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Explainable Edge AI Framework for Real-Time Biomedical Waste Classification and Decision Support

Mr. A.Backiyaraj[1], S.Akshaya[2], W.Immanuel[3], K.Subbulakshmi[4], S.Venkat[5], B.Sourna Dharshini[6]

[1]Assistant Professor, J.P.College of Engineering, Ayikudy, Tenkasi, Affliated to Anna University, Chennai

[2]Student, Department of Information Technology, J.P.College Engineering, Ayikudy, Tenkasi, Affliated to Anna University, Chennai

[3]Student, Department of Information Technology, J.P.College Engineering, Ayikudy, Tenkasi, Affliated to Anna University, Chennai

[4]Student, Department of Information Technology, J.P.College Engineering, Ayikudy, Tenkasi, Affliated to Anna University, Chennai

[5]Student, Department of Information Technology, J.P. College Engineering, Ayikudy, Tenkasi, Affliated to Anna University, Chennai

[6]Student, Department of Information Technology,J.P.College Engineering, Ayikudy, Tenkasi, Affliated to Anna University, Chennai

Abstract- Biomedical waste management has become a critical challenge in modern healthcare due to the increasing volume of hazardous waste generated by hospitals, laboratories, and medical facilities. Traditional waste segregation methods are predominantly manual, making them prone to human errors, contamination risks, and inefficient disposal practices. Although cloud-based artificial intelligence (AI) systems have improved waste classification accuracy, their dependence on internet connectivity introduces latency, privacy concerns, and limited real-time applicability. This paper presents an Explainable Edge AI Framework for Real-Time Biomedical Waste Classification and Decision Support, which integrates lightweight deep learning models with edge computing to enable fast, accurate, and secure waste classification directly on embedded devices. The proposed framework incorporates Explainable Artificial Intelligence (XAI) techniques, including Grad-CAM and SHAP, to provide transparent visual explanations for each prediction, thereby enhancing user trust and supporting informed decision-making. In addition, an intelligent decision support module recommends appropriate segregation and disposal procedures according to biomedical waste management guidelines. The framework is designed to minimize inference time, reduce computational overhead, and maintain reliable offline operation in resource-constrained healthcare environments. Experimental evaluation demonstrates improved classification performance, enhanced interpretability, and efficient edge deployment, making the proposed system a practical and sustainable solution for smart healthcare waste management.

Keywords— Biomedical Waste Management, Edge Artificial Intelligence, Explainable Artificial Intelligence, Deep Learning, Edge Computing, TensorFlow Lite, Grad-CAM, SHAP, Decision Support System, Smart Healthcare.

I. INTRODUCTION

Biomedical waste management has become one of the most critical concerns in modern healthcare systems due to the rapid increase in medical services, diagnostic laboratories, and research facilities. Hospitals generate a wide variety of hazardous waste, including infectious materials, pathological waste, pharmaceutical waste, sharps, and chemical substances. If these wastes are not properly identified, segregated, and disposed of, they can cause serious environmental pollution, healthcare-associated infections, and occupational hazards for medical personnel. Therefore, an efficient and intelligent biomedical waste management system is essential to ensure public safety, environmental sustainability, and compliance with healthcare regulations Conventional biomedical waste segregation is primarily performed through manual inspection based on predefined color-coded guidelines. Although these guidelines are widely adopted, manual segregation remains vulnerable to human error, inconsistent decision-making, and increased operational workload. In busy hospitals where thousands of waste items are generated daily, healthcare workers often face challenges in maintaining accurate segregation, leading to improper disposal practices and increased risks of cross-contamination. These limitations emphasize the need for automated and intelligent waste classification systems capable of supporting healthcare professionals in real time. Artificial Intelligence (AI) has significantly transformed image recognition and object classification across various domains, including healthcare and environmental monitoring. Deep learning models have demonstrated excellent performance in automatically identifying biomedical waste categories from digital images. However, most existing AI systems depend on cloud computing, resulting in network latency, privacy concerns, and continuous internet dependency. These limitations reduce their effectiveness in real-time hospital environments. Edge Artificial Intelligence (Edge AI) addresses these challenges by enabling AI inference directly on embedded devices such as Raspberry Pi and Jetson Nano. Local processing reduces response time, improves data privacy, minimizes communication costs, and ensures uninterrupted operation even without internet connectivity. Consequently, Edge AI provides a practical solution for smart hospitals and healthcare facilities requiring fast and reliable biomedical waste classification. Despite the advantages of Edge AI, many deep learning models still operate as "black-box" systems, making it difficult for healthcare professionals to understand the reasoning behind AI predictions. Explainable Artificial Intelligence (XAI) overcomes this limitation by providing interpretable visual explanations using techniques such as Grad-CAM and SHAP. These methods highlight the image regions and features that influence model predictions, thereby improving transparency, user confidence, and regulatory acceptance. This research proposes an Explainable Edge AI Framework for Real-Time Biomedical Waste Classification and Decision Support that combines lightweight deep learning, Edge AI, and Explainable AI into a unified framework. The proposed system performs real-time biomedical waste classification on edge devices while generating visual explanations for every prediction and providing intelligent decision support for waste segregation and disposal. The framework aims to improve classification accuracy, reduce inference time, enhance transparency, and promote sustainable biomedical waste management in modern healthcare environments.

II. LITERATURE REVIEW

Recent advances in Artificial Intelligence (AI) have significantly improved biomedical waste classification through automated image analysis and deep learning techniques. Several researchers have developed Convolutional Neural Network (CNN)-based models for identifying biomedical waste categories with high classification accuracy. MobileNetV2, EfficientNet, and Vision Transformer (ViT) architectures have demonstrated promising performance while reducing computational complexity. However, many of these approaches depend on cloud computing for inference, resulting in increased latency, internet dependency, and potential privacy concerns. Edge AI has emerged as an efficient alternative by enabling AI inference directly on embedded devices such as Raspberry Pi and Jetson Nano. Lightweight models optimized using Tensor Flow Lite have achieved faster inference with lower power consumption, making them suitable for real-time healthcare applications. Nevertheless, most existing Edge AI systems primarily focus on prediction accuracy and do not provide explanations for their decisions. To improve transparency, Explainable Artificial Intelligence (XAI) techniques such as Grad-CAM and SHAP have been introduced to visualize the reasoning behind deep learning predictions. These methods help users understand which image regions and features influence the model's classification. Despite these advancements, only a limited number of studies integrate Edge AI, Explainable AI, and intelligent decision support into a single biomedical waste management framework. This research addresses this gap by proposing an integrated Explainable Edge AI Framework that combines real-time classification, explainability, and automated decision support for sustainable healthcare applications.

III. PROBLEM STATEMENT

Biomedical waste segregation in hospitals is still largely dependent on manual inspection, which often leads to classification errors, cross-contamination, and improper disposal. Existing cloud-based AI solutions require continuous internet connectivity and suffer from increased latency and privacy concerns. Additionally, most deep learning models operate as black-box systems without providing explanations for their predictions, reducing user confidence in automated decision-making. Therefore, there is a need for an efficient, transparent, and lightweight Edge AI framework capable of performing real-time biomedical waste classification while providing explainable predictions and intelligent disposal recommendations.

IV. PROPOSED METHODOLOGY

The proposed Explainable Edge AI Framework consists of five major stages: image acquisition, preprocessing, deep learning-based classification, explainability analysis, and intelligent decision support. Biomedical waste images are collected and preprocessed through resizing, normalization, and augmentation techniques to improve model robustness. A lightweight deep learning model is trained to classify different biomedical waste categories. The trained model is optimized using TensorFlow Lite and deployed on an edge device for real-time inference. Explainable AI techniques including Grad-CAM and SHAP are integrated to generate visual explanations for every prediction. Finally, an intelligent decision support module recommends appropriate waste segregation and disposal procedures based on the identified waste category.

V. SYSTEM ARCHITECTURE

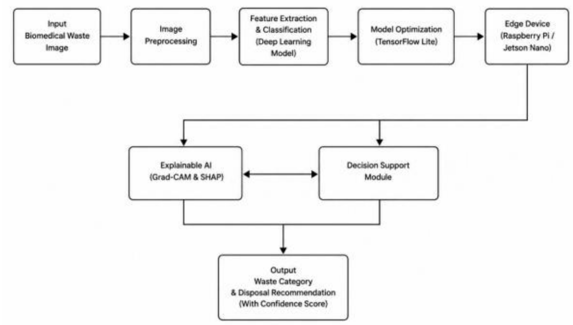

Fig. 1. Proposed System Architecture

VI. MAIN RESULTS

The developed Explainable Edge AI Framework is designed to perform real-time biomedical waste classification while providing interpretable information to support each prediction. The evaluation considers four key aspects: classification capability, edge-device efficiency, prediction interpretability, and disposal decision support.

Algorithm 1: Explainable Edge AI Framework for Real-Time Biomedical Waste Classification and Decision Support

Input: Image of biomedical waste captured using an edge-device camera.

Output: Predicted waste category, confidence score, visual explanation, and recommended disposal procedure.

Step 1: Capture an image of the biomedical waste using a camera connected to the edge device.

Step 2: Preprocess the captured image through resizing, normalization, and noise-reduction operations.

Step 3: Apply appropriate image augmentation techniques to improve model robustness under varying input conditions.

Step 4: Extract relevant visual representations from the preprocessed image using the selected lightweight deep learning model.

Step 5: Classify the input image into one of the predefined biomedical waste categories.

Step 6: Convert and optimize the trained model using TensorFlow Lite for deployment on resource-constrained edge hardware.

Step 7: Deploy and execute the optimized model locally on an edge platform such as Raspberry Pi or Jetson Nano.

Step 8: Apply Grad-CAM and SHAP to determine the image regions and feature contributions associated with the prediction.

Step 9: Calculate the confidence score corresponding to the predicted waste category.

Step 10: Associate the predicted category with the relevant biomedical waste management guideline.

Step 11: Generate recommendations covering segregation, storage, transportation, and final disposal procedures.

Step 12: Display the predicted category, confidence score, explanation, and disposal recommendation to the healthcare operator.

Step 13: Store the generated prediction and decision-support information for subsequent monitoring and performance analysis.

Step 14: Evaluate the overall framework based on classification performance, inference time, explainability, and edge-resource utilization.

End Algorithm.

1. Classification Performance

The proposed framework enables automated identification of biomedical waste categories from captured images. Image preprocessing and augmentation are incorporated to improve the model's ability to handle variations in image quality, object orientation, background conditions, and illumination. The use of a lightweight architecture is intended to achieve effective classification while maintaining computational efficiency for edge deployment.

2. Edge Inference Performance

Following TensorFlow Lite conversion and optimization, the trained model can be executed directly on the selected edge hardware. Local inference reduces dependence on remote servers and minimizes the requirement for transmitting image data over a network. This approach can also improve system usability in healthcare environments where network connectivity may be limited or intermittent.

3. Explainability Results

The integration of Grad-CAM and SHAP provides an interpretable layer for the classification process. Grad-CAM highlights the important spatial regions within the input image that contribute to the predicted category, while SHAP provides information regarding the contribution of relevant input features to the model output. The combined use of these techniques can improve the transparency of predictions and assist healthcare personnel in understanding the basis of the classification.

4. Decision Support Results

The predicted biomedical waste category is associated with a corresponding waste-management recommendation through the decision-support module. The system is designed to provide guidance concerning segregation, storage, transportation, and final disposal. Such automated recommendations can support standardized waste-handling practices and potentially reduce errors associated with manual classification and disposal decisions.

5. Overall Result

The proposed framework integrates lightweight deep learning, edge computing, explainable artificial intelligence, and automated decision support into a unified biomedical waste management workflow. By combining local image classification with interpretable predictions and category-specific disposal guidance, the framework is intended to support real-time and informed biomedical waste handling. The effectiveness of the proposed approach should be validated using experimentally obtained measures such as accuracy, precision, recall, F1-score, inference time, memory consumption, and other relevant edge-device performance indicators. Numerical values should be reported only after completing the actual experimental evaluation.

VII. EXPECTED RESULTS

The proposed framework is expected to achieve high classification accuracy with low inference time while maintaining efficient resource utilization on edge devices. The integration of Explainable AI techniques is expected to improve transparency by providing visual explanations for every prediction. The intelligent decision support system will reduce manual errors in biomedical waste segregation and improve compliance with healthcare waste management regulations. Overall, the framework aims to enhance operational efficiency, environmental safety, and sustainable healthcare practices.

Future Scope

Future research can focus on integrating federated learning to enable collaborative model training across multiple hospitals without sharing sensitive patient data. The framework can be extended by incorporating robotic waste segregation, IoT-enabled smart waste bins, blockchain-based waste tracking, and digital twin technology for real-time monitoring. Furthermore, multimodal AI models and advanced transformer architectures can be explored to improve classification accuracy, scalability, and autonomous biomedical waste management in next-generation smart hospitals.

VIII. CONCLUSION

This paper presented an Explainable Edge AI Framework for Real-Time Biomedical Waste Classification and Decision Support that integrates lightweight deep learning, edge computing, and Explainable Artificial Intelligence into a unified healthcare solution. The proposed framework enables accurate and efficient biomedical waste classification while providing transparent visual explanations and intelligent disposal recommendations. By reducing inference latency, improving data privacy, and supporting offline operation, the system offers a practical solution for modern healthcare environments. The proposed approach has the potential to improve biomedical waste management practices, enhance environmental sustainability, and support the adoption of trustworthy AI in smart healthcare systems.

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