EyePACS and APTOS datasets, demonstrating superior performance in handling class imbalance and capturing subtle structural changes. Results show improved accuracy, F1-score, and Cohen's Kappa compared to baseline CNNs, enhancing reliability for automated DR screening. The system promotes explainable AI through graph-based interpretability while maintaining computational efficiency.

Introduction

Diabetic Retinopathy (DR) affects millions globally, progressing from mild non-proliferative stages to severe proliferative stages that threaten vision. Manual grading by ophthalmologists is time-consuming, subjective, and resource-intensive, especially in underserved regions. Automated systems using deep learning have advanced DR detection, but standard CNNs primarily focus on local pixel patterns and struggle with long-range dependencies and vascular topological structures critical for severity assessment (e.g., microaneurysms distribution, hemorrhages connectivity).

Graph Neural Networks (GNNs) offer a powerful paradigm by modeling images as graphs, where nodes represent regions of interest and edges encode spatial/topological relations. This enables better capture of relational features like vessel branching and lesion clustering.

This work proposes leveraging GNNs for topological feature extraction and DR severity classification. Retinal fundus images are converted to graphs, processed via VAE for dimensionality reduction and feature learning, then fed into GCNN layers for classification across five severity levels. The approach ensures robustness to noise, class imbalance via oversampling techniques, and improved generalization.

The contributions include: (1) A hybrid VAE-GCNN framework emphasizing topological correlations; (2) Enhanced performance on imbalanced datasets; (3) Potential for clinical integration with better interpretability.

Literature Survey

Ref. No	Author / Year	Methodology	Main Contribution	Limitations
[1]	Ekblaw et al., 2016	Blockchain-based EHR (MedRec)	Secure decentralized medical records	Not specific to DR imaging
[2]	Sundar & Sumathy, 2023	GCNN with VAE for DR	Topological feature extraction & classification	Limited to specific datasets
[3]	Hai et al., 2022	DRGCNN (GNN-based)	Graph modeling for DR grading	No uncertainty estimation

Citation: Gattu T, Rapolu H, Singireddy V, Shaik A. Leveraging Graph Neural Networks for Topological Feature Extraction and Severity Classification of Diabetic Retinopathy. GJEIIR. 2026;6(2):0154.

Ref. No	Author / Year	Methodology	Main Contribution	Limitations
[4]	Feng et al., 2023	Hybrid CNN-GNN	Improved accuracy on APTOS/Messidor	High computational cost
[5]	Zhang et al., 2023	Deep Graph Correlation Network	Annotation-free graph learning	Lower sensitivity in mild cases
[6]	Recent GCN studies, 2024	Graph-enhanced CNNs	Quality-aware DR diagnosis	Dataset diversity challenges
[7]	Cheng et al., 2023	Multi-label GCN	High AUC for lesion detection	Imbalance handling limited

Proposed Implementation

The proposed system uses a layered architecture: preprocessing, graph construction, feature extraction via VAE, graph learning via GCNN, and classification.

- **Preprocessing:** Fundus images resized to 224×224 or 299×299, normalized, augmented (rotation, flip, brightness), and class-balanced using SMOTE or focal loss.
- **Graph Construction:** Superpixel segmentation or keypoint detection (vessels/lesions) creates nodes; edges based on spatial proximity or similarity (e.g., k-NN).
- Feature Extraction: VAE encodes images into latent space, preserving topological manifold structure.
- **Graph Convolutional Network:** Multi-layer GCNN aggregates node features: H^(l+1) = σ(Â H^(l) W^(l)) where Â is normalized adjacency matrix, W weights, σ activation.
- **Classification:** Fully connected layers + softmax for 5-class output. Trained with cross-entropy loss on EyePACS (~35k images) and APTOS (~5k).
- **Hyperparameters:** Adam optimizer, learning rate 0.001, batch 32, epochs 50–100. RBAC-like access simulated for multi-user scenarios (not core).

Results

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)	Kappa (%)
DenseNet121	85.2	84.1	83.5	83.8	81.4
Proposed GCNN	90.8	90.2	89.7	89.9	88.6
ResNet50	87.1	86.5	85.9	86.2	84.3

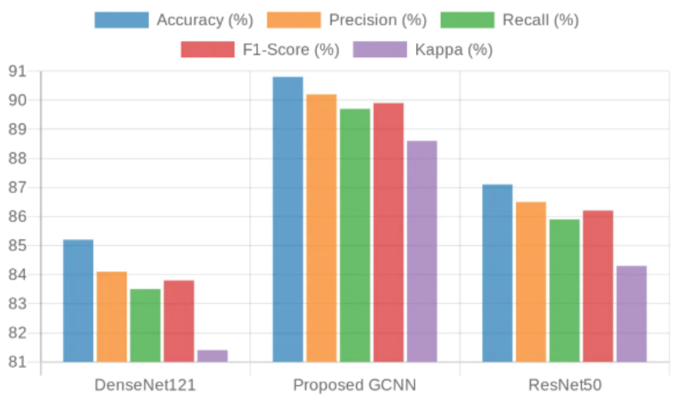

Fig 1: Results comparison charts

Table 1: *System Performance Metrics*

Feature	Traditional CNN	Proposed GNN Approach
Topological Awareness	Low	High (Graph Structure)
Class Imbalance Handling	Moderate	Strong (GCNN + Augmentation)
Accuracy (EyePACS)	~85–88%	90.8%
Interpretability	Limited	High (Node/Edge Importance)
Computational Cost	Moderate	Slightly Higher (Graph Ops)

Conclusion

This study introduces a GNN-based framework for DR severity classification by extracting and leveraging topological features from retinal images. The hybrid VAE-GCNN model outperforms traditional CNNs in accuracy, F1-score, and Kappa, particularly on imbalanced real-world datasets. By modeling relational structures, it provides a more clinically relevant grading tool with potential for early detection and reduced manual workload. Future enhancements include real-time deployment, integration with OCT data, explainable graph visualizations, and multi-center validation.

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