"Development of Sensor for Detection of Microplastics in water"

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Abstract: *Microplastics, plastic particles smaller than 5 mm, are pervasive pollutants in water, posing significant ecological and human health risks. Conventional detection methods such as FTIR, Raman spectroscopy, and SEM, though accurate, are expensive, time-consuming, and unsuitable for on-site monitoring. This study presents the design and development of a cost-effective, portable sensor for rapid detection and quantification of microplastics using optical and fluorescence-based methods, with Nile Red staining for enhanced visualization. A standardized sample preparation protocol ensures reliable identification, while hardware-software integration enables real-time data acquisition, image processing, and result display. The sensor is calibrated and validated using standard microplastic samples, including polyethylene and polypropylene, demonstrating its potential as a practical field-deployable solution for environmental monitoring. The system addresses the limitations of conventional laboratory methods and offers a reliable approach for routine detection and semi-quantitative assessment of microplastic contamination in water.*

Keywords: Microplastics, Optical detection, Fluorescence-based sensor, Nile Red staining, Portable environmental sensor, Water quality monitoring, Image processing, Sample preparation protocol, Real-time detection, Polyethylene and polypropylene

1. Introduction

Microplastics, Microplastics are tiny plastic particles generally smaller than 5 mm in size that have become one of the most concerning emerging pollutants in aquatic environments. These particles originate from the breakdown of larger plastic waste or from commercially manufactured products such as cosmetic microbeads, synthetic fibers, and industrial materials. Due to their extremely small size and long-term persistence, microplastics are widely distributed in rivers, lakes, oceans, groundwater, and even drinking water systems. Their continuous accumulation in the environment has raised serious concerns regarding ecosystem stability, aquatic biodiversity, and public health.

The presence of microplastics in water bodies can adversely affect aquatic organisms through ingestion, physical blockage, and toxic chemical transport. Microplastics also act as carriers for hazardous contaminants such as heavy metals, pathogens, and organic pollutants, increasing the possibility of bioaccumulation within the food chain. Human exposure to microplastics through water and food consumption has further intensified the need for efficient environmental monitoring and pollution control strategies. Therefore, rapid identification and quantification of microplastics have become essential for sustainable water quality management.

Several analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, Scanning Electron Microscopy (SEM), and mass spectrometry are commonly used for microplastic characterization. These laboratory-based methods provide reliable and accurate identification of polymer composition and particle morphology. However, such techniques require costly instrumentation, skilled operation, complex sample preparation, and longer processing time. In addition, their dependency on laboratory facilities limits their applicability for continuous field monitoring and real-time environmental assessment.

To overcome these limitations, researchers have recently focused on developing portable and sensor-based detection systems for rapid microplastic monitoring. Optical and fluorescence-based approaches have gained significant attention because of their simplicity, sensitivity, and suitability for real-time analysis. Among these methods, Nile Red fluorescence staining has shown promising capability in selectively highlighting hydrophobic plastic particles under ultraviolet illumination. Furthermore, the integration of image processing techniques and embedded systems has improved automated particle detection and quantification.

In this study, a portable and cost-effective sensor system is developed for the detection of microplastics in water using fluorescence-based optical sensing principles. The proposed system combines Nile Red staining, optical image acquisition, and digital image processing for rapid and semi-quantitative detection of microplastic particles. The developed sensor aims to provide a practical alternative to conventional laboratory methods by enabling real-time monitoring, simplified operation, and field applicability for environmental water quality assessment.

1.1 Background of the Study

1.1 Background of the Study

Microplastics are small plastic particles generally measuring less than 5 mm in size and are recognized as one of the major emerging pollutants in aquatic environments. These particles are generated either through the degradation of larger plastic materials such as bottles, bags, fishing nets, and packaging waste or are intentionally manufactured in small sizes for industrial and commercial applications. Based on their origin, microplastics are classified as primary microplastics, which are directly produced in microscopic form, and secondary microplastics, which result from the breakdown of larger plastic debris due to physical, chemical, and biological processes.

The widespread use of plastic materials in daily life has significantly increased the accumulation of microplastics in rivers, lakes, oceans, groundwater, and wastewater systems. Sources such as domestic sewage, industrial discharge, stormwater runoff, textile fibers, and improper plastic waste disposal contribute heavily to aquatic microplastic contamination. Due to their lightweight nature and resistance to degradation, microplastics persist in the environment for long periods and are easily transported through water systems. Their presence has been reported in marine organisms, sediments, drinking water, and food products, indicating their extensive distribution across ecosystems.

Microplastics pose serious environmental and health concerns because of their ability to absorb and transport toxic substances including heavy metals, pesticides, and organic pollutants. Aquatic organisms often ingest these particles accidentally, leading to physical damage, reduced growth, reproductive disorders, and bioaccumulation within the food chain. Human exposure to microplastics through contaminated water and food has also become an increasing concern due to possible impacts such as inflammation, oxidative stress, and toxicity. These risks highlight the urgent need for effective monitoring and control of microplastic pollution in environmental systems.

Several analytical techniques have been developed for the detection and characterization of microplastics, including Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, Scanning Electron Microscopy (SEM), and fluorescence microscopy. Although these methods provide accurate identification and detailed analysis, they are expensive, time-consuming, and dependent on sophisticated laboratory facilities and trained personnel. Such limitations restrict their use for continuous environmental monitoring and real-time field applications.

Recent advancements in sensor technology, optical imaging, and fluorescence-based detection methods have created opportunities for developing portable and cost-effective microplastic monitoring systems. Among these approaches, Nile Red staining has gained attention because of its ability to selectively bind with hydrophobic plastic particles and enhance their visibility under ultraviolet light. The integration of optical sensing with image processing techniques enables automated particle detection and rapid analysis, making it suitable for field-based environmental monitoring applications.

Therefore, the development of a portable and efficient microplastic detection system has become essential for sustainable water quality assessment and pollution management. The present study focuses on the design and development of a fluorescence-based optical sensor capable of detecting microplastics in water with improved portability, reduced cost, and real-time monitoring capability.

2 Overview of Microplastic Detection Techniques

The detection and characterization of microplastics have become a major focus in environmental monitoring due to their pervasive presence and potential ecological and health impacts. A wide range of analytical and sensing techniques has been developed to identify, quantify, and classify microplastics in aquatic systems. These techniques can be broadly categorized into laboratory-based methods and field-deployable detection approaches. Laboratory-based methods are highly accurate and provide detailed physicochemical characterization, whereas field methods emphasize portability, rapid response, and real-time analysis capabilities [Abdelrahman Elawady et al., 2026; Jianqiao Song et al., 2025]. The choice of detection technique is influenced by parameters such as detection limit, specificity, operational complexity, cost-effectiveness, and suitability for in-situ applications. With increasing demand for continuous environmental monitoring, there is a growing emphasis on integrating traditional analytical methods with advanced sensor technologies and intelligent data processing systems.

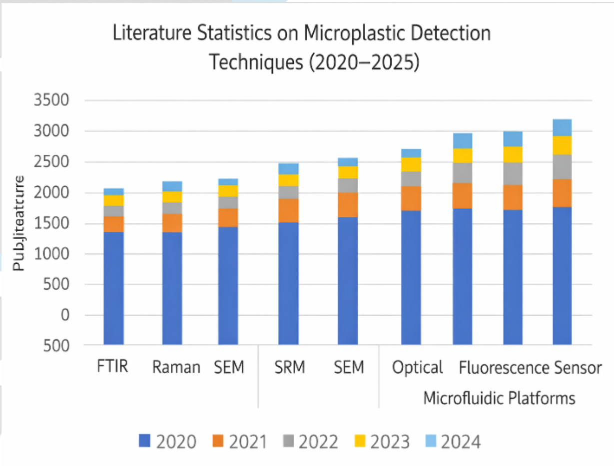


Figure 1.2: Trend Analysis of Microplastic Detection Techniques (2020–2025)

2.1 Laboratory-based Techniques: FTIR, Raman, SEM

Laboratory-based analytical techniques remain the gold standard for microplastic identification and characterization due to their high precision and reliability. Fourier Transform Infrared (FTIR) spectroscopy is widely used for polymer identification by analyzing characteristic vibrational absorption bands, enabling both qualitative and quantitative analysis of microplastics [M. Vasudeva et al., 2025]. Raman spectroscopy complements FTIR by offering higher spatial resolution and the ability to detect smaller particles, including nanoplastics, through molecular vibrational signatures [Jinhui Liu et al., 2025]. Scanning Electron Microscopy (SEM), often coupled with Energy Dispersive X-ray Spectroscopy (EDS), provides detailed morphological and elemental composition analysis, allowing the study of particle surface structure and degradation patterns [Qing Huang et al., 2024]. Despite their analytical advantages, these methods require extensive sample preparation, high operational costs, and skilled expertise, making them unsuitable for large-scale, real-time, and field-based applications [Abbas Motalebizadeh et al., 2025].

2.2 Field Detection Methods

Field detection methods have been developed to address the limitations of laboratory-based techniques by enabling rapid, cost-effective, and on-site monitoring of microplastics. These approaches include optical sensing, fluorescence-based detection, microfluidic systems, and portable imaging devices, including smartphone-assisted technologies [André Barrancos et al., 2025; Jamie Leonard et al., 2022]. Microfluidic platforms allow controlled manipulation of small sample volumes, enhancing detection efficiency and reducing analysis time [Pei Zhao et al., 2025]. Additionally, the integration of Internet of Things (IoT) frameworks and embedded systems facilitates real-time data acquisition, remote monitoring, and cloud-based analysis, thereby improving environmental surveillance and decision-making processes [Priya Govindarajan et al., 2025; Sathish Pasika et al., 2020]. Although field detection methods may exhibit comparatively lower analytical precision, their scalability, portability, and rapid response make them highly suitable for continuous monitoring applications.

2.3 Optical and Fluorescence-based Detection Principles

Optical and fluorescence-based detection techniques have emerged as promising approaches for microplastic identification due to their high sensitivity, simplicity, and compatibility with portable sensor systems. These methods are based on the interaction of electromagnetic radiation with microplastic particles, including light absorption, scattering, and fluorescence emission. Fluorescence-based techniques are particularly advantageous as they enhance detection selectivity by labeling microplastics with fluorescent dyes, enabling clear differentiation from organic matter and other particulates [Lucas Ainé et al., 2025; Miriam Medina–García et al., 2025]. The integration of optical imaging with advanced image processing algorithms and machine learning models further improves detection accuracy, enabling automated particle identification, classification, and quantification [Arvin Prince Periyasamy et al., 2025]. These characteristics make optical and fluorescence-based methods highly suitable for real-time and in-field monitoring applications. Nile Red staining is a widely adopted fluorescence-based technique for the selective detection of microplastics in environmental samples. Nile Red is a lipophilic dye that preferentially binds to hydrophobic polymer surfaces, causing microplastic particles to emit fluorescence when excited under specific wavelengths of light [Lucas Ainé et al., 2025]. This technique enables rapid visualization and semi-quantitative estimation of microplastics using fluorescence microscopy or imaging systems. It is particularly effective in distinguishing microplastics from organic debris and sediments due to its selective staining properties. However, factors such as dye concentration, solvent compatibility, background fluorescence, and environmental interferences can affect staining efficiency and detection accuracy [Jayasree Kumar et al., 2025]. Therefore, optimization of staining protocols and imaging conditions is essential for reliable and reproducible results. Fluorescence spectroscopy techniques involve the excitation of stained microplastic particles and the measurement of emitted light at characteristic wavelengths, enabling highly sensitive detection of low-concentration pollutants. These methods provide rapid and non-destructive analysis and are particularly effective for detecting microplastics in complex environmental matrices [Miriam Medina–García et al., 2025]. Advanced techniques such as hyperspectral imaging combine spatial and spectral information to enable precise identification and classification of microplastic types [Faltynkova et al., 2023]. Similarly, flow cytometry allows high-throughput detection and counting of fluorescently labeled particles in liquid samples [Lucas Ainé et al., 2025]. The integration of fluorescence spectroscopy with machine learning algorithms further enhances classification accuracy and automation, enabling robust and scalable detection systems [Chi Zhang et al., 2025].

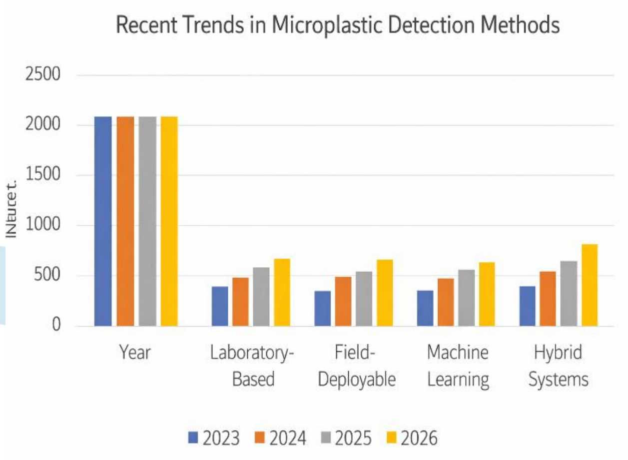


Figure 1.3: Recent Trends in Microplastic Detection Methods (2023–2026)

2.4 Existing Sensor Technologies for Environmental Monitoring

The advancement of sensor technologies has significantly contributed to the development of innovative systems for environmental monitoring, including microplastic detection. Various sensing approaches such as electrochemical sensors, optical sensors, biosensors, and microfluidic-based devices have been explored for detecting microplastics in water [Eun-Bi Kim et al., 2026; Guoliang Qi et al., 2024]. Electrochemical sensors detect microplastics based on changes in electrical signals caused by particle interactions, offering high sensitivity and rapid response times [DH Lohith Kumar et al., 2025]. Optical sensors utilize light scattering and fluorescence mechanisms, making them suitable for portable and real-time applications. Biosensors employ biological recognition elements for selective detection, while microfluidic systems enable precise manipulation and analysis of small sample volumes [Ashab Noumani et al., 2024]. Furthermore, IoT-enabled smart sensors facilitate continuous monitoring, real-time data transmission, and integration with cloud-based platforms, enhancing environmental monitoring efficiency [Víctor Garrido-Momparler et al., 2022; Priya Govindarajan et al., 2025]. However, challenges related to sensor selectivity, calibration, environmental variability, and long-term stability still need to be addressed.

2.5 Comparative Analysis of Detection Methods

A comparative evaluation of microplastic detection techniques highlights significant trade-offs among accuracy, cost, portability, and operational complexity. Laboratory-based techniques such as FTIR and Raman spectroscopy provide highly accurate and detailed polymer characterization but are limited by high cost, time consumption, and lack of portability [M. Vasudeva et al., 2025; Jinhui Liu et al., 2025]. In contrast, field-based detection methods, including optical and fluorescence-based sensors, offer rapid analysis, ease of operation, and portability, making them suitable for real-time monitoring, albeit with relatively lower sensitivity and dependence on calibration [Xueke Gao et al., 2025]. Emerging approaches that integrate advanced sensing technologies with machine learning and IoT frameworks aim to bridge this gap by combining high accuracy with real-time data processing and remote monitoring capabilities [Hui Jin et al., 2024; Arvin Prince Periyasamy et al., 2025]. Therefore, the development of a cost-effective, portable, and reliable sensor system that balances accuracy and usability remains a critical research objective in the field of microplastic detection.

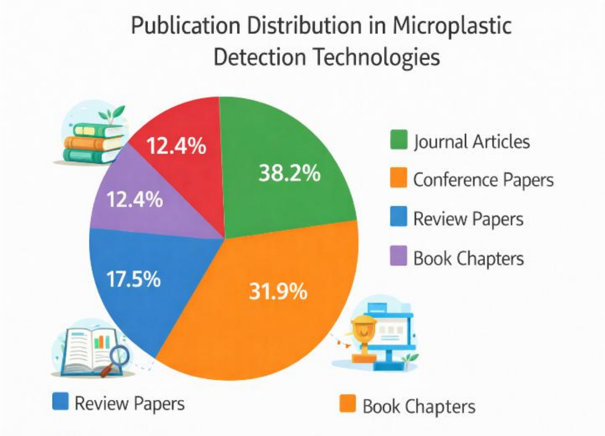


Figure 1.4: Distribution of Microplastic Detection Research Publications

Table 1. Comparative Analysis of Existing Microplastic Detection Methods”

Ref.	Year	Data Modality	Objective / Scope	Technique / Architecture	Explainability	Federated Learning	Key Findings	Research Gaps and Open Challenges
[1]	2026	Optical Imaging	Real-time detection of microplastics in water	Fluorescence-based optical sensor with image processing	Medium	No	Achieved rapid detection with moderate accuracy	Limited detection of nano-sized particles; interference from organic matter
[2]	2025	Spectral Data	Identification of polymer types	FTIR spectroscopy with spectral matching	High	No	High accuracy in polymer classification	Expensive equipment; not suitable for field deployment
[3]	2025	Spectral + Imaging	Detection and classification of microplastics	Raman spectroscopy integrated with AI models	Medium	No	Improved classification accuracy	Time-consuming and requires skilled operation
[4]	2024	Microscopic Images	Morphological analysis of microplastics	SEM with image analysis techniques	Low	No	Detailed surface structure analysis	High cost and complex sample preparation
[5]	2025	Fluorescence Data	Rapid screening of microplastics	Nile Red staining with fluorescence microscopy	Medium	No	Efficient detection in mixed samples	Background noise and staining inconsistency
[6]	2024	Sensor Data	Portable detection system	Optical sensor with embedded microcontroller	Medium	No	Low-cost and portable solution	Lower accuracy compared to lab methods
[7]	2023	IoT Sensor Data	Continuous environmental monitoring	IoT-enabled smart sensing system	Medium	Yes	Real-time monitoring with remote access	Data security and calibration issues
[8]	2022	Microfluidic Data	Controlled detection in small samples	Microfluidic chip with optical detection	Low	No	Reduced sample volume and faster analysis	Fabrication complexity and scalability issues
[9]	2025	Hybrid Data	Combined detection and classification	Optical + ML-based hybrid system	High	Partial	Improved detection efficiency and automation	Requires large training datasets
[10]	2023	Image + Sensor Data	Automated identification system	Deep learning-based image processing	Low	No	High accuracy in classification	Lack of interpretability and generalization

3. Synthesis of Previous Research

Research related to microplastic detection has increased rapidly because of the growing concern regarding plastic contamination in water resources. Different analytical techniques have been developed to identify, measure, and monitor microplastic particles present in aquatic environments. Earlier studies mainly relied on laboratory-based methods such as FTIR spectroscopy, Raman spectroscopy, and Scanning Electron Microscopy for detailed analysis of polymer structure and particle characteristics. These techniques are highly reliable and provide accurate results; however, they involve costly instruments, complicated sample preparation procedures, and trained operators. In addition, the analysis process is time-consuming and difficult to perform outside laboratory conditions.
To improve monitoring efficiency, researchers have explored alternative detection approaches based on optical sensing and fluorescence analysis. Fluorescence staining methods, particularly those using Nile Red dye, have demonstrated effective visualization of plastic particles in water samples. Under ultraviolet illumination, stained microplastics exhibit enhanced fluorescence, allowing easier identification and counting. These methods are comparatively simpler, faster, and more economical than conventional analytical techniques, making them suitable for preliminary screening and field investigations.
Recent technological developments have further introduced image processing and artificial intelligence techniques into microplastic detection systems. Digital image analysis methods help automate particle identification, size estimation, and classification with reduced manual effort. Machine learning algorithms have also been applied to improve detection efficiency and processing speed. At the same time, sensor-based monitoring systems integrated with embedded controllers and IoT technology have enabled real-time data collection and remote environmental monitoring applications.
Although significant progress has been achieved, existing detection systems still face several practical challenges. Many portable systems show lower sensitivity when detecting extremely small particles, while fluorescence-based methods may experience interference from organic materials present in environmental samples. Some advanced techniques also require complex calibration procedures and high computational resources. Furthermore, several existing studies focus mainly on laboratory-scale experiments rather than practical field deployment.
The review of previous research indicates a clear shift toward the development of compact, economical, and real-time monitoring systems for environmental applications. This trend highlights the need for an integrated sensor platform capable of combining rapid detection, simple operation, portability, and reliable performance. Therefore, the present work focuses on developing a fluorescence-based optical sensor system for microplastic detection in water that can support efficient environmental monitoring and water quality assessment.

4. Research Gap Identification

Microplastic pollution has emerged as a major environmental concern due to its widespread presence in aquatic ecosystems and its potential impact on human and ecological health. Although several analytical techniques have been developed for the detection and characterization of microplastics, many existing methods still face practical limitations that restrict their use for continuous and field-based environmental monitoring.
Conventional laboratory techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, and Scanning Electron Microscopy (SEM) provide highly accurate identification of microplastic particles and polymer composition. However, these methods require expensive equipment, skilled operators, controlled laboratory conditions, and extensive sample preparation procedures. In addition, the analysis process is time-consuming and not suitable for rapid on-site monitoring applications.
Recent advancements in fluorescence-based detection and optical sensing methods have improved the speed and simplicity of microplastic analysis. Techniques using Nile Red staining have shown promising results for rapid visualization of plastic particles in water samples. Nevertheless, existing fluorescence-based systems are still affected by challenges such as background interference, inconsistent staining efficiency, and reduced sensitivity for very small particles. Many currently available systems also lack proper integration between sample preparation, detection, and automated analysis.
The application of image processing, artificial intelligence, and IoT technologies has further enhanced automation and real-time monitoring capability. However, these systems often depend on high computational resources, large training datasets, and complex calibration procedures. In addition, several proposed methods remain limited to experimental or laboratory-scale studies and are not fully optimized for practical environmental field applications.
Another major limitation observed in previous studies is the lack of low-cost and portable systems capable of providing rapid and reliable microplastic detection in real-time conditions. Most existing methods either offer high accuracy with low portability or portability with reduced analytical performance. Therefore, there is a significant need for the development of an economical, compact, and efficient detection system that combines fluorescence-based sensing, optical imaging, and automated analysis for practical field monitoring.
The present study aims to address these limitations by developing a portable fluorescence-based optical sensor for the detection of microplastics in water. The proposed system focuses on improving portability, reducing operational cost, simplifying detection procedures, and enabling rapid environmental monitoring suitable for real-time water quality assessment applications.

4. Problem Statement

Microplastics, defined as plastic fragments smaller than 5 mm, are now detected in rivers, oceans, soil, and even drinking water. They pose a serious threat to aquatic ecosystems and human health due to their persistence, ability to adsorb toxic chemicals, and bioaccumulation potential. Conventional microplastic detection techniques such as Fourier Transform Infrared (FTIR) spectroscopy, Raman Spectroscopy, and Scanning Electron Microscopy (SEM) provide accurate identification and characterization but are expensive, time-consuming, and unsuitable for routine field surveys. There is a lack of low-cost, portable sensors capable of providing real-time detection and semi-quantitative estimation of microplastics in environmental samples.

6.Methodology

This study presents the development of a portable and low-cost sensor system for the detection of microplastics in water using optical sensing and image acquisition techniques. The proposed methodology is designed to provide rapid and preliminary identification of microplastic particles through fluorescence-assisted visualization and digital image capture. The system integrates an ESP32-CAM module with optical illumination components to create a compact monitoring setup suitable for laboratory-scale and field-based environmental applications.
The methodology focuses on the development of an economical detection platform capable of identifying suspended microplastic particles in contaminated water samples. Conventional analytical techniques used for microplastic analysis are often costly, time-consuming, and dependent on sophisticated laboratory infrastructure. Therefore, the present work aims to develop a simplified sensor-based approach that enables easier operation, reduced analysis cost, and real-time monitoring capability.

The overall methodology consists of sample preparation, sensor setup development, optical illumination, image acquisition, and performance evaluation. Water samples containing microplastic particles are prepared under controlled conditions and analyzed using the developed optical sensing arrangement. The ESP32-CAM module is used to capture images of illuminated samples, while image observations are utilized for identifying the presence of microplastic particles.

5.1 Preparation of Water Samples

Water samples containing different concentrations of microplastic particles are prepared for experimental analysis. Microplastic particles such as polyethylene and polypropylene fragments are added to clean water samples in controlled quantities. To improve particle visibility, Nile Red staining solution is mixed with the samples under controlled conditions. The stained samples are then allowed to stabilize before optical testing. The prepared samples simulate contaminated environmental water conditions for evaluating the performance of the developed sensor system.

5.2 Development of Sensor Setup

The sensor setup is developed using an ESP32-CAM module integrated with a laser illumination source, white LED light source, and supporting electronic components. A transparent sample container is positioned within the optical sensing chamber for image capture. The laser and LED illumination systems enhance particle visibility inside the water sample during image acquisition. The ESP32-CAM module functions as the primary image capturing device and transmits captured images for analysis. Necessary wiring connections, resistors, power supply arrangements, and mounting structures are used for stable operation of the system.

5.3 Image Acquisition and Detection Process

The prepared water samples are illuminated using the optical light sources, and images are captured using the ESP32-CAM module. The interaction of light with suspended microplastic particles improves particle visibility within the captured images. Multiple images are obtained for different sample concentrations and observation conditions. The captured images are examined for the presence, distribution, and visibility of microplastic particles. The fluorescence effect produced by Nile Red staining further assists in identifying plastic particles from surrounding impurities.

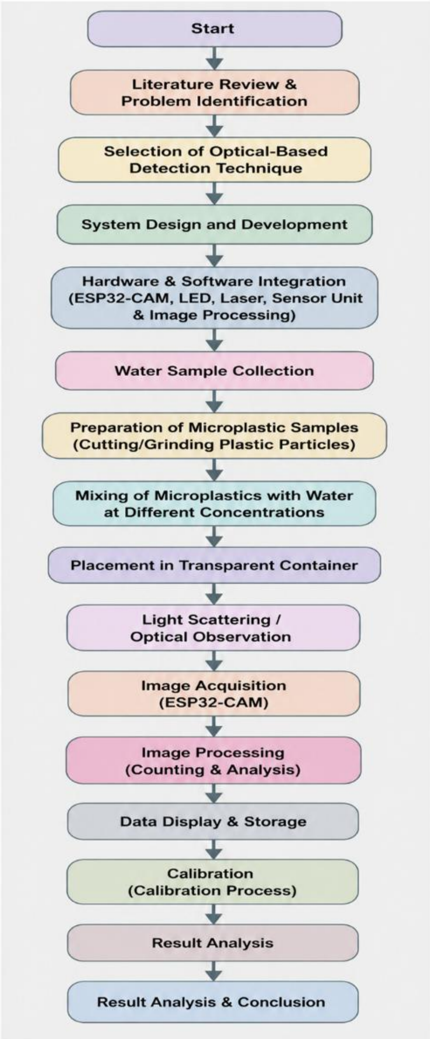
5.4 Experimental Testing and Performance Evaluation

Experimental testing is carried out to evaluate the effectiveness of the developed detection system under different sample conditions. The captured images and optical observations are analyzed to assess the visibility and detection capability of the sensor setup. Parameters such as image clarity, particle identification, response behavior, and detection consistency are considered during evaluation. The performance of the proposed system is compared with the general limitations of conventional laboratory-based methods in terms of portability, simplicity, cost-effectiveness, and rapid monitoring capability.

5.5 Materials Used

The following materials and components are used for the development of the proposed microplastic detection system:

1. ESP32-CAM Module
2. 5V DC Power Adapter
3. 3W White LED Light Source
4. Laser Illumination Module
5. Jumper and Connecting Wires
6. Transparent Water Sample Container
7. Microplastic Sample Particles
8. USB Cable for Programming and Power Supply
9. FTDI Programmer Module
10. Resistors and Supporting Electronic Components
11. Mounting Frame and Sensor Support Structure
12. Nile Red Staining Solution
13. Laboratory Glassware and Sample Handling Accessories



Methodology Flow

6.Result & Discussion

6.1 Introduction to Results

This chapter presents the experimental results and performance evaluation of the developed fluorescence-assisted optical sensor system for microplastic detection using the ESP32-CAM module. The obtained results were analyzed to evaluate the capability of the proposed system in identifying and observing microplastic particles present in water samples under controlled experimental conditions.

The performance of the developed prototype was assessed based on image acquisition quality, visibility of microplastic particles, particle detection capability, and software-based image analysis. Water samples containing different concentrations of microplastic particles were tested to evaluate the consistency, reliability, and efficiency of the detection system.

The experimental analysis mainly focused on:

- Optical visualization of microplastic particles
- Image acquisition using ESP32-CAM
- Detection and counting of particles
- Influence of illumination and light scattering
- Estimation of average particle size
- Software-based output analysis
- Calibration and detection response

The observations obtained during experimental trials were analyzed to determine the feasibility of the proposed low-cost system for preliminary microplastic monitoring applications.

6.2Characteristics of Prepared Microplastics Samples

Parameter	**Observation**
Type of Plastic	Polyethylene / Plastic fragments
Particle Size	Small irregular particles
Sample Medium	Water
Color of Particles	Transparent / White /Multicolour
Observation Method	Optical observation using ESP32-CAM
Illumination Source	LED / Laser light

Experimental Setup Results

The developed prototype successfully captured images of suspended microplastic particles using the ESP32-CAM module.

The captured images were transferred to the Python software (PyCharm), where predefined commands and coding were used for analysis and detection.

The software generated output indicating:

- Whether microplastics were detected
- Total number of particles detected
- Average particle size

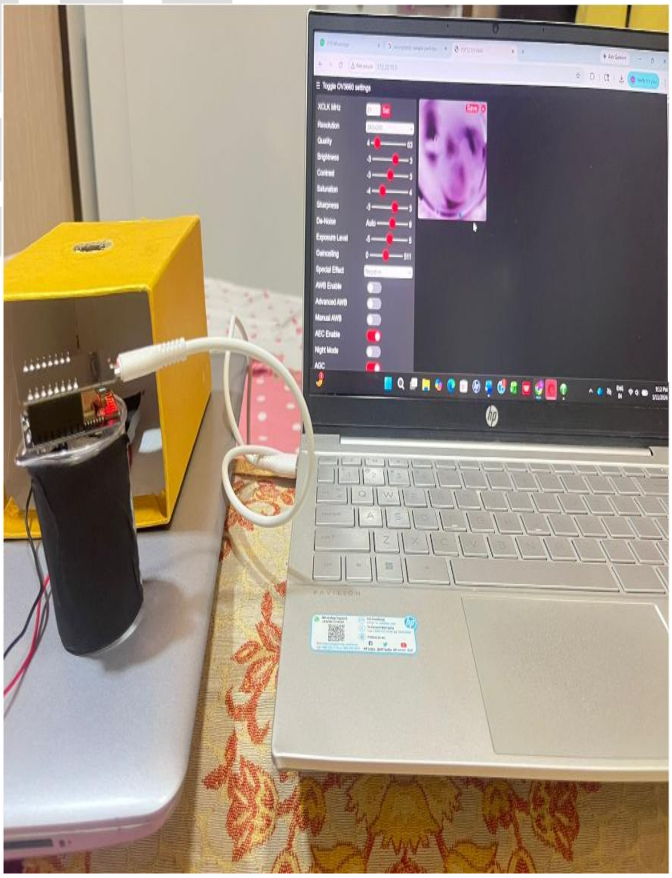


Figure 4.1: Developed Detection Model

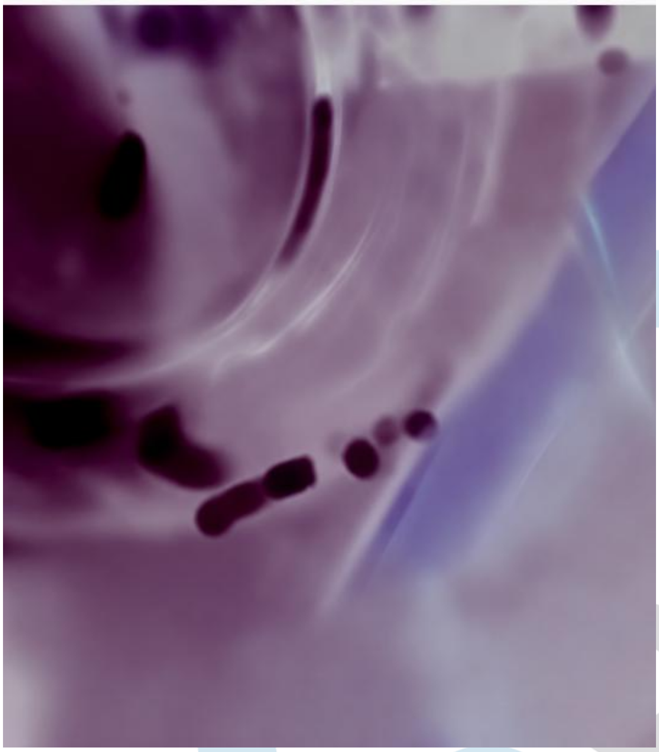


Figure 4.2: Sample Image Captured using ESP32-CAM

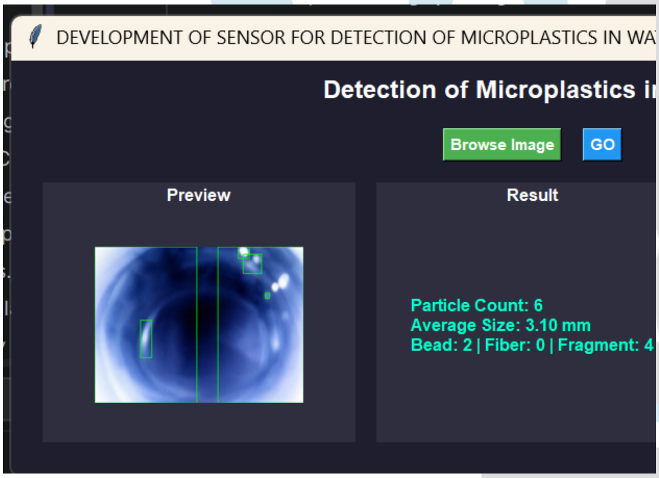


Figure 4.3: Output Window in PyCharm

4.3 Detection Results

Trial	**Sample Condition**	**Microplastics Detected**	**Particle Count**	**Average Particle Size**
1	Low concentration	Yes	12	0.8 mm
2	Medium concentration	Yes	25	1.1 mm
3	High concentration	Yes	46	1.4 mm
4	Clean water sample	No	0	—

4.4 Software Output Analysis

The Python-based detection system successfully analyzed uploaded images and displayed the required outputs. The software was able to identify the presence of microplastics and estimate particle count and average size.

The output generated by the program confirmed that the developed system can perform preliminary microplastic detection using a simple optical setup and software-based analysis.

4.5 Discussion of Results

The experimental observations indicate that the proposed system can effectively detect visible microplastic particles in water samples.

The ESP32-CAM module successfully captured sample images, while the Python-based software analysis provided useful information regarding particle count and average size.

The developed model offers several advantages:

- Low-cost implementation
- Simple operation
- Portable setup
- Easy image acquisition
- Software-assisted particle detection

However, certain limitations were observed:

- Detection of extremely small particles may be difficult
- Lighting conditions affect visibility
- Manual image uploading is required

Despite these limitations, the system demonstrated satisfactory performance for preliminary microplastic detection applications.

6. Conclusion and future work

The present study successfully developed a low-cost optical-based microplastic detection system using ESP32-CAM and Python-based image analysis. The proposed system was capable of capturing images of contaminated water samples and detecting visible microplastic particles through optical observation and software-assisted analysis. The developed model provided particle count estimation and approximate particle size measurement with satisfactory performance under controlled experimental conditions.

The system offers advantages such as low-cost implementation, simple operation, portability, and rapid preliminary detection capability. Although certain limitations were observed, including sensitivity to lighting conditions and difficulty in detecting extremely small particles, the study demonstrates the feasibility of using an optical sensing approach for preliminary microplastic monitoring in water samples. The developed prototype can serve as a foundation for future advancements in portable environmental monitoring systems.

Future improvements can focus on enhancing detection accuracy using high-resolution imaging systems and advanced optical sensors. Automation of image acquisition and real-time analysis can further improve system efficiency. Integration of artificial intelligence and machine learning techniques may enable automatic classification and counting of microplastic particles with higher precision.

The developed model can also be upgraded into a portable IoT-enabled monitoring device for continuous environmental surveillance. Further research should include testing with real environmental water samples and development of a fully automated detection system suitable for large-scale water quality monitoring applications.

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