

Smart Portable Sensor System for Microplastic Detection in Water

Bavatharani K.¹, Janani S.², Leena Sri S.³, Preethi Monika K.⁴

^{1,2,3}Student, ⁴Assistant Professor, Department of Artificial Intelligence and Data Science, NPR College of Engineering and Technology, Dindigul, India.

E-mail: ¹bavatharanik920822243012@nprcolleges.org, ²jananis920822243021@nprcolleges.org,

³leenasris920822243029@nprcolleges.org, ⁴preethimonikak@nprcolleges.org

Abstract

Microplastic contamination is existing as one of the major environmental issues, which needs to be addressed in an efficient manner using economical detection methods. Existing microplastics detection methods use spectroscopic and microscopic approaches to provide accurate results but these methods rely on expensive equipment and sample preparation processes. In the proposed system, LED is used, while the photodiode measures the change in the intensity of transmitted light with the LM358 being the operational amplifier used for signal conditioning. The Arduino Uno serves as the microcontroller, which takes the data input and classifies the level of contamination based on a threshold level. The contamination level is indicated by using an OLED interface and indicator LEDs is used to enable instant interpretation for the users. Experiments carried out using water with various levels of contamination showed reliable sensor operation with quick response time and accurate classification of the contamination level.

Keywords: Microplastics, Water Quality Monitoring, Optical Sensing, Photodiode Sensor, Embedded Detection System, Threshold-Based Classification, Real-Time Contamination Detection.

1. Introduction

Microplastic pollution has become a significant environmental problem due to the prevalence of the pollutants in rivers, lakes, seas, and drinking water supplies. These particles are less than 5 mm in size, and they arise through the breakdown of large plastic pieces and

from numerous industrial and household sources. Due to their resistance and tendency to be incorporated into the food chain, they represent a threat to ecology and may even have adverse effects on humans.

Microplastics detection techniques such as Fourier Transform Infrared (FTIR) spectroscopy, Raman spectroscopy, and microscopy are able to effectively identify and characterize plastic particles. However, these techniques need expensive laboratory equipment, highly trained experts, and lengthy sample preparation processes that make them inconvenient and impractical for routine field testing and real-time environmental assessment. Therefore, the development of inexpensive and user-friendly portable detection devices is increasingly becoming a necessity.

To address these challenges, this research proposes a smart portable optical sensor for real-time detection of microplastics that are suspended in the water by using the principles of optical sensors. The sensor uses an LED as a light source and a photodiode as a detector of changes in the transmitted light due to the microplastics. The signals from the sensor are then amplified and analyzed via the Arduino microcontroller, followed by classification using threshold based decision-making method. The contamination state is displayed via OLED screen and LED indicators.

2. Literature Review

Microplastic pollution has been identified as a a serious environmental threat, which needs to be managed effectively by implementing monitoring and sustainable management systems so that the negative impacts on aquatic ecosystems and water sources can be minimized [1]. Techniques for assisted spectral detection using machine learning have enhanced the accuracy and automation in identification of the contaminants; however, they need advanced instruments and laboratories [2]. Migration and distribution of microplastics in freshwater sources has pointed out the necessity for environmental monitoring on a continuous basis [3]. Recent researches have also considered effective removal systems in order to enhance water quality [4]. Various techniques for sampling, detection, and characterization have been adopted for identifying microplastics in environmental samples [5]. Raman spectroscopy and multivariate analysis have shown high accuracy in identifying microplastics; however, they depend on the laboratory settings [6]. Improved analytical techniques have been introduced to detect the

presence of microplastics in sediments and water samples. However, there are challenges in implementing these analytical techniques [7]. Optical imaging has provided improved capability in rapidly detecting microplastics without causing any damage [8]. Portable optical sensor technology has proved that microplastic detection is feasible at low costs and even in the field [9]. Various research works done on freshwater and drinking water pollution have stressed the need for development of cost effective and real time detection systems [10].

2.1 Research Gap

Although existing microplastics analysis methods can offer high precision and accuracy in their analyses, most of them involve the use of lab-based tools which are costly, laborious and require expert supervision. Advances in optical sensing technology have made it easier to detect microplastics. However, most of the systems that exist are not portable, do not respond in real-time and are costly. Besides, there is only limited research focusing on development of a portable device that will integrate optical sensing technology, real time signal processing and contamination classification all at once. There is therefore a need for a cheap and portable system for detecting microplastics.

3. Proposed Methodology

The proposed methodology involves designing a portable optical sensor that will be used in the real-time detection of microplastics in water. The principle of operation involves the measurement of the difference in light intensity due to the presence of the microplastics in the water. In contrast to traditional approaches, which use laboratory-based systems, the proposed approach involves the utilization of real-time sensing and contamination of water through hardware-based components that allow for low cost, real-time, and portable water testing. The process flow includes optical signal acquisition, signal conditioning, analog-to-digital conversion, contamination classification based on threshold values, and real-time visualization. The combination of optical sensors and embedded signal processing helps in detection with low power consumption and ease of operation.

3.1 System Overview and Hardware Configuration

The proposed sensor includes the functions of optical detection, signal conditioning, embedded signal processing, and instant output into a portable device that detects microplastics

in the water samples. In the process of measurements, the water sample is placed between the light source LED and photodiode in such a way that changes in the optical transmission due to presence of particles can be detected by the sensing unit. The photodiode signal is then amplified by the LM358 operational amplifier and transformed into the digital form by the ADC of the Arduino Uno device. The detected signals are further processed with the help of the threshold technique for detecting contamination at the specified concentrations of 10, 50, 150, and 500 PPL.

The hardware platform consists of a high brightness white LED, silicon photodiode, LM358 op-amp, Arduino Uno with ATmega328P microcontroller, 128x64 I²C OLED display, color coded status indicator LEDs, and 5V battery power source. The technical specifications and respective functionalities of these elements have been tabulated in Table 1. The LED serves as the optical source, whereas the photodiode receives the light transmitted variations. The processed output is analyzed using the Arduino Uno and the status of water contamination is displayed via OLED display and status indicator LEDs.

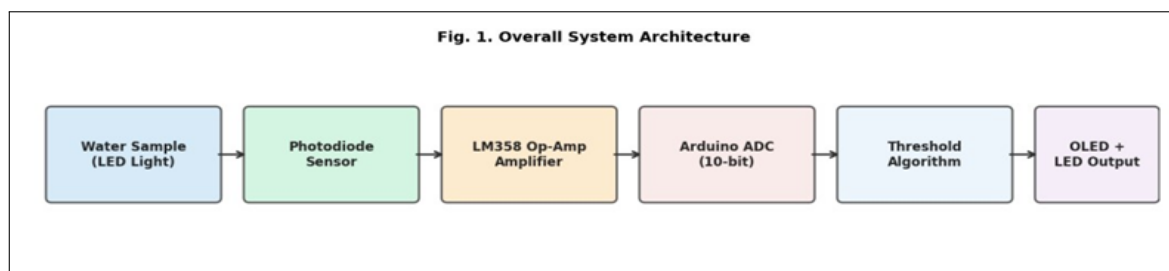


Figure 1. Architecture of the proposed optical sensor based microplastic detection system

In the proposed Figure 1, the components used include an integrated embedded hardware platform consisting of the LED light source, photodiode sensor, LM358 operational amplifier, Arduino Uno microcontroller, 128 x 64 OLED screen, indicator LEDs, and a 5V power supply battery. The specifications and function of the hardware components are illustrated in Table 1. The LED acts as the optical illuminating source, and the photodiode senses changes in the intensity of transmitted light due to the presence of the microplastics suspended in water. The sensor signal is then amplified through the use of LM358 operational amplifier and then converted into digital format using the ADC present in Arduino.

Table 1. Hardware components of the proposed system

Component	Specification	Function
Arduino Uno	ATmega328P	Sensor data acquisition and processing
LED	High brightness white LED	Optical illumination source
Photodiode	Silicon photodiode	Measures transmitted light intensity
LM358	Operational amplifier	Signal amplification
OLED Display	128 × 64 I ² C	Displays contamination level and ADC value
Indicator LEDs	Green, Amber, Red	Visual contamination indication
Power Supply	5 V Battery	Portable system operation

3.2 Water Sample Preparation

To evaluate the proposed optical sensing technique, the lab-prepared water samples having varying concentrations of microplastics were used. The commercially prepared polyethylene microplastics with a size range between 100-500 m were mixed with the distilled water so that different contamination levels could be created, which included clean, low, medium, and high contamination levels. Each of these water samples was properly stirred before conducting the test so that an even distribution of these particles could be achieved to avoid their settling down during the sensing process.

3.3 Data Acquisition and Signal Pre-processing

The experimental data were measured directly by the designed optical sensor system based on lab-prepared water samples instead of the predetermined dataset. In other words, real-time analysis of water samples with varying concentrations of microplastics was done by measuring the intensity of transmitted light via the photodiode sensor. Because of its susceptibility to external disturbances and electrical noise, the acquired analog signal was subjected to signal conditioning before contamination detection. For that purpose, the weak signal was amplified by using the operational amplifier LM358 and then converted into digital form via the 10-bit ADC of the Arduino microcontroller. In order to increase the measurement stability, several samples

were measured via the sensor and their mean value was calculated.

The proposed system does not depend on a fixed dataset since all the measurements will be obtained from the sensing system directly in the process. The water samples with microplastic particles of various concentrations are tested in real-time by measuring the light intensity that passes through the water samples by means of the photodiode sensor. However, since the analog signal obtained will be subject to interference from the environment and electrical noises, signal processing has to be carried out prior to performing contamination analysis. Amplification of the weak signal is done with the help of LM358 operational amplifier and digitization of the analog signal is done by using the 10-bit ADC in the Arduino microcontroller. Several measurements are obtained from the sensors in order to generate the average sensor reading. This is then normalized to remove the fluctuations due to varying conditions in the measurement. The normalization process is expressed as

$$x_{\text{norm}} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

where x represents the measured ADC value, while $x_{\min}$ and $x_{\max}$ denote the minimum and maximum observed sensor readings, respectively. Further enhancing robustness, the averaging of the sensor data can be done by calculating it as

$$x_{\text{avg}} = \frac{1}{N} \sum_{i=1}^N x_i \quad (2)$$

where N represents the total number of sensor measurements and x_i denotes each individual ADC reading. Such a preprocessing step minimizes measurement variance and ensures valid inputs for the classification of contaminants.

3.4 Signal Processing and Contamination Classification

After pre-processing, the normalized sensor outputs are analyzed by using a thresholding decision algorithm for the determination of contamination level. The process involves optical signal acquisition, noise removal, amplification of signals, analog to digital conversion, and finally contamination classification, as shown in Figure 2. The algorithm works by comparing the average ADC value with experimental threshold values for different contamination levels. The lower the reduction of transmitted light intensity, the lower the ADC value, which implies higher levels of microplastics. In this way, the water sample is categorized into Low, Medium, and

High contamination without applying machine learning and off-line training. The contamination classification algorithm is represented as

$$C = f(ADC_{avg}, T_{low}, T_{high}) \quad (3)$$

where ADC_{avg} denotes the averaged sensor reading, while T_{low} and T_{high} represent the experimentally defined threshold values used for decision making. The simple signal processing scheme employed allows for fast real-time classifications with reduced computational overhead, thus making the design well suited to portable embedded implementations.

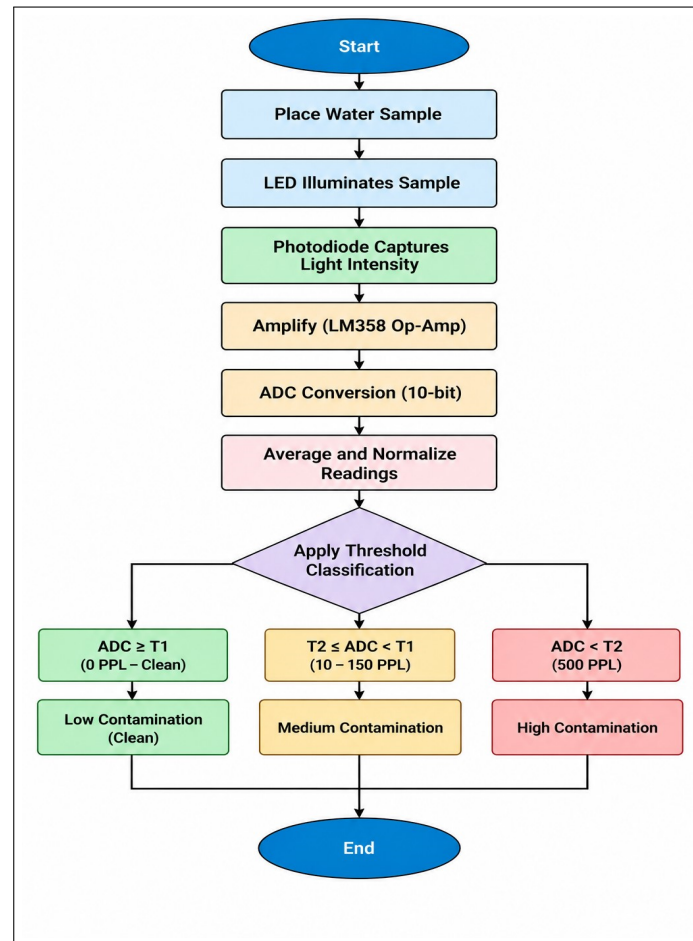


Figure 2. Signal acquisition and threshold based contamination classification workflow

3.5 Communication and Output System

This proposed system integrates a communication module for the proper presentation of sensing data. An OLED display of size 128×64 will be interfaced with the microcontroller to continuously show the ADC value and the level of contamination. This will update after every measurement process and therefore make it possible to monitor the water quality in real time.

In addition to the OLED display, there are also three colored indicator LEDs that help in providing an easy-to-understand visualization of the level of contamination. Green LEDs indicate low levels of contamination, amber indicates medium levels of contamination, and red LEDs indicate high levels of contamination. Dual output technology not only helps in making quantitative information available but also gives visual cues, thus obviating the need of any external computer system.

4. Results and Discussion

4.1 System Performance Evaluation

Table 2. System performance evaluation metrics

Metric	Value
Overall Classification Accuracy	89.2%
Sensitivity (True Positive Rate)	91.4%
Specificity (True Negative Rate)	87.3%
False Positive Rate	12.7%
Avg. ADC Response (Clean Water)	980 ± 6
Avg. ADC Response (High MP)	642 ± 18
Avg. Detection Time per Sample	3.8 seconds
Power Consumption	210 mW
Battery Life (3000 mAh)	> 10 hours

To analyze the performance of the presented optical sensor, water samples were prepared in the laboratory with five different concentration levels of microplastics contamination, from uncontaminated to severely contaminated water. For each concentration level, multiple tests were conducted to check the reliability of the sensor. The photodiode detected the intensity of the transmitted light, which was amplified, digitized by the Arduino ADC, and then processed according to the developed threshold-based classification algorithm. The results of the system's performance analysis are provided in Table 2, and they show that the proposed optical sensor is reliable and provides fast and low-power detection of water contamination.

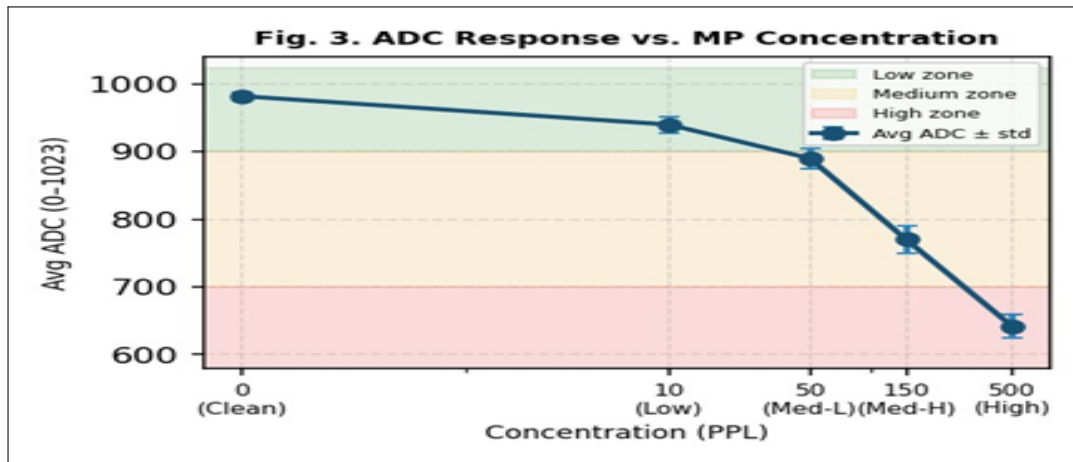


Figure 3. ADC response at different microplastic concentrations

The fluctuation in the ADC response of the photodiode due to microplastic concentrations of 10, 50, 150, and 500 PPL along with the clean-water condition is shown in Figure 3. The response of the ADC drops continuously with an increase in the concentration of microplastics since the suspended particles cause attenuation and scattering of the optical signal. In this experiment, 10 PPL shows the low pollution level, while 50 and 150 PPL indicate the medium pollution level. The high pollution level is represented by 500 PPL.

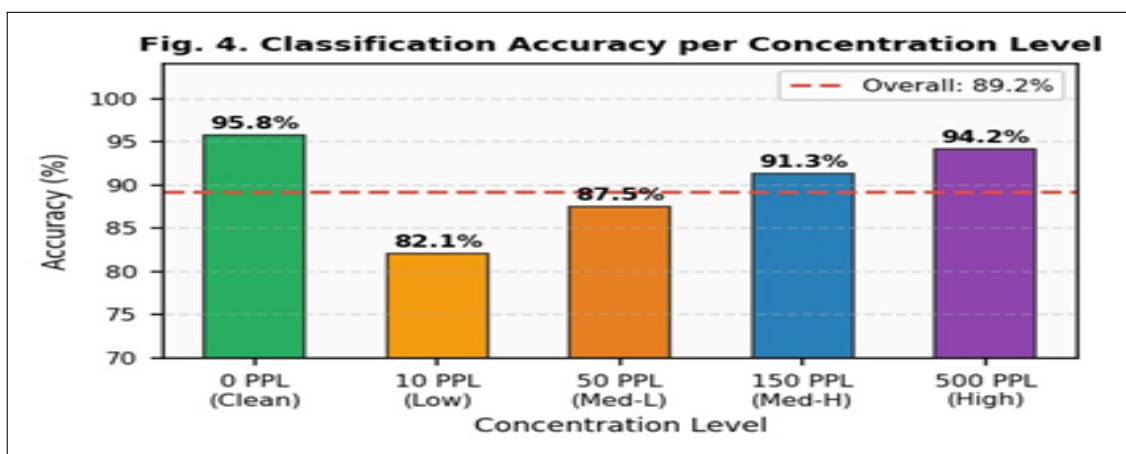


Figure 4. Classification performance across different microplastic concentration levels

The achieved classification performance for various contamination levels is shown in Figure 4. The proposed threshold method successfully distinguishes the contamination classes by using the normalized ADC value of the sensing procedure. Higher classification performance is achieved in the case of medium and high concentrations since the decrease of light intensity becomes more visible. Small deviations in lower concentrations are mostly related to small changes in optical attenuation and noise of the sensor. In any case, the achieved results prove the

efficiency of the proposed approach to the sensing process.

4.2 Comparative Analysis

Qualitative comparisons of the proposed system and existing systems for detecting microplastics are outlined in Table 3. Traditional laboratory methods such as FTIR spectroscopy, Raman spectroscopy, and advanced analysis methods offer accurate identification of polymer composition but usually rely on the use of complex instruments, complicated sample preparation, and laboratory environment. Optical sensing systems and portable sensor-based approaches have made it more convenient to conduct field observations; yet the issues associated with the complexity of the system and calibration are still present. On the other hand, the proposed optical sensing system consists of an LED, photodiode, signal conditioning and classification through a threshold value in a single embedded device.

Table 3. Qualitative comparison of existing microplastic detection methods

Detection Method	Principle	Limitations
FTIR Spectroscopy [5], [10]	Identifies polymer composition using infrared spectral signatures	Requires laboratory instrumentation, sample preparation, and skilled operators
Raman Spectroscopy [6]	Detects microplastics based on molecular vibrational characteristics	High equipment cost and limited portability for field applications
Advanced Analytical Methods [7]	Combines microscopy and spectroscopic techniques for detailed characterization	Time consuming and unsuitable for rapid on-site monitoring
Optical Imaging [8]	Uses optical imaging techniques for particle identification and analysis	Sensitive to imaging conditions and computational complexity
Portable Optical Sensor [9]	Employs optical sensing for compact and field deployable detection	Requires calibration for different environmental conditions

Proposed System	LED and photodiode based optical sensing with threshold-based classification	Provides low cost, portable, and real time microplastic detection for field monitoring
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5. Conclusion and Future Work

The current research has presented a portable embedded system that is capable of detecting microplastics in real time through optical sensing for the purpose of water quality assessment. The combination of LED light source, photodiode sensor, signal conditioning circuit based on LM358, Arduino-based processing unit and threshold-based contamination classification have made the proposed system quick, efficient and economical in nature which doesn't need any sophisticated laboratory setup for detection of microplastics. The validation of the proposed system through experimental analysis has proven its sensing capabilities along with effective contamination classification for water samples having different features. It is evident that the proposed system has become more practical for monitoring the quality of water in real time. Further efforts will be made in future to improve the detection sensitivity for small-size microplastic particles, integration of machine learning algorithm for adaptive contamination classification, wireless IoT-based data transmission capabilities of the system and its validation under various environmental conditions.

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