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# Noise-Robust Hybrid Machine Learning and Deep Learning Framework for Early Tuberculosis Detection from Cough Audio Recordings

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## Abstract

*Tuberculosis (TB) remains a major global health challenge, particularly in regions with limited access to rapid and reliable diagnostic facilities. Traditional diagnostic methods are often time-consuming, expensive, and require specialized infrastructure, which delays early detection. To address these limitations, this paper proposes a noise-robust hybrid framework for early tuberculosis detection using cough audio recordings. The system integrates preprocessing techniques for noise reduction, feature extraction using Mel-Frequency Cepstral Coefficients (MFCCs) and spectrograms, and classification using both machine learning models (Support Vector Machine, Random Forest) and deep learning architectures (Convolutional Neural Networks and CNN–RNN). An ensemble decision-making approach is employed to combine predictions from multiple models and improve reliability. Experimental results demonstrate that the proposed method achieves an accuracy of 94.8% and performs effectively even in noisy real-world conditions. The framework provides a scalable, cost-effective, and non-invasive solution for tuberculosis screening, making it suitable for deployment in resource-constrained environments.*

***Keywords:*** *Tuberculosis Detection; Cough Analysis; Machine Learning; Deep Learning; Ensemble Model.*

## 1. Introduction

Tuberculosis (TB) remains one of the leading infectious diseases worldwide, causing significant mortality, especially in developing countries [1]. Early detection is essential for effective treatment and to reduce transmission. However, conventional diagnostic methods such as sputum microscopy, chest X-rays, and molecular testing require laboratory infrastructure, skilled personnel, and considerable time, making them less accessible in resource-limited settings [2].Recent advancements in artificial intelligence have enabled the use of cough sound analysis as a non-invasive and cost-effective alternative for respiratory disease detection [3]. Machine learning approaches using handcrafted features such as Mel-Frequency Cepstral Coefficients (MFCCs) have demonstrated promising results [4], while deep learning models like Convolutional Neural Networks (CNNs) can automatically learn complex patterns from spectrogram representations [5]. Hybrid models combining CNN and Recurrent Neural Networks (RNNs) further improve performance by capturing both spatial and temporal features of cough signals [6].Despite these developments, existing approaches often struggle with real-world challenges such as background noise, recording variability, and limited generalization capability [7]. To address these limitations, this paper proposes a noise-robust hybrid framework that integrates machine learning and deep learning models with an ensemble decision-making approach. The proposed system aims to improve detection accuracy and robustness, making it suitable for practical tuberculosis screening applications.

## 2. Novelty and Contributions

The novelty of this work lies in integrating noise-aware signal processing with hybrid machine learning and deep learning models within an ensemble framework for tuberculosis detection from cough audio signals. Unlike existing approaches that rely solely on classical machine learning [1], [5] or deep learning models [3], [12], the proposed method combines both while incorporating noise-robust

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mechanisms to improve real-world performance [6], [11].

The main contributions are as follows:

- Development of a noise-resilient preprocessing pipeline for cough signal enhancement in real-world environments [6], [11].
- Extraction of key acoustic features such as MFCC, spectrogram, pitch, and energy for effective cough analysis [9], [13].
- Implementation of hybrid machine learning and deep learning models for improved classification performance [2], [3], [12].
- Use of an ensemble decision-making approach to enhance diagnostic reliability [14].
- Experimental validation demonstrating improved performance under noisy conditions [15].

## 3. Literature Review

Automated cough sound analysis has gained attention for respiratory disease detection. Early studies used handcrafted acoustic features such as MFCCs, spectral energy, and temporal parameters with traditional classifiers like Support Vector Machines and Random Forests [1], [5], [9]. While effective, these methods depend on manual feature design.With advancements in deep learning, data-driven approaches such as Convolutional Neural Networks (CNNs) have been widely used to analyze spectrograms and automatically extract discriminative features from cough signals [3], [2], [12]. Hybrid models combining CNN with recurrent architectures like LSTM and GRU further improve performance by capturing both spatial and temporal patterns [2], [13].However, most existing approaches are trained on clean datasets and perform poorly in real-world noisy conditions due to background noise and device variability [6], [11]. Additionally, reliance on single models limits robustness and generalization [14]. To address these challenges, this work proposes a noise-robust hybrid ensemble framework for improved tuberculosis detection in practical scenarios [15].

## 4. Problem Statement

Despite recent advancements, reliable tuberculosis detection using cough audio signals remains challenging [3], [10]. Real-world recordings are affected by environmental noise, background speech, and device variability, which degrade signal quality and reduce model performance [6], [11].Moreover, many existing approaches rely solely on either traditional machine learning or deep learning models, limiting their ability to generalize across diverse conditions [1], [12], [14]. Therefore, there is a need for a robust hybrid and ensemble-based framework capable of handling noisy data while maintaining high diagnostic accuracy in real-world scenarios [15].

## 5. Proposed Methodology

The proposed tuberculosis detection framework consists of five major stages

- Data Acquisition
- Preprocessing and Noise Reduction
- Feature Extraction
- Hybrid Classification
- Ensemble Decision Making

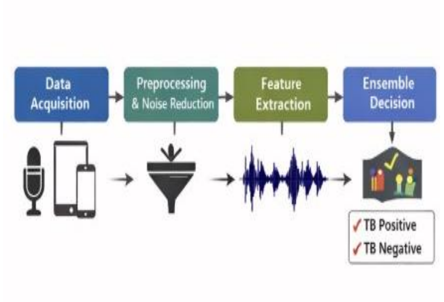


**Figure 1 Conceptual workflow of the proposed tuberculosis detection framework**

The system begins with the collection of cough recordings from real-world environments. The signals are preprocessed to remove noise and irrelevant segments. Acoustic features are then extracted and used to train both machine learning and deep learning models. Finally, predictions from multiple classifiers are combined using an ensemble strategy to generate the final detection result [14], [15].

### 5.1.Data Acquisition

Cough recordings are collected from tuberculosis-positive and healthy individuals using smartphones and low-cost devices in real-world conditions [13], [15].

### 5.2.Preprocessing and Noise Reduction

Preprocessing includes silence removal, band-pass

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filtering, spectral subtraction, and normalization to enhance signal quality and reduce noise [6], [11].

### 5.3.Feature Extraction

Features such asMFCC, spectrogram representations, pitch, energy, and zero-crossing rate are extracted to capture both spectral and temporal characteristics of cough signals. (Figure 2)

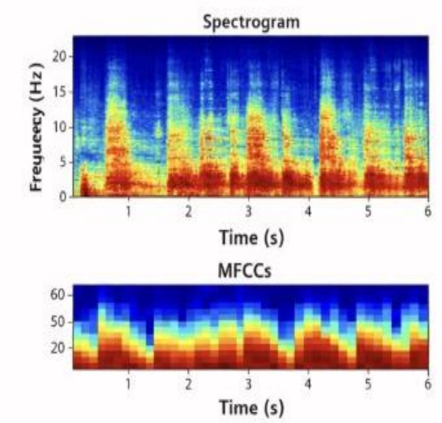


**Figure 2 Spectrogram and MFCC representation of cough audio signals used for feature extraction**

### 5.4.Hybrid Classification

The framework uses a combination of machine learning models (SVM, Random Forest) and deep learning models (CNN, CNN–RNN) to improve classification performance [1], [2], [3], [5], [12].

### 5.5.Ensemble Decision Making

Predictions from all models are combined using majority voting and weighted averaging to improve robustness and diagnostic accuracy, especially in noisy conditions (Figure. 3) [6], [14], [15].

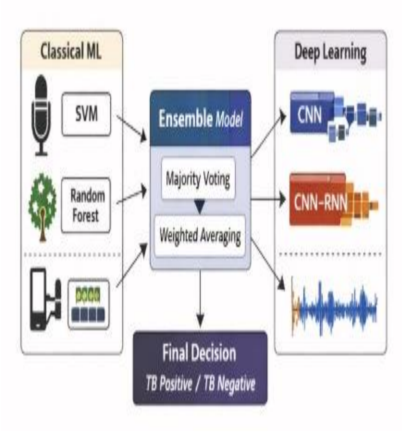


**Figure 3 A hybrid machine learning and deep learning ensemble classification model**

### 5.6.Algorithms

Algorithm 1: Proposed Noise-Robust Hybrid Framework

**Objective:**

To detect tuberculosis from cough audio signals using a noise-robust hybrid and ensemble framework.

**Input:** Raw cough audio recordings

**Output:** Tuberculosis detection result (TB Positive / TB Negative)

**Steps:**

1. Preprocess cough signals (noise removal and normalization) [6], [11], [13].
2. Extract MFCC and spectrogram features [1], [9].
3. Train ML (SVM, RF) and DL (CNN, CNN–RNN) models [2], [3], [5], [12].
4. Generate predictions from all models.
5. Apply ensemble (voting/averaging) to obtain final output [14], [15].

The models were trained using 50 epochs with a batch size of 32. The Adam optimizer and categorical cross-entropy loss function were used for deep learning models.

## 6. Experimental Setup and Evaluation Metrics

### 6.1.Dataset Description

The dataset consists of cough audio recordings collected from tuberculosis-positive and healthy individuals using publicly available datasets and mobile devices [9], [13], [15]. It includes 1750 cough samples, with 850 TB-positive and 900 healthy recordings. The data was collected at a sampling rate of 16 kHz and split into training (80%) and testing (20%) sets for model evaluation.

**Table 1 Summary of the Cough Audio Dataset**

| Category | Number of Samples |
|---|---|
| TB Positive | 850 |
| Healthy | 900 |
| Total | 1750 |
| Average Duration | 3–5 sec |

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### 6.2.Evaluation Metrics

The performance of the proposed system is evaluated using standard metrics, including Accuracy, Precision, Recall, F1-Score, and Area under the Curve (AUC), which are widely used in classification tasks [1], [10], [14]. These metrics provide a comprehensive assessment of the model's ability to correctly identify tuberculosis cases while minimizing false predictions.

## 7. Results and Discussion

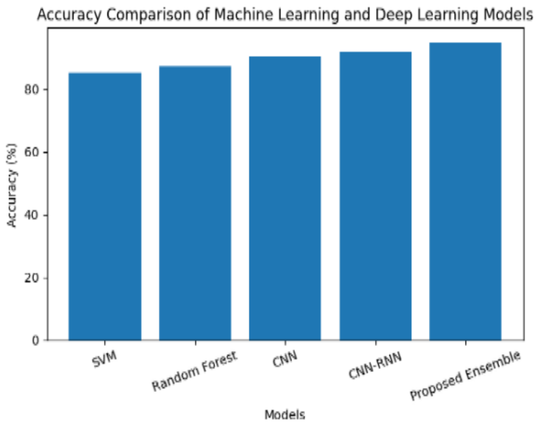


**Figure 4 Accuracy comparison of different machine learning and deep learning models for tuberculosis detection**

This framework is built based on the conventional approaches to carbon accounting, including LCA, GHG Protocol, and ISO. It assists in making emission calculations within the given boundaries and based on a particular functional unit and emission sources .The proposed approach creates a strong basis for achieving comparable results. It is characterized as static since it does not consider any real-world changes.

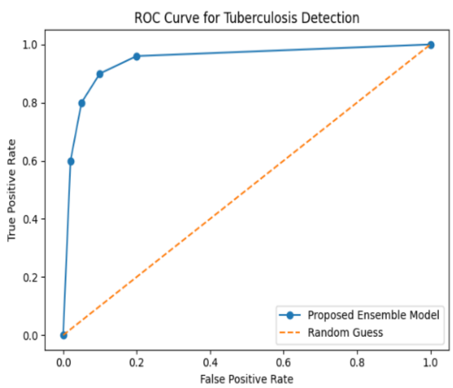


**Figure 5 Receiver Operating Characteristic (ROC) curve of the proposed ensemble model**

**Table 2 Performance Comparison of Different Model**

| Model | Accuracy (%) | Precision (%) | Recall (%) | F1-Score (%) |
|---|---|---|---|---|
| Support Vector Machine (SVM) | 85.2 | 84.6 | 83.9 | 84.2 |
| Random Forest | 87.4 | 86.8 | 86.1 | 86.4 |
| Convolutional Neural Network (CNN) | 90.6 | 89.8 | 89.3 | 89.5 |
| CNN–RNN Hybrid Model | 92.1 | 91.5 | 90.8 | 91.1 |
| Proposed Ensemble Model | 94.8 | 94.2 | 93.7 | 93.9 |

Classical machine learning models such as SVM and Random Forest provide moderate performance but are sensitive to noise and limited in capturing complex temporal patterns [1], [5], [6], [11]. Deep learning models improve performance by learning discriminative features from spectrogram data, with the CNN–RNN model achieving better results due to its ability to capture both spatial and temporal characteristics [2], [3], [12],[13]. The proposed ensemble model achieves the highest accuracy of 94.8% by combining predictions from multiple classifiers, reducing bias and improving robustness [14]. Noise-resilient preprocessing further enhances performance under real-world conditions [6], [15]. Overall, the results demonstrate that the proposed framework is effective for practical tuberculosis detection. A confusion matrix was also generated to

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evaluate classification performance in terms of true positives, false positives, true negatives, and false negatives.

## 8. Limitations

The proposed framework demonstrates high accuracy for tuberculosis detection using cough audio signals. However, certain limitations need to be considered. The performance of the system may be influenced by the size and diversity of the dataset used for training and evaluation. The current study utilizes a limited set of real-world recordings, and further validation on larger and more diverse populations is required to ensure generalization.Additionally, variations in recording devices, environmental noise, and user conditions may affect the quality of input signals, which can impact model performance. Addressing these challenges is essential for improving the robustness and scalability of the proposed system in real-world deployment scenarios [11].

## Conclusion

This paper presented a noise-robust hybrid framework for early tuberculosis detection using cough audio recordings collected in real-world environments [15]. The proposed approach addresses key challenges such as environmental noise, recording variability, and limited model generalization [6], [11].By integrating preprocessing, acoustic feature extraction, hybrid machine learning and deep learning models, and ensemble decision-making, the system achieves reliable diagnostic performance [2], [3], [14]. Experimental results show that the ensemble model outperforms individual classifiers, achieving higher accuracy and robustness under noisy conditions [1], [12], [14].Overall, the proposed framework provides a scalable, non-invasive, and cost-effective solution for tuberculosis screening, particularly in resource-constrained settings [10], [15]. This demonstrates the practical applicability of the proposed system for real-world tuberculosis screening.

## Future Work

Future work will focus on expanding the dataset and improving noise-robust learning techniques to enhance generalization. Advanced models such as attention-based and transformer architectures may be explored for better temporal feature learning. Additionally, integrating multimodal data and deploying the system as a mobile or web-based application can enable real-time and large-scale tuberculosis screening

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