



IoT-Based Real-Time Microplastic Detection and Analysis System Using Deep Learning

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Abstract: Microplastic pollution has become a serious environmental issue affecting oceans, rivers, and drinking water. Detecting microplastics manually under a microscope is time-consuming, costly, and prone to human error. This paper presents a low-cost and automated microplastic detection system using an ESP32-CAM module and a Convolutional Neural Network (CNN) based deep learning model. The system captures images of water samples, processes them using image preprocessing techniques such as adaptive thresholding and morphological operations, and identifies microplastic particles automatically.

In addition to detection, the system also counts the number of particles and estimates their size using pixel-to-millimeter calibration. A web-based dashboard is developed to display live streaming, detection results, confidence percentage, statistical graphs, and downloadable PDF reports.

Experimental results show that the proposed system provides accurate detection with reduced processing time and lower cost compared to traditional laboratory methods. This solution can be used for real-time environmental monitoring and scalable water quality analysis.

Index Terms - Microplastic Detection, ESP32-CAM, Internet of Things (IoT), Convolutional Neural Network (CNN), Deep Learning, Image Processing, OpenCV, Particle Size Estimation, Environmental Monitoring, Real-Time Water Analysis, Computer Vision, Adaptive Thresholding.

Chapter 1

Introduction

Background of the Study :

Microplastics are tiny plastic particles measuring less than 5 millimeters in size, commonly found in oceans, rivers, lakes, and even drinking water systems. These particles originate from the breakdown of larger plastic waste or from industrial and household products such as synthetic fibers, cosmetics, and packaging materials. Due to their small size and persistent nature, microplastics are difficult to remove from the environment and pose serious threats to marine life, ecosystems, and human health. In recent years, the rapid increase in plastic production and improper waste management has significantly contributed to the spread of microplastic pollution worldwide. Studies have shown that microplastics can enter the food chain through aquatic organisms and eventually reach humans. Long-term exposure to microplastics may cause potential health risks, including toxic chemical accumulation and inflammatory

responses. Traditional microplastic detection methods primarily rely on manual microscopy and laboratory-based spectroscopic techniques. While these methods provide high accuracy, they are time-consuming, expensive, and require specialized equipment and expert analysis. This limits large-scale monitoring and real-time environmental assessment, especially in developing regions. With advancements in Internet of Things (IoT) and Artificial Intelligence (AI), automated and low-cost solutions have become possible. Image processing and deep learning techniques, particularly Convolutional Neural Networks (CNNs), have demonstrated strong performance in object detection and classification tasks. By integrating IoT-based image acquisition devices such as ESP32-CAM with deep learning algorithms, it is possible to develop an affordable, real-time microplastic detection system.

Therefore, this study focuses on designing and implementing a low-cost, automated microplastic detection framework that combines IoT hardware, image preprocessing techniques, and CNN-based classification. The system aims to improve detection efficiency, reduce human effort, and provide accurate particle counting and size estimation through a web-based dashboard interface.

Problem Statement :

Microplastic pollution has become a major environmental challenge due to the continuous increase in plastic waste and its fragmentation into microscopic particles. Detecting and analyzing microplastics in water samples is essential for environmental monitoring and public health protection. However, existing detection methods face several limitations. Traditional approaches rely heavily on manual microscopy analysis, where experts visually inspect water samples to identify and count microplastic particles. This process is time-consuming, labor-intensive, and prone to human error. Additionally, laboratory-based techniques such as spectroscopy and chemical analysis require expensive equipment, specialized training, and controlled environments, making them inaccessible for large-scale or real-time monitoring.

Another major challenge is the lack of affordable and portable systems capable of automated detection. Most advanced detection systems are confined to research laboratories and are not suitable for field deployment or continuous monitoring. Furthermore, manual methods do not provide real-time statistical analysis, automated size estimation, or digital record maintenance.



Image 1.2 Problem Statement

Objectives of the Project :

The main objective of this project is to design and develop a low-cost, automated microplastic detection system using IoT and deep learning techniques. The system aims to improve the efficiency, accuracy, and accessibility of microplastic analysis in water samples.

The specific objectives of this project are:

- ❖ **To develop a real-time image acquisition system** using the ESP32-CAM module for capturing microscopic images of water samples.
- ❖ **To implement image preprocessing techniques** such as grayscale conversion, adaptive thresholding, noise filtering, and morphological operations to enhance particle visibility.
- ❖ **To design and train a Convolutional Neural Network (CNN)** model for accurate detection and classification of microplastic particles.
- ❖ **To perform automatic particle counting** using contour detection and image analysis techniques.
- ❖ **To estimate particle size** by calibrating pixel measurements into millimeter (mm²) units.
- ❖ **To build an interactive web-based dashboard** for:
 - Live streaming from ESP32-CAM
 - Displaying detection results
 - Showing model confidence percentage
 - Generating statistical graphs (pie chart and bar chart)
 - Downloading automated PDF reports
- ❖ **To store detection results in a database (SQLite)** for maintaining history and performing total analysis.
- ❖ **To create a low-cost, scalable, and portable environmental monitoring solution** suitable for real-time water quality assessment.

Scope of the Project:

The scope of this project focuses on the design and implementation of a low-cost, IoT-based microplastic detection system using image processing and deep learning techniques. The system is developed to automate the detection, counting, and size estimation of microplastic particles present in water samples.

This project includes the following scope:

- ❖ **Image Acquisition**
The system uses an ESP32-CAM module to capture images of water samples in real time. The camera acts as a low-cost image acquisition device suitable for laboratory or field environments.
- ❖ **Image Processing and Enhancement**
Preprocessing techniques such as grayscale conversion, Gaussian blurring, adaptive thresholding, and morphological operations are applied to improve image clarity and particle visibility.
- ❖ **Deep Learning-Based Detection**
A Convolutional Neural Network (CNN) model is trained and integrated into the system to classify and detect microplastic particles automatically.
- ❖ **Particle Counting and Size Estimation**

The system identifies contours of detected particles, counts them, and converts pixel area into millimeter units using calibration factors.

❖ **Web-Based Dashboard Interface**

A Flask-based web application is developed to:

- Display live ESP32 camera streaming
- Show detection results and model confidence Generate statistical charts (bar and pie charts)
- Maintain detection history
- Provide downloadable PDF reports

❖ **Database Integration**

SQLite database is used to store detection results, timestamps, and particle counts for analysis and future reference.

Chapter 2

Literature Survey

Existing Methods for Microplastic Detection :

Title: **Eco-Sensing System for Water Pollution and Microplastic Detection**

by : **Song, Y. K**

This paper proposes an eco-sensing system designed to detect water pollutants, including microplastics, using sensor-based monitoring techniques. The system integrates environmental sensors with data acquisition modules to monitor water quality parameters such as turbidity, pH, and contamination levels.

For microplastic detection, the study emphasizes automated sensing combined with image-based analysis techniques to improve accuracy. The system is capable of real-time environmental monitoring and provides alerts when pollution levels exceed safe limits.

However, the limitation of this method is that it mainly focuses on general pollution monitoring rather than detailed particle-level classification using deep learning. The detection accuracy may also vary depending on environmental conditions and sensor calibration.

Title: **Automated Microplastic Detection and Classification Using Image Processing Techniques**

By: **Kristian Dokic.**

This research focuses on detecting microplastic particles using digital image processing methods. The authors applied grayscale conversion, thresholding, contour detection, and morphological operations to identify microplastic particles in water samples.

The system calculates particle count and estimates particle size based on pixel measurements. Some advanced versions also use machine learning classifiers to improve detection performance.

Although this approach improves automation compared to manual microscopy, it may struggle with complex backgrounds and noise in real-world samples. Additionally, traditional image processing methods may not achieve high classification accuracy compared to deep learning-based CNN models.

Research Gap and Motivation:

Although several research studies have focused on detecting microplastics in water, most existing systems rely either on manual laboratory analysis or basic image processing techniques. Traditional methods such as visual inspection under microscopes are time-consuming, require expert supervision, and are not suitable for real-time monitoring.

Some automated systems use simple thresholding and contour detection methods, but their accuracy decreases when the background is complex or when particle sizes vary significantly. Additionally, many existing systems do not integrate live monitoring, deep learning-based classification, cloud-based storage, or automated reporting. Very few research works combine IoT devices like ESP32-CAM with CNN-based models for intelligent microplastic detection. There is also a lack of systems that provide real-time dashboards, statistical visualization (graphs and charts), particle size measurement with calibration, and downloadable PDF reports for analysis and documentation.

This creates a clear research gap in developing a complete, low-cost, intelligent, and real-time microplastic detection system.

The motivation behind this project is to design an advanced yet affordable system that integrates ESP32-CAM live streaming, TensorFlow CNN deep learning models, image preprocessing techniques, particle size calibration (pixel to millimeter conversion), database storage, and an interactive web dashboard. By combining IoT, Artificial Intelligence, and Web Technologies, this project aims to provide a practical solution for continuous environmental monitoring and faster microplastic analysis.

References for this subtopic:

Component	Specification / Details
Microcontroller	ESP32-CAM, 32-bit Tensilica Xtensa LX6, 240 MHz
Camera	OV2640 2MP CMOS Camera
Illumination	Adjustable LED ring or LED panel for uniform lighting
Memory	4GB SRAM, 4 MB Flash; SD card support for storage
Connectivity	Wi-Fi 802.11 b/g/n, supports remote data transmission
Power Supply	5V DC (via USB or battery pack)
Computer / Processing Unit	Laptop or desktop with at least 8GB RAM and GPU (optional for faster AI)

Chapter 3

System Specification

Hardware Requirements :

The proposed microplastic detection system requires a combination of IoT hardware components and computing devices to perform image acquisition, processing, and analysis. The following hardware components are used in this project:

1. ESP32-CAM Module

The ESP32-CAM is the primary image acquisition device used in this system. It is a low-cost microcontroller with a built-in Wi-Fi module and OV2640 camera sensor.

Specifications: 32-bit ESP32 processor.OV2640 2MP camera.Wi-Fi (2.4 GHz) connectivity.Supports JPEG image capture.MicroSD card support (optional).The ESP32-CAM captures water sample images and streams them to the web dashboard for analysis.

2. ESP32-CAM-MB Programmer Board

The ESP32-CAM-MB board is used for: Uploading Arduino code.Powering the ESP32-CAM.USB-to-Serial communication.It simplifies programming and reduces wiring complexity.

3. Laptop / Desktop Computer

A computer system is required to: Train the CNN deep learning model.Run the Flask web application.Perform image processing using OpenCV.Store results in SQLite database.**Minimum Requirements:**Processor: Intel i5 or equivalent.RAM: 8GB (recommended).Storage: 256GB SSD or higher.Operating System: Windows / Linux

4. Wi-Fi Network (2.4 GHz)

A stable 2.4 GHz Wi-Fi network is required for communication between: ESP32-CAM.Laptop/Server running Flask.This enables real-time streaming and data transmission.

5. Microscope Setup (Optional but Recommended)

To clearly visualize microplastic particles, a microscope or magnifying lens attachment may be used with the ESP32-CAM. This improves detection accuracy by enhancing particle visibility.

6. Power Supply

5V USB power supply.Provided via ESP32-CAM-MB or external adapter.Stable power ensures uninterrupted streaming and image capture.

Software Requirements :

The proposed microplastic detection system integrates multiple software technologies to enable image acquisition, processing, deep learning analysis, and real-time dashboard visualization. The software components are carefully selected to ensure accuracy, scalability, and ease of implementation.

Operating System

The system is developed and tested on a Windows-based operating system. However, it is platform-independent and can also be deployed on Linux-based systems. The operating system provides the necessary environment for running Python, Arduino IDE, and other supporting frameworks.

Arduino IDE

The Arduino Integrated Development Environment (IDE) is used to program the ESP32-CAM module. It enables writing, compiling, and uploading embedded C/C++ code to the microcontroller. Through this IDE, the camera is configured for image capture, Wi-Fi connectivity, and live streaming functionality. The ESP32 board package is installed in the Arduino IDE to support camera initialization and wireless communication features.

Python Programming Language

Python is the core programming language used in this project due to its simplicity, extensive libraries, and strong support for artificial intelligence and image processing. It is used for: Implementing the Flask web server. Performing image preprocessing. Running the Convolutional Neural Network (CNN) model. Generating analytical reports. Managing database operations. Python ensures flexibility and rapid development of the system.

Flask Web Framework

Flask is a lightweight Python web framework used to build the interactive dashboard. It handles: HTTP requests and responses. Image uploads from ESP32-CAM. Real-time streaming display. Integration with the CNN model. Flask enables seamless backend and frontend communication.

OpenCV Library

OpenCV (Open Source Computer Vision Library) is used for image processing and computer vision tasks. It plays a crucial role in improving detection accuracy by performing: Image resizing. Noise filtering. Adaptive thresholding. Morphological operations. Contour detection. Particle size measurement. These preprocessing steps enhance microplastic visibility before CNN classification.

TensorFlow and Keras

TensorFlow is the deep learning framework used to build and train the Convolutional Neural Network (CNN) model. Keras, integrated within TensorFlow, simplifies model architecture design.

The CNN model is responsible for: Learning microplastic patterns. Classifying images. Providing model confidence percentage. Improving detection accuracy through training optimization. TensorFlow enables scalable and efficient AI integration into the system.

SQLite Database

SQLite is used as a lightweight relational database to store: Image names. Date and time of analysis. Particle count. Model confidence values. Measured particle sizes. It ensures structured storage and easy retrieval of historical results within the dashboard.

Matplotlib Library

Matplotlib is used to generate graphical visualizations such as: Line graphs, Bar charts, Pie charts. Detection trend analysis. These graphs provide analytical insights into microplastic distribution and detection patterns.

Report Generation Tools

The system automatically generates downloadable PDF reports containing: Analysis date. Total particle count. Individual particle size measurements. Detection graphs. This feature improves documentation and research usability.

System Requirements:

The proposed microplastic detection system requires a combination of embedded hardware, computing infrastructure, networking capability, and intelligent software support to function efficiently. The system is designed to operate in a laboratory or environmental monitoring setup where water samples are collected and analyzed using a camera-based imaging approach integrated with artificial intelligence.

The primary hardware requirement includes an ESP32-CAM module equipped with an OV2640 camera sensor for capturing high-resolution images of water samples. The module must support Wi-Fi connectivity to transmit captured images to the local server. A stable 2.4 GHz wireless network is required to ensure uninterrupted communication between the ESP32-CAM and the processing system. A computer or laptop with moderate processing capability, preferably with at least 8 GB RAM and a multi-core processor, is required to run the Flask server, perform image preprocessing, execute the Convolutional Neural Network model, and generate analytical reports. For improved deep learning performance, a system with GPU support is recommended but not mandatory.

On the software side, the system requires Python as the primary programming environment along with essential libraries such as OpenCV for image processing, TensorFlow and Keras for CNN-based microplastic classification, Flask for web-based dashboard development, SQLite for database storage, and Matplotlib for generating graphical visualizations. The Arduino IDE is required to program and configure the ESP32-CAM module for image capture and live streaming functionality. Additionally, a modern web browser is necessary to access the dashboard interface and view real-time results, analytical graphs, and downloadable reports.

The system also requires sufficient storage capacity to save captured images, processed outputs, database records, and generated PDF reports. Proper calibration of the imaging setup is required to convert pixel measurements into real-world millimeter values for accurate particle size estimation. A stable power supply must be provided to the ESP32-CAM module to ensure continuous operation during live streaming and image capture sessions.

Advantages of the Proposed System:

The proposed microplastic detection system offers several significant advantages over traditional laboratory-based detection methods. One of the primary benefits is automation. Unlike manual microscopic analysis, which requires trained experts and considerable time, the developed system uses image processing and deep learning techniques to automatically detect and count microplastic particles. This reduces human error and increases consistency in results.

Another major advantage is real-time monitoring capability. By integrating the ESP32-CAM module with a web-based dashboard, the system allows live image streaming and instant analysis. This enables faster decision-making in environmental monitoring applications. The ability to process images immediately after capture improves operational efficiency and reduces the delay typically associated with conventional testing methods.

The system also provides enhanced accuracy through the use of Convolutional Neural Networks (CNN) and advanced preprocessing techniques such as adaptive thresholding, morphological operations, and noise filtering. These techniques improve particle segmentation and classification performance, leading to more reliable detection results. Additionally, model confidence percentage estimation provides transparency in prediction reliability.

A key advantage of the proposed system is particle size estimation and measurement. Through calibration of pixel-to-millimeter conversion, the system not only counts microplastics but also calculates their approximate size. This feature adds analytical depth and supports quantitative environmental assessment.

The integration of graphical analysis tools such as bar charts and pie charts allows users to visualize particle distribution and detection statistics clearly. The automatic generation of downloadable PDF reports further enhances usability by providing structured documentation suitable for research and

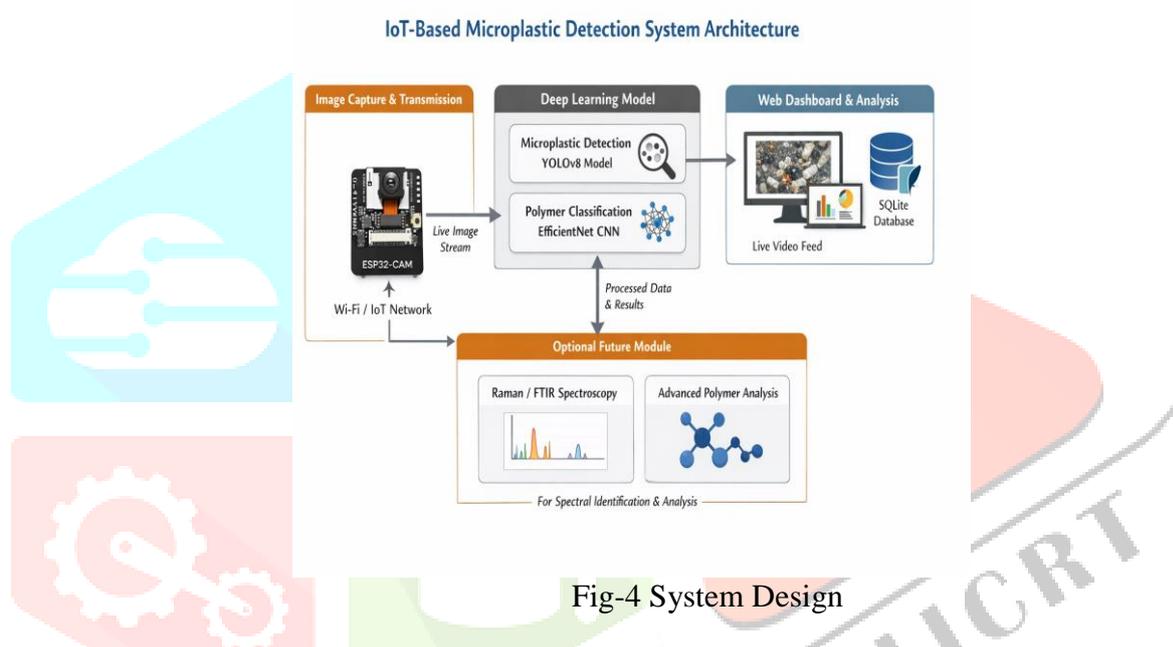
environmental compliance reporting.

Cost-effectiveness is another important benefit. The use of affordable hardware such as the ESP32-CAM module and open-source software frameworks significantly reduces overall system cost compared to sophisticated laboratory instruments. This makes the system accessible for academic institutions, research laboratories, and small environmental monitoring units.

Finally, the inclusion of a database system ensures historical data storage and retrieval. This enables long-term trend analysis and supports comparative studies across different samples and time periods. The system is scalable and can be upgraded with improved models or additional sensors in the future.

Chapter 4

System Design:



The proposed microplastic detection system is designed as an integrated IoT-based intelligent monitoring platform that combines embedded hardware, deep learning algorithms, and a web-based analytical dashboard. The system architecture consists of three major components: image acquisition layer, processing layer, and visualization and reporting layer.

At the image acquisition layer, the ESP32-CAM module is used to capture high-resolution images of water samples placed under a microscope. The module is connected to a 2.4 GHz Wi-Fi network, enabling wireless transmission of captured images to the local server. This setup ensures real-time data collection without requiring complex wired communication.

In the processing layer, the captured images are received by a Flask-based Python server. The images undergo preprocessing using OpenCV techniques such as grayscale conversion, noise filtering, adaptive thresholding, and morphological operations. These steps enhance particle visibility and improve segmentation accuracy. After preprocessing, the images are passed to a Convolutional Neural Network (CNN) model developed using TensorFlow and Keras. The CNN analyzes image features to detect and classify microplastic particles. The system calculates total particle count, estimates particle size using pixel-to-millimeter calibration, and generates model confidence scores. The processed data is then stored in an SQLite database, which maintains records of image names, timestamps, detected particle counts, particle size measurements, and model confidence percentages. This structured storage enables historical tracking and comparative analysis. In the visualization and reporting layer, the results are displayed on a web-based dashboard built using Flask. The dashboard provides real-time streaming, detection results, bar charts, pie charts, and statistical summaries. Users can download automated PDF reports that include particle count, size distribution tables, graphical analysis, and detection date. The system also includes history tracking and total analysis sections for long-term environmental monitoring.

Methodology:

The methodology of the proposed microplastic detection system follows a structured process that integrates image acquisition, preprocessing, deep learning analysis, and result visualization. The system is designed to ensure accurate detection, particle counting, and size estimation in an automated manner.

The first stage of the methodology is image acquisition. Water samples are placed under a microscope setup, and images are captured using the ESP32-CAM module. The module transmits images wirelessly to a local server through a 2.4 GHz Wi-Fi network. In addition to live streaming, the system also supports manual image upload for analysis through the web dashboard.

The second stage involves image preprocessing using OpenCV. The captured images are converted to grayscale to simplify computation and highlight particle contrast. Gaussian blurring is applied to reduce noise and smooth irregularities. Adaptive thresholding is then used to segment microplastic particles from the background under varying lighting conditions. Morphological operations such as closing are performed to remove small gaps and improve contour detection accuracy. These preprocessing steps enhance the visibility of microplastic particles and improve overall detection reliability.

In the third stage, the preprocessed images are passed to a Convolutional Neural Network (CNN) model developed using TensorFlow and Keras. The CNN model extracts important image features through convolutional layers and classifies regions containing microplastic particles. The model outputs detection results along with confidence percentages, which indicate the reliability of predictions. The integration of deep learning improves accuracy compared to traditional threshold-based detection methods.

The fourth stage involves particle counting and size estimation. Contour detection is used to identify individual particles, and their pixel area is calculated. A calibration factor is applied to convert pixel measurements into real-world millimeter square (mm^2) values. This enables quantitative analysis of microplastic size distribution in the sample.

In the fifth stage, analytical visualization is performed. The system generates statistical graphs such as line graphs, bar charts, and pie charts to represent particle distribution and detection trends. All results, including particle count, size measurements, confidence levels, and timestamps, are stored in an SQLite database for future reference.

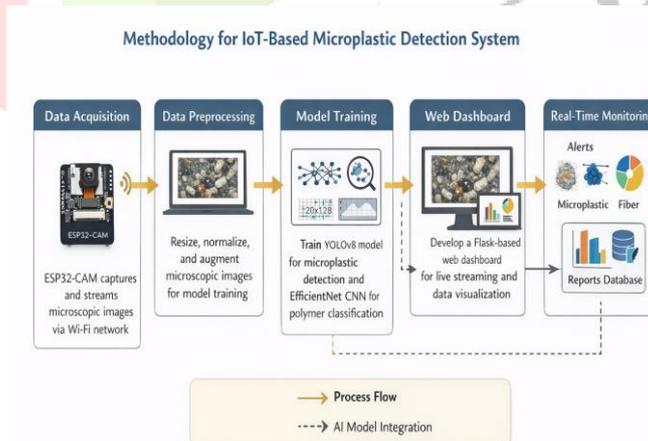


Fig-4.3 methodology

Chapter 5

5. Results and Discussion

5.1 Result:

The developed microplastic detection system was evaluated using a dataset of microscopic water sample images containing both microplastic particles and non-plastic materials. The dataset was divided into training and validation sets to assess the performance of the proposed deep learning model. The EfficientNet-based convolutional neural network was trained using transfer learning to improve classification accuracy while reducing training time. Data augmentation techniques such as rotation, flipping, zooming, and brightness adjustment were applied to increase the diversity of the training data and improve model generalization. After training, the model achieved a **validation accuracy exceeding 95%**, demonstrating its effectiveness in identifying microplastic particles from microscopic images. The use of transfer learning significantly improved feature extraction capability, allowing the model to distinguish between microplastic particles and other small debris commonly found in water samples. The trained model was integrated into a web-based monitoring interface that receives image frames from the ESP32-CAM module. When a frame is captured, it is processed by the trained model to determine the presence of microplastics. The prediction results are displayed on the web interface along with statistical analysis graphs showing the distribution and frequency of detected particles. The experimental evaluation shows that the system is capable of performing near real-time microplastic detection with reliable performance. The integration of embedded hardware with a deep learning model allows continuous monitoring of water samples without the need for expensive laboratory equipment.

Overall, the proposed system demonstrates that low-cost hardware combined with deep learning can provide an effective solution for automated microplastic detection and monitoring in environmental studies.

5.2 Conclusion:

This study presented a deep learning-based system for automated microplastic detection using microscopic image analysis. The proposed framework integrates an ESP32-CAM module for image acquisition, a convolutional neural network for particle classification, and a web-based interface for monitoring and visualization. The use of transfer learning with an EfficientNet architecture enabled the model to achieve high detection accuracy while maintaining efficient computational performance. The experimental results demonstrate that the system can reliably identify microplastic particles from microscopic images with an accuracy above 95%.

In addition to classification, the developed platform provides visual analysis and statistical reporting, which can assist researchers and environmental agencies in monitoring microplastic contamination in water samples. The low-cost hardware design also makes the system accessible for educational and field research applications..

Overall, the proposed system provides a scalable and cost-effective approach for automated microplastic detection and contributes to ongoing efforts in environmental monitoring and pollution analysis.

Chapter 6

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