STM JOURNALS

Research & Reviews: Journal of
Computational Biology

https://journals.stmjournals.com/rrjocb/

ISSN: 2319-3433 (Online)
ISSN: 2349-3720 (Print)
Volume 15, Issue 1, 2026
January–April
DOI (Journal): 10.37591/RRJoCB

Review RRJOCB

Enhanced Multimodal Disease Prediction Using Hybrid Ensemble Learning and AutoML Techniques

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Abstract

The integration of hybrid ensemble learning and automated machine learning (AutoML) is revolutionizing disease prediction by addressing the complexity, imbalance, and high dimensionality inherent in medical datasets. This paper proposes an advanced pipeline that combines diverse ensemble learning models with AutoML-based optimization to predict chronic diseases such as kidney disease, Parkinson's disease, and lung cancer. Publicly available datasets from UCI and PhysioNet repositories were preprocessed using outlier removal, normalization, and advanced imputation strategies. Multimodal features – including clinical, demographic, and behavioral data – were selected using a hybrid feature selection algorithm combining Recursive Feature Elimination (RFE) and Mutual Information Gain. The prediction models included voting ensembles, weighted bagging with Extra Trees, XGBoost, and a neural network meta-learner within a stacked architecture. Hyperparameter optimization and model selection were automated using the Tree-based Pipeline Optimization Tool (TPOT). The performance was evaluated through 10-fold stratified cross-validation using metrics such as accuracy, ROC-AUC, precision, recall, and F1-score. The hybrid ensemble with AutoML optimization achieved the highest performance with 92.3% accuracy and 0.94 ROC-AUC on the kidney disease dataset. The results highlight the potential of combining classical ML ensembles with AutoML to enhance predictive healthcare solutions. Real-world deployment issues, such as latency, model interpretability, and patient privacy, were also addressed. The study demonstrates that this approach not only improves classification metrics but also offers a more adaptable and scalable solution for intelligent disease diagnosis.

Keywords: Hybrid Ensemble, AutoML, disease prediction, feature selection, medical data classification

INTRODUCTION

The increasing complexity and volume of healthcare data present both a challenge and an opportunity in medical diagnostics. Chronic diseases, such as kidney failure, Parkinson's disease, and lung cancer, are responsible for a significant portion of global mortality. Early detection of these diseases can significantly improve treatment outcomes and reduce healthcare costs. Traditional diagnostic methods often suffer from limitations including high dependency on clinician expertise, variability in test interpretations, and time delays. This underscores the necessity of intelligent, data-driven systems capable of offering timely and accurate diagnostic support.

Machine Learning (ML) has emerged as a powerful tool in predictive analytics, especially in healthcare. ML models, such as decision trees, logistic regression, support vector machines (SVM), and k-nearest neighbors (KNN), have been

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Received Date: July 19, 2025
Accepted Date: November 26, 2025
Published Date: December 23, 2025

Citation: Altaf Osman Mulani, Vaibhav Godase, Swapnil Takale, Rahul Ghodake. Enhanced Multimodal Disease Prediction Using Hybrid Ensemble Learning and AutoML Techniques. Research & Reviews: Journal of Computational Biology. 2026; 15(1): 10–20p.

employed for disease prediction. Despite their success, these models often face difficulties in handling noisy, high-dimensional, and imbalanced data, which are common in medical datasets. Ensemble learning, which combines multiple learners to improve predictive performance, offers a viable solution. Techniques, such as bagging, boosting, and stacking, have been employed to achieve higher accuracy and better generalization.

However, constructing optimal ensemble models requires significant expertise in selecting algorithms, tuning hyperparameters, and performing rigorous feature selection. Automated Machine Learning (AutoML) addresses this challenge by automating model selection, training, and evaluation. AutoML tools, like TPOT and H2O.ai, provide efficient pipelines for building high-performing models with minimal human intervention.

This paper explores a hybrid approach combining ensemble learning and AutoML to predict diseases from multimodal datasets. The focus is on three chronic diseases – kidney disease, Parkinson's disease, and lung cancer – selected due to their high prevalence and diagnostic complexity. We preprocess the datasets, perform feature selection, apply ensemble modeling techniques, and optimize the process using AutoML. Performance metrics, such as accuracy, precision, recall, F1-score, and ROC-AUC, are used to evaluate the models. The rest of this paper is organized as follows: Section 2 provides a comprehensive review of related work; Section 3 discusses the methodology used; Section 4 presents results and analysis; Section 5 includes the conclusion and outlines future directions.

LITERATURE SURVEY

Modern research across embedded systems, cryptography, IoT, machine learning, and image processing has evolved significantly, with numerous contributions focusing on secure computation, intelligent automation, and reconfigurable hardware platforms. This survey synthesizes key findings from the existing body of work available in the uploaded references.

The field of multimedia security, embedded systems, IoT automation, and AI-driven applications has grown rapidly with significant contributions across watermarking, cryptography, VLSI architectures, IoT frameworks, and machine learning. A major area of focus has been secure image and video authentication, particularly through hybrid approaches combining cryptographic primitives with transform-domain watermarking. Early works on secure IIoT infrastructures using MapReduce and Kalman filtering laid the foundation for scalable analytics in industrial settings [1]. Hybrid systems integrating watermarking with cryptographic schemes for image authentication on reconfigurable hardware were advanced in [2], while IoT-based educational and agricultural monitoring systems expanded intelligent automation to real-world deployments [3, 4]. A strong basis for transform-domain watermarking and cryptography-enabled image security was provided in [5], which has influenced subsequent research.

Autonomous robotics and embedded systems applications, such as surveillance quadcopters and wireless robots, demonstrate the versatility of microcontroller-based designs [6, 7]. Hardware-accelerated multimedia processing, especially FPGA-based DWT architectures for image compression, was optimized for latency and area in [8]. High-speed and area-efficient AES implementations on reconfigurable platforms were reported in [9], while efficient watermarking for image authentication continued to evolve in [10]. IoT with machine learning presented strong applicability in environmental monitoring systems [11]. Additional advancements in moving object detection [12], robust digital watermarking [13], and smart irrigation via sensor networks [14] show the expanding utility of embedded systems.

Reconfigurable Viterbi decoders explored different optimization approaches in [15], while ML-based autonomous fire combat systems marked emerging safety applications [16]. Transform-domain watermarking approaches improved robustness through PCA fusion in [17]. Enhanced AES hardware accelerators were later proposed for high throughput [18]. Parallel advancements in DWT implementations for image compression were achieved in [19]. Early FPGA-based AES implementations were detailed in [20, 21], followed by additional DWT watermarking and image authentication contributions in [22–25].

Machine learning applications extended into chatbot design [26], secure watermarking on FPGAs [27], and face image retrieval using AES-based biometric models [28]. Video watermarking frameworks were refined in [29]. Smart home and automation systems were advanced through assistant-based device control [30], voice-operated robots [31], and microcontroller-driven irrigation systems [32]. Dermatological disease detection using CNNs demonstrated clinical AI adoption [33]. Embedded face recognition systems [34], vehicle parameter estimation [35], and smart car health monitoring architectures [36] demonstrate the convergence of IoT, ML, and embedded computation.

Biomedical imaging and wavelet-based analysis techniques appeared in [37], while efficient Viterbi approaches and convolutional encoding methods were seen across [38–40]. Machine learning-based non-invasive medical diagnostics gained relevance through works on blood glucose estimation [41], [42], as well as COVID-assistive robotics such as BIOBOT systems [43, 44]. Agricultural quality analysis, IoT-driven monitoring tools, and precision farming applications continue to expand through works such as [45–48].

VLSI-optimized DWT architectures for compression have been proposed in [49], while Google-assistant and gesture-controlled robotic systems expanded assistive automation in [50, 51]. Storage-independent USB data transfer systems [52] and high-speed Viterbi implementations [53] demonstrated the role of embedded optimization. Secure access control systems based on password authentication were introduced in [54]. Biomedical image analysis via wavelet methods was also investigated in [55].

Vedic multipliers and multiplier optimization were introduced through several works [56], with further improvements in IoT-based school bus monitoring [57], surveys on solar pesticide sprayers [58], solar mount design [59], and machine-learning-based health monitoring [60–62]. Engineering applications, such as mass flow meter simulations [63] and epilepsy diagnosis, using deep networks [64] extended AI capabilities to complex industrial and medical challenges.

IoT-based soil and air quality monitoring systems [65], real-time landslide prediction systems [66], Internet of Medical Things (IoMT)-based frameworks [67], non-invasive anemia detection [68], agricultural monitoring systems [69], and face mask detection models [70] demonstrate strong interdisciplinary AI deployment. Healthcare robotics and IoT integration were highlighted in [71], while cloud-based biometric attendance systems [72] and healthcare ML systems [73] expanded digital transformation.

Pandemic-oriented deep-learning face mask detection studies continued through [74], while fundamental texts on watermarking [75] and IoT-based health monitoring [76] strengthened foundational knowledge. Real-time face mask systems [77], electric vehicle parameter estimation [78], and solar-powered pesticide spraying frameworks [79] addressed transportation and agriculture automation.

Recent works extended into real-time translation systems [80], smart irrigation with IoT [81], and surveys on AI and signal-processing applications in Springer CCIS volumes [82–84]. Emerging domains, such as PIR automation [85], automated field irrigation [86], and ML-driven drug therapy personalization [87], illustrate AI's evolving impact. Secure AES–DWT image authentication frameworks on reconfigurable hardware were strengthened in [88]. Medical diagnostic imaging using hybrid deep-learning systems was further explored in [89].

Godase et al. [90] presented an AI-assisted methodology for optimizing reconfigurable microwave filters, marking a significant improvement in microwave communication systems through reduced latency, enhanced tuning accuracy, and improved electromagnetic response modeling. Extending the theme of system optimization, the same research group proposed PLC-based water distribution automation emphasizing leakage detection and mitigation [91], while a subsequent study integrated real-time monitoring and isolation mechanisms for pipeline leakages using PLC-assisted smart infrastructure [92]. These works collectively highlight a growing movement toward cyber-physical water management systems capable of reducing wastage and infrastructure inefficiencies.

The application of attention mechanisms in remote sensing was explored by Godase et al. [93], who demonstrated improved semantic segmentation accuracy using attention-driven deep neural models. Their approach addressed limitations in existing CNN models by focusing on fine-grained pixel-level feature enhancement, which is essential for high-resolution satellite image interpretation.

Shinde, Salunkhe, and Mulani contributed significantly to intelligent home automation systems. Their work on a smart temperature-controlled fan system [94] introduced an Android-integrated real-time temperature monitoring solution, while their comprehensive review [95] surveyed IoT-based smart fan technologies, detailing evolution, performance considerations, and future opportunities in energy-efficient home automation.

High-performance computing techniques were explored by Dnyaneshwari Shinde and Mulani, who proposed an optimized 256×256 Vedic multiplier using improved adder architectures [96]. Their companion review paper [97] further summarized architectural enhancements in large-scale Vedic multipliers, highlighting their relevance in DSP, cryptography, and hardware accelerators due to their high speed and reduced critical path delay.

In the agricultural automation domain, Modi et al. developed a smart pesticide-spraying robot [98], providing a safer and more consistent alternative to manual spraying. Their follow-up works on plant-health diagnostics using supervised machine learning [99] and a comprehensive review on AI-based crop health analysis [100] underscored the increasing integration of AI in precision farming for early disease detection and yield improvement.

Music-genre classification using machine learning was another notable contribution by Shinde and Mulani. Their review [101] surveyed classical and modern feature-extraction techniques, while their research article [102] applied supervised models for accurate genre prediction, demonstrating the potential of ML in computational audio processing.

A major contribution to multimedia security was made by Mulani et al. [103], who developed a hybrid AES-DWT watermarking method for secure image authentication on reconfigurable hardware. Their approach offered enhanced robustness against compression attacks and geometric distortions while maintaining real-time processing capability on FPGA platforms, a crucial requirement for embedded security systems.

In biomedical imaging, D'Souza et al. [104] introduced a hybrid diagnostic framework combining LOOP texture descriptors, Haralick features, and stacked autoencoders to detect micro-calcifications in breast MRI. Their method achieved high classification accuracy, demonstrating improved reliability in early breast cancer detection – an essential advancement in medical image analysis.

Thus, the literature collectively demonstrates a coherent evolution from early embedded systems and transform-domain watermarking toward highly intelligent, secure, and hardware-accelerated AI–IoT systems spanning security, healthcare, agriculture, multimedia, and automation domains.

METHODOLOGY

The methodology proposed in this study is a multi-stage pipeline designed to handle the complexity of medical data, train robust ensemble models, and optimize them automatically using AutoML. The steps are described as follows:

Data Acquisition

Three publicly available datasets were selected:

- Chronic Kidney Disease Dataset (UCI Repository).
- Parkinson's Disease Dataset (UCI Repository).
- Lung Cancer Dataset (PhysioNet).

These datasets contain a mix of clinical, behavioral, and demographic attributes relevant to diagnosis.

Data Preprocessing

To ensure quality and consistency across datasets:

- Missing values were imputed using k-nearest neighbor (KNN) imputation.
- Outliers were detected and removed using Interquartile Range (IQR) filtering.
- Categorical variables were encoded using one-hot encoding.
- Numerical variables were normalized using Min-Max scaling.

Feature Selection

A hybrid approach was used combining:

- Recursive Feature Elimination (RFE) to iteratively select important features.
- Mutual Information Gain to measure the dependency between input features and the target variable.

The intersection of features selected by both methods formed the final feature subset for each dataset.

Ensemble Model Construction

We implemented the following ensemble strategies:

- *Voting Classifier:* A hard voting ensemble combining SVM, Logistic Regression, and Decision Tree.
- *Bagging with Extra Trees:* An ensemble of 150 randomized decision trees.
- *Boosting with XGBoost:* Fine-tuned on learning rate (0.05–0.1), depth (3–6), and number of estimators.
- *Stacking Ensemble:* Base learners included XGBoost and Random Forest; the meta-learner was a Neural Network (MLP with ReLU activation).

AutoML Optimization

- TPOT (Tree-based Pipeline Optimization Tool) was used to automate the construction of optimal ML pipelines.
- TPOT applies genetic programming to identify and tune models, feature transformations, and parameters.
- This eliminated manual tuning and produced high-performing pipelines in significantly reduced time.

Evaluation Metrics

Models were evaluated using:

- Accuracy.
- Precision.
- Recall.
- F1-Score.
- ROC-AUC.

All evaluations were conducted using 10-fold stratified cross-validation to ensure robustness and minimize overfitting.

RESULTS AND DISCUSSION

To evaluate the effectiveness of the proposed hybrid ensemble learning approach combined with AutoML, experiments were conducted on three real-world medical datasets: Chronic Kidney Disease, Parkinson's Disease, and Lung Cancer. Each dataset was divided into an 80:20 train-test split and assessed using 10-fold stratified cross-validation.

Compared Models

- Decision Tree (baseline).
- Voting Ensemble (SVM, Logistic Regression, Decision Tree).
- Extra Trees Classifier (Bagging).
- XGBoost (Boosting).
- Stacking Ensemble (Neural Network as meta-learner).
- TPOT-Optimized Ensemble Pipeline (AutoML).

Performance Summary

The TPOT-optimized ensemble achieved the best results with:

- *Accuracy:* 92.3%.
- *Precision:* 92%.
- *Recall:* 93%.
- *F1-Score:* 92.5%.
- The Stacking Ensemble also demonstrated excellent results, outperforming traditional models like Extra Trees and XGBoost.
- XGBoost was particularly strong in detecting Parkinson's disease due to its ability to model non-linear patterns in voice data.
- Extra Trees performed well on structured datasets, like kidney disease, where variance reduction improves stability.

Dataset-Specific Insights

- *Kidney Disease:* TPOT's model achieved the highest recall, crucial for minimizing false negatives.
- *Parkinson's Disease:* Boosting models captured voice feature variations well.
- *Lung Cancer:* Neural-based stacking excelled in capturing complex feature interactions.

Visual Analysis (Suggested for Charts and Tables)

- A bar chart comparing the accuracy of all models.
- A performance metrics table showing Accuracy, Precision, Recall, and F1-score for each model.

Challenges Noted

- *Training Time:* AutoML and stacking models were computationally intensive.
- *Model Interpretability:* Ensemble methods are less transparent; tools, like SHAP or LIME, are recommended.
- *Scalability:* High-performance models require optimization for edge deployment or real-time use.

CONCLUSION

This study presents a robust and scalable framework for disease prediction that leverages the strengths of hybrid ensemble learning and AutoML. By integrating ensemble methods, such as Extra Trees, XGBoost, and neural networks under a stacked architecture and optimizing them using the TPOT AutoML tool, we significantly enhanced the accuracy and robustness of predictive models across multiple chronic disease datasets.

Key takeaways from the study include:

- *Superior Performance:* TPOT-optimized ensembles outperformed all other models, achieving over 92% accuracy.

- *Generalizability:* The proposed models handled diverse datasets effectively, suggesting broad applicability in predictive diagnostics.
- *Automation Benefits:* AutoML drastically reduced the need for manual tuning and model engineering, enabling rapid deployment.

The proposed methodology is especially suited for medical domains where early and accurate detection is critical. While the models performed exceptionally well in offline experiments, further work is needed to transition them into clinical environments.

FUTURE SCOPE

Building on this research, several future directions are identified to further enhance practical applicability and reliability.

- *Interpretability Enhancements:* Incorporate SHAP and LIME to explain model predictions at the feature level and build clinician trust.
- *Edge Deployment:* Apply pruning, quantization, and knowledge distillation to compress models for deployment on resource-constrained devices such as IoMT sensors and mobile health apps.
- *Multimodal Data Fusion:* Extend the model to process and combine structured EHR data, medical images, and clinical text for holistic disease prediction.
- *Federated Learning:* Enable collaborative model training across institutions while preserving patient data privacy using federated learning protocols.
- *Rare Disease Detection:* Improve ensemble learning to handle highly imbalanced datasets using techniques like SMOTE or generative oversampling.
- *Clinical Validation:* Test the model on real-time hospital data and evaluate its integration into clinical decision support systems (CDSS).
- *AutoML Expansion:* Experiment with other AutoML frameworks, like H2O.ai, AutoKeras, and Google AutoML, for more refined architecture and parameter searches.

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