

**Deep Learning and Automated Diagnostic Systems for Tuberculosis
Detection: A Comprehensive Study**

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Abstract

This study provides a comprehensive overview of tuberculosis (TB) as a major global public health concern and highlights the evolving role of advanced computational technologies in its diagnosis and management. Despite significant improvements in India's healthcare system, communicable diseases such as TB continue to pose serious challenges, particularly in low- and middle-income countries. The study emphasizes the epidemiology, transmission, symptoms and global burden of TB, with a special focus on India, which accounts for a substantial share of global cases. It further explores the limitations of traditional diagnostic methods and the growing importance of computerized and automated diagnostic systems. The integration of deep learning, machine learning and hybrid approaches such as genetic algorithms and neuro-fuzzy systems has significantly enhanced diagnostic accuracy, efficiency and early detection capabilities. These technologies enable faster processing of medical images, reduce human error and support clinical decision-making, especially in resource-constrained settings. The study concludes that the adoption of advanced artificial intelligence-based diagnostic tools, along with strong public health strategies, can play a crucial role in achieving the goal of tuberculosis elimination.

Keywords: Tuberculosis (TB), Deep Learning, Machine Learning, Computerized Diagnosis, Medical Image Processing, Neural Networks, Public Health, Automated Detection Systems, Genetic Algorithm, ANFIS

Introduction

Tuberculosis (TB) remains one of the most significant global public health challenges, particularly in developing countries such as India, where the burden of the disease is disproportionately high. Despite substantial advancements in healthcare infrastructure, medical technologies and public health initiatives, TB continues to pose serious threats to human health and economic productivity. India, being one of the fastest-growing economies, has witnessed considerable progress in improving healthcare delivery systems, including increased life expectancy, reduced mortality rates and better accessibility to medical services. However, communicable diseases, especially tuberculosis, continue to affect a large segment of the population, highlighting persistent gaps in disease control and management. Tuberculosis is an infectious disease caused by *Mycobacterium tuberculosis*, primarily affecting the lungs and spreading through airborne transmission. It is estimated that nearly one-quarter of the global population is infected with TB, making it one of the most widespread communicable diseases worldwide. Factors such as poverty, malnutrition, overcrowding and inadequate healthcare facilities contribute significantly to its transmission, particularly in low- and middle-income

countries. Although TB is preventable and curable, delayed diagnosis, poor treatment adherence and the emergence of drug-resistant strains such as multidrug-resistant TB (MDR-TB) and extensively drug-resistant TB (XDR-TB) have complicated its control.

Traditional diagnostic methods for tuberculosis, which rely heavily on manual examination and laboratory-based techniques, are often time-consuming, resource-intensive and prone to human error. These limitations are further exacerbated in rural and remote areas, where access to trained healthcare professionals and advanced diagnostic facilities is limited. As a result, there is an increasing need for efficient, accurate and cost-effective diagnostic solutions that can facilitate early detection and timely treatment of TB. In recent years, rapid advancements in artificial intelligence (AI), particularly in machine learning and deep learning, have opened new avenues for improving medical diagnostics. Deep learning models, such as convolutional neural networks (CNNs), have demonstrated remarkable success in image classification, object detection and pattern recognition tasks, making them highly suitable for analyzing medical images such as chest X-rays and sputum smear microscopy images. These models can automatically extract relevant features from complex datasets, reducing the need for manual intervention and improving diagnostic accuracy. Furthermore, the integration of deep learning with advanced computational techniques, including genetic algorithms and adaptive neuro-fuzzy inference systems (ANFIS), has further enhanced the efficiency and reliability of TB detection systems. These hybrid approaches combine the strengths of different methodologies to achieve better optimization, improved decision-making and higher classification accuracy. Additionally, computerized and automated diagnostic systems enable faster processing, standardized analysis and effective storage of patient data, thereby supporting healthcare professionals in clinical decision-making and disease management. Therefore, this study aims to explore the role of deep learning and automated diagnostic systems in tuberculosis detection, highlighting their potential to overcome the limitations of conventional methods. By examining recent advancements, challenges and future prospects, the study emphasizes the importance of integrating technology with public health strategies to achieve effective disease control and ultimately contribute to the global goal of tuberculosis elimination.

India is among the fastest-growing economies in the world, experiencing significant transformation across various dimensions, including economic, educational, demographic and health sectors. A substantial portion of household income is spent on essential needs such as food, shelter, education and health-related social security. The government has undertaken several major initiatives to improve the standard of living of the general population; however, according to the World Health Organization (WHO), the expected outcomes are yet to be fully achieved. [1] Over the past few decades, the health sector in India has undergone considerable changes in the healthcare delivery system. Notable improvements include an increase in life expectancy, a decline in maternal mortality rate, infant mortality rate and under-five mortality rate, eradication of several diseases and enhanced accessibility to healthcare services. [2] Despite these advancements, the spread of communicable and non-communicable diseases remains a major public health concern in both urban and rural areas. Future projections suggest that these diseases may pose a significant threat to global health security. Managing chronic

and epidemic diseases such as HIV, tuberculosis, malaria, COVID-19, influenza, respiratory disorders and diarrheal diseases continues to be a challenge for healthcare systems. Prior to the outbreak of COVID-19, tuberculosis (TB) was the leading cause of death from infectious diseases worldwide, surpassing even HIV infection. It is estimated that more than one-quarter of the global population is infected with TB, making it one of the most prevalent communicable diseases. However, tuberculosis is both preventable and curable and approximately 85 percent of diagnosed patients can recover completely with proper treatment adherence. At the same time, non-communicable diseases have emerged as a major cause of mortality and are increasing rapidly. Sedentary lifestyles, unhealthy dietary habits and substance abuse, including alcohol, tobacco and drugs, significantly increase the risk of illness among otherwise healthy individuals.

Tuberculosis (TB) remains one of the most significant global public health concerns, with approximately one-quarter of the world's population infected with the disease. It is among the leading causes of death from infectious diseases, second only to COVID-19 in recent years. In 2020, tuberculosis was responsible for approximately 1.5 million deaths worldwide and nearly 10 million people developed the disease. TB spreads from person to person through airborne transmission and can easily cross national borders. Factors such as overcrowding, poor ventilation and malnutrition significantly contribute to its transmission. The disease is present in almost all countries and affects individuals across all age groups.

Global estimates indicate that about 86% of all TB cases occur in countries with the highest disease burden. Nearly two-thirds of new cases are concentrated in eight countries: India (26%), China (8.5%), Indonesia (8.4%), the Philippines (6.0%), Pakistan (5.7%), Nigeria (4.6%), Bangladesh (3.6%) and South Africa (3.3%). The global number of individuals infected with TB was estimated to reach approximately 2.59 billion in 2021, with low- and middle-income countries bearing the greatest burden of the disease. Tuberculosis is caused by the bacterium *Mycobacterium tuberculosis*, which can affect various parts of the body; however, pulmonary tuberculosis (PTB) is the most common form. It is transmitted through droplet nuclei released by infected individuals. Early detection and effective treatment are essential to prevent disease transmission, as a person with untreated pulmonary tuberculosis can infect 10 to 15 individuals annually. Although tuberculosis is curable with appropriate medication, strict adherence to the prescribed treatment regimen is necessary to ensure complete recovery and prevent complications. The emergence of drug-resistant forms of tuberculosis, including multidrug-resistant TB (MDR-TB) and rifampicin-resistant TB (RR-TB), has become a major global concern. In India, approximately 130,000 cases of drug-resistant TB were reported in 2018, but only 46,569 patients received treatment. A significant proportion of MDR-TB cases remained untreated or undiagnosed, highlighting gaps in detection and management. Drug resistance may develop due to various factors, including poor treatment adherence, adverse drug reactions, inadequate absorption of medications and behavioral factors. [4] Extensively drug-resistant tuberculosis (XDR-TB) has been reported in most high-prevalence countries and poses a serious threat to global public health. Since 2011, India has witnessed a rising number of XDR-TB cases, with estimates suggesting that more than 8,000 new cases emerge annually.

[5] The bacteria responsible for MDR-TB and XDR-TB are more difficult to treat than drug-sensitive TB and require prolonged and complex chemotherapy regimens, which are often more expensive and associated with severe adverse drug reactions. Although the implementation of effective control strategies, along with improvements in social and economic conditions, has significantly reduced the burden of tuberculosis in many developed countries, low- and middle-income countries continue to face TB as a major public health challenge. In India, it is estimated that more than half of incident TB cases are attributable to undernutrition, highlighting the strong association between nutritional status and disease prevalence. In 2014, the World Health Assembly adopted the End TB Strategy, developed by the World Health Organization (WHO), with the objective of ending the global tuberculosis epidemic by 2035. The strategy aims to reduce TB deaths by 95 percent and decrease the incidence rate by 90 percent, while ensuring that no family faces catastrophic financial burdens due to tuberculosis. This initiative reflects a strong global commitment to eliminating TB and strengthening public health systems worldwide. In India, both government and private healthcare sectors play a crucial role in providing treatment and care for tuberculosis patients. The Revised National Tuberculosis Control Programme (RNTCP) in the public sector has been modernized and renamed the National Tuberculosis Elimination Programme (NTEP). India has committed to eliminating tuberculosis by 2025, which is five years ahead of the target set under the United Nations Sustainable Development Goals (SDGs). [6] The tuberculosis control programme in India has undergone significant transformation in recent years, leading to substantial improvements in service delivery and patient care. The programme now emphasizes a patient-centered approach and focuses on providing comprehensive supportive treatment and care. The Ministry of Health and Family Welfare (MoHFW) developed the National Strategic Plan (NSP) for Tuberculosis Elimination (2017–2025), which builds upon the achievements and lessons learned from previous strategies and outlines innovative measures to eliminate tuberculosis in India.

Tuberculosis (TB)

Tuberculosis (TB) is an infectious disease caused by the bacterium *Mycobacterium tuberculosis*. It primarily affects the lungs and is a potentially serious condition that spreads easily from person to person. TB is an airborne disease transmitted through respiratory droplets released when an infected individual coughs, sneezes, speaks, spits, or performs similar actions. The disease mainly affects the lungs, a condition known as pulmonary tuberculosis. However, it can also spread to other parts of the body, resulting in extra-pulmonary tuberculosis, which may involve organs such as the brain, spinal cord, kidneys, nervous system and other body systems. The tuberculosis bacterium is characterized by its rod-shaped structure, moderate growth rate and variable curvature, with a length ranging from approximately 1 μm to 10 μm . Figure 1.1 presents a representative image of TB bacilli in the lungs. The major symptoms of tuberculosis include a persistent cough lasting more than three weeks, coughing up blood, loss of appetite, fever, fatigue, weight loss, night sweats and chest pain. If left untreated, tuberculosis can lead to severe complications and may eventually result in death. Recovery from TB requires strict adherence to a prescribed course of multiple medications over several months. [9]

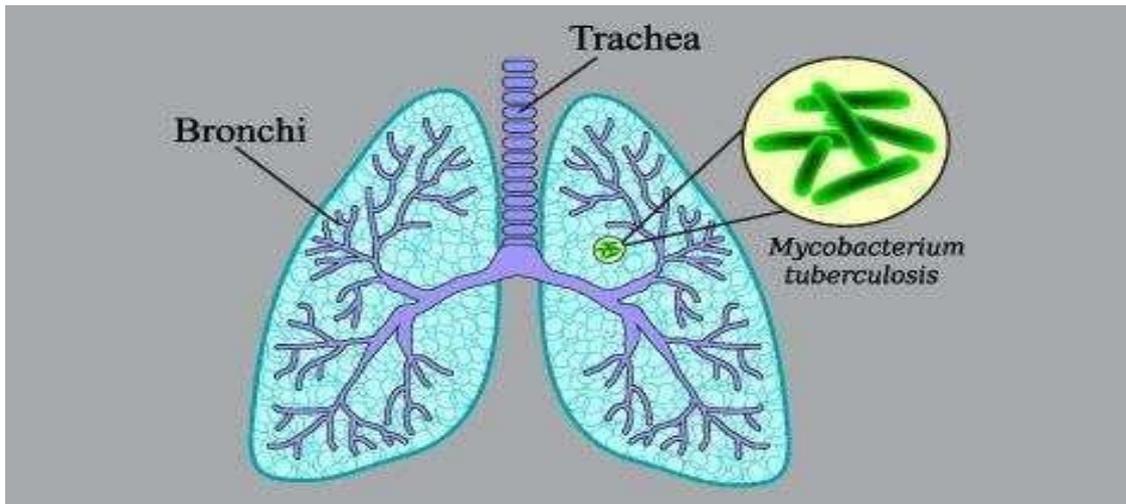


Figure 1.1: TB bacilli in lungs (Image Source: Rodriguez, 2016).

The figure 1.1 displays the microscopic appearance of *Mycobacterium tuberculosis*, the bacterium responsible for causing tuberculosis (TB).

The World Health Organization (WHO) reported in 2019 that approximately one-fourth of the world's population is infected with tuberculosis (TB). Since 1997, the WHO has been publishing the Global Tuberculosis Report, which provides updated assessments of the progress made in controlling the TB epidemic at global, regional and national levels. According to the WHO Global Tuberculosis Report (2020), an estimated 10 million people worldwide were affected by tuberculosis.

Tuberculosis affects individuals of all age groups, including children and adults. However, certain demographic groups show higher vulnerability. According to WHO (2019), TB prevalence was reported among children (11%), women (32%) and men (57%), indicating that adults, particularly males, are more commonly affected. The majority of TB cases and deaths occur in developing countries, with the highest burden observed in India (27%), followed by China (14%), Indonesia (8%) and the Philippines (6%). Due to its widespread impact and serious public health consequences, the World Health Organization has declared tuberculosis a global health emergency. Estimates reflecting the national burden of tuberculosis are illustrated in Figure 1.2.

Medical professionals generally classify tuberculosis into two main categories: active tuberculosis and latent tuberculosis. Active TB is the most severe form of the disease and can be fatal if not treated properly. Latent tuberculosis, also referred to as silent TB, occurs when the infection remains inactive within the body without causing symptoms and cannot be transmitted to others. However, latent TB may progress to active disease, particularly among individuals with weakened immune systems.

Computerized TB Detection System

In recent years, computer-assisted diagnostic technologies have been increasingly adopted in the healthcare sector to provide high-quality and cost-effective treatment. Conventional diagnostic procedures that rely on manual examination of specimens are often time-consuming and prone to human error, which may affect diagnostic accuracy. Studies suggest that

diagnostic errors contribute significantly to patient mortality, with reports indicating that at least one out of twelve patients may die due to incorrect diagnosis. [21] Furthermore, many rural and remote areas face a shortage of qualified and well-trained medical technicians, which further limits the efficiency and reliability of traditional diagnostic methods. In such situations, computer-assisted diagnostic tools or automated diagnostic systems serve as valuable solutions. These technologies help overcome human limitations by improving diagnostic accuracy, reducing processing time and enhancing clinical decision-making. Automation in healthcare diagnostics offers several advantages, particularly increased precision and faster decision-making. Automated systems minimize human intervention, standardize diagnostic procedures and ensure consistent and reliable results. Additionally, previous studies [22] have highlighted several key benefits of automated diagnostic systems, including:

—(i) improved safety of patients, (ii) improved efficiency in healthcare outcome and (iii) improved quality of care.

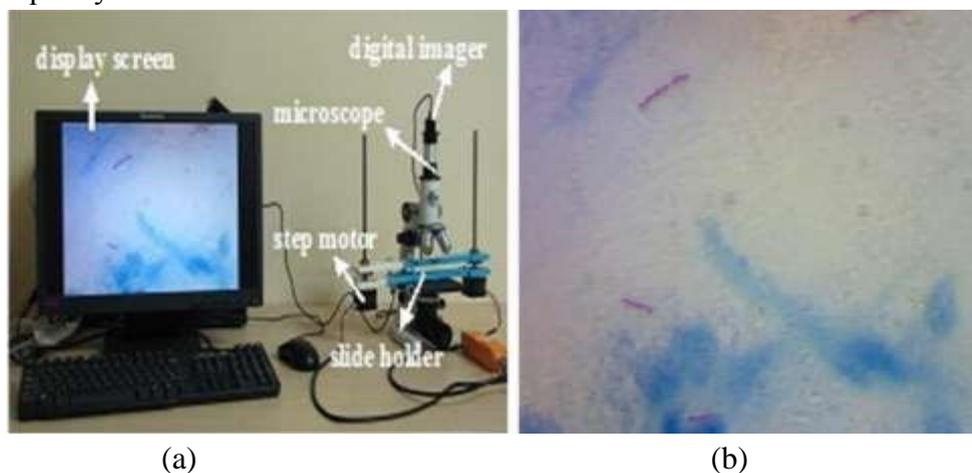


Figure 1.5: Computerized TB detection system (a) and acquired TB image (b).

Modern automated diagnostic technologies are capable of screening a large number of microscopic fields on a slide in accordance with World Health Organization (WHO) guidelines and can detect active tuberculosis cases at an early stage. These technologies significantly reduce screening time, improve diagnostic accuracy and facilitate faster clinical decision-making, thereby enhancing overall efficiency and productivity. In addition, automated systems enable the storage of patient data and microscopic images, allowing healthcare professionals to easily access treatment history and monitor disease progression for individual patients. As a result, many healthcare institutions are increasingly adopting computerized medical diagnostic systems and automated instruments to improve clinical quality and service delivery. One such innovation is the automated tuberculosis detection system, which serves as a supportive tool for healthcare professionals, particularly physicians and laboratory technicians involved in TB diagnosis. These systems automatically detect tuberculosis bacilli using microscopic images of sputum smear samples. A typical computerized TB detection system consists of several components, including a computer or laptop, a microscope, a stepper motor, a slide holder and a digital imaging device. The stepper motor is primarily used for the automatic focusing of the microscope, ensuring the capture of clear and precise images. A digital camera attached to the

microscopic eyepiece is used to capture images of TB bacilli, enabling digital recording and retrieval of patient records. A representative image of the system and the acquired TB sample is illustrated in Figure 1.5. Additional benefits of computerized TB detection systems have been discussed in the introduction section.

Deep Learning

Early research on neural networks was primarily motivated by the goal of developing computer systems capable of mimicking the functioning of the human brain. This objective led to the emergence of artificial neural networks as computational models inspired by biological neurons. Since the 1950s, when the concept of the perceptron was introduced [43], the foundations of deep learning have been established. The perceptron, based on the functioning of human neurons, served as the fundamental building block of early neural network models and was successfully applied to tasks such as character recognition. Building upon this concept, more advanced learning techniques were developed over time, leading to extensive research in cognitive learning and neural network architectures. Artificial neural networks consist of multiple layers of interconnected processing units (neurons), commonly referred to as perceptrons. These networks are typically trained using optimization techniques such as backpropagation, which enables efficient adjustment of network parameters. Subsequently, convolutional neural networks (CNNs) were developed and successfully applied to handwriting recognition, laying the foundation for modern character recognition systems. With recent advancements in artificial intelligence, cutting-edge machine learning techniques based on deep architectures have been developed. Deep learning refers to the use of deep neural networks composed of multiple hidden layers between input and output layers. These layers are interconnected and each layer processes input data, extracts relevant information and passes the results to the subsequent layer. Through hierarchical learning, each layer progressively extracts more abstract features, beginning with basic elements such as edges, lines and color gradients and advancing to more complex representations.

Deep learning models are particularly effective in tasks such as image segmentation, object recognition and image classification, as they can directly analyze raw input data (e.g., RGB images) and automatically learn meaningful feature representations. Unlike traditional machine learning methods that rely on manually engineered features, deep learning techniques learn representations automatically, thereby reducing human intervention and improving model performance. Due to their ability to extract meaningful patterns from large-scale data, deep learning methods have achieved remarkable success in computer vision and natural language processing applications. In recent years, deep learning models have significantly outperformed traditional machine learning approaches across various domains. They have established new benchmarks in tasks such as object detection, motion tracking, activity recognition, human pose estimation and instance recognition. Among these applications, image classification remains one of the most fundamental and widely studied tasks in computer vision. Deep learning has demonstrated its ability to address complex challenges that conventional machine learning techniques struggle to solve and is increasingly being applied to large-scale scientific problems. It has emerged as one of the most prominent research areas in modern artificial

intelligence. Although deeper neural networks generally offer improved performance, they require substantial computational resources and are more difficult to train. However, advancements in parallel computing technologies, particularly Graphics Processing Units (GPUs), along with the availability of large-scale, high-quality labeled datasets, have significantly accelerated the training of deep learning models. Furthermore, powerful software frameworks such as TensorFlow have facilitated rapid model development and prototyping, enabling the construction of large neural networks with millions of parameters. Significant progress has also been made in network architecture design, optimization techniques and training methodologies. Deep learning has shown exceptional potential in the analysis of microscopic images, including applications such as nuclei detection, cell segmentation and tissue segmentation. In recent years, it has gained considerable attention, particularly in image classification tasks, due to its ability to learn hierarchical feature representations and uncover hidden patterns within high-dimensional image data. While traditional machine learning approaches require extensive feature engineering, deep learning significantly reduces or eliminates this requirement. Overall, deep learning has emerged as a highly promising approach for microscopy image analysis and is currently regarded as one of the most effective techniques for solving complex problems in medical image processing and computer vision.

Rajesh S. Prasad et.al.(2023) [47] this review paper aims to provide a comprehensive overview of existing studies that compare the application of machine learning (ML) and deep learning (DL) techniques in the diagnosis of tuberculosis (TB). Numerous studies have demonstrated the significant potential of deep learning methods in TB detection, classification and prediction. The review examines various deep learning models employed for TB diagnosis, including convolutional neural networks (CNNs), recurrent neural networks (RNNs) and hybrid models that combine multiple approaches. The study also explores different types of datasets used in TB diagnosis, such as genomic data, chest X-ray images and sputum smear microscopy images. Furthermore, it evaluates the advantages and limitations of each deep learning technique and compares their performance across different TB datasets, thereby providing insights into their effectiveness and reliability. In addition, the review discusses current challenges and future research directions in the application of deep learning for tuberculosis diagnosis. The authors emphasize that the findings of this study may serve as a valuable resource for researchers, clinicians and healthcare professionals working in the field of tuberculosis detection and medical image analysis.

Juveriya Parmar et.al. (2023) [48] early detection of *Mycobacterium tuberculosis* is essential for reducing the spread of tuberculosis and improving disease control. This study proposes a machine learning–based, label-free graphene-based refractive index biosensor for the detection of *Mycobacterium tuberculosis*. The proposed biosensor design allows optimization of several structural parameters to enhance sensitivity, including substrate thickness, resonator thickness and incident angle. Machine learning techniques are employed to predict absorption characteristics at different wavelengths. The proposed model considers four key parameters: the contact angle between the biosensor and the surface, substrate thickness, resonator thickness and the chemical potential of graphene. To improve detection sensitivity, the plus-

shaped metasurface structure is coated with a hybrid layer of graphene and silicon dioxide. The performance of this design is evaluated and compared with previously developed sensor configurations. The proposed sensor demonstrates high sensitivity and shows potential for biomedical applications, particularly in the detection of *Mycobacterium tuberculosis*. The predictive performance of the K-Nearest Neighbour (KNN) regression model is evaluated to estimate absorption values at intermediate wavelengths. Two test scenarios, namely R-50 and U-50, are used to assess the performance of the regression models, with varying values of K considered. Model accuracy is evaluated using the coefficient of determination (R^2 score). Experimental results indicate that the KNN regression model achieves highly accurate predictions, particularly when smaller values of K are used.

Integration of Deep Learning with Advanced Algorithms in TB Diagnosis

Integrating additional algorithms with neural networks can further enhance their performance. Techniques such as fuzzy logic, genetic algorithms and artificial immune systems have been combined with neural networks to improve diagnostic accuracy. These hybrid approaches have been successfully applied in the detection of tuberculosis, demonstrating their effectiveness in medical diagnosis.

Adaptive Neuro-Fuzzy Inference System

Fuzzy logic (FL) enables the simultaneous processing of both qualitative and quantitative inputs. It operates through a rule-based mapping mechanism that converts multiple input values into a single output, where the relationship between numerical values is defined through mapping functions. In knowledge-based systems, fuzzy logic incorporates human reasoning abilities to support decision-making processes. While neural networks are highly effective in data classification, pattern recognition and prediction, they often lack interpretability. In contrast, fuzzy systems provide clear reasoning and justification for decisions but have limited adaptability to dynamic environments. To improve tuberculosis detection, an Adaptive Neuro-Fuzzy Inference System (ANFIS) has been applied, which combines neural networks with fuzzy logic. This system uses TB symptoms as input variables and generates outputs such as sputum analysis results, chest X-ray findings and weight loss indicators through a rule-based framework. It is particularly useful in remote areas where access to medical professionals is limited. The system was further enhanced by developing an ANFIS model with 159 rules and a backpropagation algorithm to minimize output errors. A triangular fuzzifier and MATLAB implementation were also used for data processing. In another study, eleven TB symptoms were used as inputs and the model employed a trapezoidal membership function along with backpropagation for evaluation, demonstrating efficient learning and accurate diagnostic performance.

Genetic Algorithm with Deep Learning

Genetic algorithms (GAs) are bio-inspired optimization techniques commonly used to solve complex search problems. They operate using evolutionary principles such as selection, mutation and crossover to identify optimal solutions. In this approach, a population of potential solutions is randomly generated and evaluated using a fitness function, which determines the quality of each solution. The best-performing individuals are selected and reproduced, while

weaker ones are eliminated, following the principle of “survival of the fittest.” This iterative process continues across multiple generations to improve results. Compared to neural networks, genetic algorithms require less input information and are widely applied in artificial intelligence for searching optimal solution subsets. The application of genetic algorithms in tuberculosis diagnosis has also been explored. In one study, nine important features were selected using a genetic algorithm and combined with a neural network trained through a backpropagation classifier based on the Levenberg–Marquardt algorithm. The GA-NN model achieved a classification accuracy of 96.3% on test data. Additionally, hybrid models integrating genetic algorithms with artificial neural networks have been developed for diagnosing chest diseases, including tuberculosis. These models evaluate output errors and error gradients using backpropagation and have demonstrated effectiveness in supporting early detection of tuberculosis.

Conclusion

Tuberculosis remains one of the most serious infectious diseases globally, with a disproportionately high burden in developing countries such as India. Although it is both preventable and curable, challenges such as delayed diagnosis, drug resistance and lack of healthcare resources continue to hinder effective disease control. The study demonstrates that traditional diagnostic methods alone are insufficient to address the growing complexity of TB detection and management. The integration of advanced technologies, particularly deep learning and automated diagnostic systems, has significantly improved accuracy, speed and reliability in TB diagnosis. Hybrid approaches combining neural networks with optimization and fuzzy logic techniques further enhance system performance and adaptability. These innovations are especially beneficial in rural and underserved areas where access to skilled healthcare professionals is limited. However, successful implementation requires adequate infrastructure, data availability and policy support. Overall, a combined approach involving technological advancement, public health initiatives and patient-centered care is essential to achieve the long-term goal of tuberculosis elimination and improved global health outcomes.

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