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An IoT Based Low-Cost Optical System for Early Detection of Microplastics in Water Sources

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Abstract –
Microplastics pollution has been recognized as an issue of concern for the environment with implications for freshwater and marine ecosystems at the global level. Conventional techniques for microplastics detection, such as Raman spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), and electron microscopy, enable accurate detection of microplastics in water. However, these techniques require sophisticated laboratory facilities and expert technical support. These limitations hinder the continuous monitoring of the environment and detection of microplastics in water. This paper proposes an Internet of Things (IoT)-based microplastics detection in water using an optical sensing technique. The proposed system comprises ultraviolet and blue light-emitting diodes, silicon photodiodes, and an ESP32 microcontroller for detecting changes in the scattering of light caused by microplastics in water. Instead of conducting an experiment, this paper examines the feasibility of microplastics detection in water using experimental results obtained in previous literature. Comparative analysis of experimental results of various studies on the intensity-concentration relationships of microplastics in water indicates an attenuation trend in the intensity of light with an increase in microplastics concentration.

Keywords: IoT, Microplastics Detection, Optical Sensing, ESP32, Environmental Monitoring, Water Quality.

I. INTRODUCTION

This research is a response to the increasingly alarming environmental issue of plastic pollution, with a particular focus on microplastics, which refer to plastics smaller than five millimeters and result from the degradation of other plastics and industrial waste. Due to their small size and chemical properties, microplastics accumulate in water systems and bioaccumulate through the food chain. Current detection methods for microplastic pollution primarily rely on spectroscopy and imaging equipment; however, these systems are highly accurate yet expensive and not suitable for field deployment. As a result, water contamination monitoring is often not feasible in underdeveloped regions where specialized equipment is not readily available.

Recent developments in embedded systems and wireless communication technologies enable the development of Internet of Things (IoT) systems. Optical sensing is a promising approach for microplastic detection because the optical properties of microplastic particles differ from those of natural particles. This research proposes a microplastic detection IoT framework using affordable components and the Internet of Things. The components include ultraviolet and blue light-emitting diodes, silicon photodiodes, and an ESP32 microcontroller. The conceptual framework developed in this research serves as the foundation for the next stage of prototype development and water quality analysis using machine learning.

II.LITERATURE REVIEW

A. *Optical Detection of Microplastics*

Previous studies have demonstrated that optical scattering and fluorescence methods can help in distinguishing microplastics from organic matter. The multispectral method shows good results in the classification of microplastics, but it is prone to turbidity.

B. *Imaging and AI-Based Methods*

Camera systems using artificial intelligence and smartphone microscopes have been studied to detect microplastics. These methods improve the performance of microplastic classification, but they require image processing capabilities.

C. *Low-Cost Monitoring Systems*

Several researchers have proposed microscopes and monitoring systems, but they are mostly laboratory-based and cannot be used in real-time applications.

D. *IoT-Based Environmental Monitoring*

The IoT concept using ESP32 and sensor devices has been implemented in agricultural and water monitoring systems, which have been successful in monitoring water quality.

From the above literature, it is observed that microplastic detection systems are yet to be developed, which motivated the authors to propose a method that can be used to develop a prototype in the near future and machine learning–based water quality assessment systems.

III. LIMITATIONS OF EXISTING SYSTEMS

The existing methodologies for the detection of microplastic are limited due to several reasons, such as the cost of equipment, the need for skilled manpower, lack of portability, and the time consumed in the laboratory. These limitations emphasize the need for cost-effective, Internet of Things-based sensing.

IV. PROPOSED MODEL

The proposed system is a conceptual form of an Internet of Things (IoT) optical sensing system.

A. *System Architecture*

The proposed system architecture includes the following components:

- ESP32 microcontroller
- Ultraviolet/Blue Light Emitting Diode (LED) source (400-450 nm)
- Silicon photodiode sensor
- Signal conditioning circuitry
- IoT cloud dashboard (ThingSpeak/Blynk)

When light passes through aqueous solutions, the suspended particles scatter the light. This variation in the intensity of the scattered light is measured and processed.

B. *Working Principle*

1. The LED emits controlled optical radiation.
2. This radiation is scattered in all directions due to the presence of microplastic particles.
3. This radiation is received and converted to an electric current.
4. This electric current is read and converted to analog-to-digital Converter (ADC) values.
5. These values are transmitted to the cloud platform.
6. Contamination detection is done by comparing the intensity of the received radiation.

C. *Detection Algorithm*

Step 1: Initialize sensors and establish Wi-Fi connectivity
Step 2: Measure the photodiode voltage
Step 3: Compare the measured intensity with a baseline value
Step 4: If the intensity falls below the baseline value, send a contamination alert
Step 5: Send the measured data to the cloud dashboard
Step 6: Continue the monitoring process.

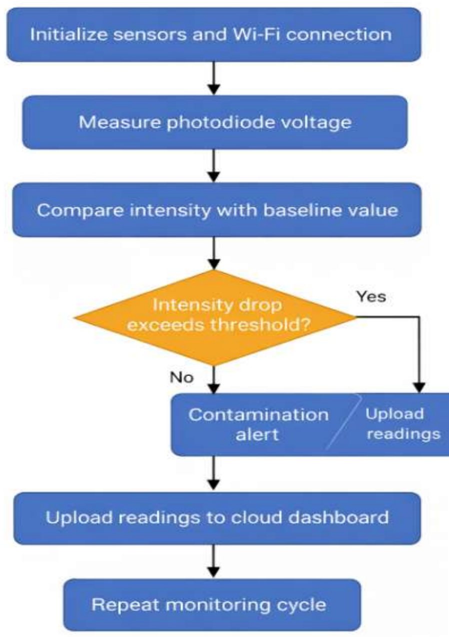

Fig 1. Flowchart of the Proposed system

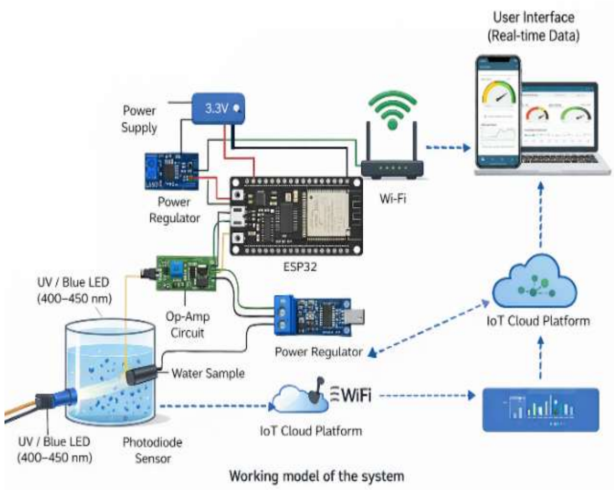

Fig 2. Working model of the system

V. COMPONENT DESCRIPTION

A. *ESP32 Microcontroller*

The ESP32 microcontroller acts as the main processing and communication unit for the proposed IoT-based optical sensing system. The ESP32 microcontroller, designed and developed by Espressif Systems, consists of a dual-core processor, analog-to-digital converter, wireless communication, and power management functions integrated into a single device.

The main functions of the ESP32 microcontroller for the proposed system are as follows:

- Receiving analog signals from the photodiode using the built-in 12-bit analog-to-digital converter.
- Processing the sensor data and performing the threshold-based detection.
- Wireless communication for sending the measured data to the cloud server using the Wi-Fi feature.

The ESP32 microcontroller offers the following operating modes:

- Active mode
- Modem sleep mode
- Deep sleep mode

The ESP32 microcontroller consists of a TCP/IP stack, eliminating the requirement for any separate communication module. This minimizes the complexity and cost of the proposed system.

Fig 3. ESP32 Node MCU Board

B. *UV/Blue LED Source*

The optical illumination unit uses ultraviolet or blue light-emitting diodes, which fall in the range of 400 to 450 nm. This range is used because, at these wavelengths, the optical scattering and fluorescence of microplastic polymers are more pronounced. As light passes through water, several interactions take place, such as Rayleigh and Mie scattering, depending on the size of the suspended particles. These interactions are dependent on the refractive index of the suspended particles. In general, microplastic particles have a higher refractive index compared to natural organic matter, and this difference is reflected as a change in the intensity of transmitted and scattered light. Shorter wavelengths increase scattering efficiency according to optical scattering theory:

$$I \propto \frac{1}{\lambda^4}$$

where λrepresents wavelength.

Advantages of UV/Blue LEDs:

- High optical efficiency
- Low power consumption
- Narrow emission spectrum
- Compact size and low cost
- Enhanced sensitivity to polymer particles

The LED is aligned opposite the photodiode inside a dark optical chamber to minimize ambient light interference.

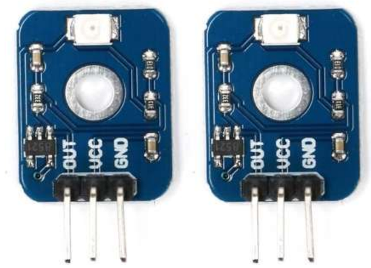

Fig 4. UV Sensor Module

C. *Silicon Photodiode*

The silicon photodiode acts as the optical detector which converts the energy of the incident light into an electric current. This is achieved on the basis of the photoelectric effect. Here, photons of the incident light produce electron-hole pairs.

When photons strike the photodiode surface:

1. Photons transfer energy to electrons.
2. Electron-hole pairs are generated.
3. A photocurrent proportional to light intensity is produced.

The generated current is given approximately by:

$$I_p = R \times P_{opt}$$

where:

- I_p= photocurrent
- R= responsivity (A/W)
- P_{opt}= incident optical power

In this system, increased microplastic concentration causes greater scattering and absorption, reducing transmitted light reaching the photodiode. This produces a measurable decrease in photocurrent.

Reasons for choosing silicon photodiodes:

- High sensitivity in visible and near-UV range
- Fast response time
- Low noise characteristics
- Linear response to illumination
- Low cost and high reliability

The photodiode is operated in reverse-bias mode to improve response speed and measurement accuracy.

Fig 5. BPW34 Silicon Photodiode Sensor

D. *Signal Conditioning Circuit*

Photodiodes have very low current output, measured in the range of nanoamperes or microamperes, making it difficult for a microcontroller's ADC to measure such a low current output. Therefore, a signal conditioning component needs to be added. This component uses a transimpedance amplifier, which consists of an op-amp configuration.
The output voltage is defined as:

$$V_{out} = -I_p \times R_f$$

where:

- I_p= photodiode current
- R_f= feedback resistor
- Functions of the Signal Conditioning Circuit:
- Amplifies weak photodiode signals
- Improves signal-to-noise ratio
- Provides stable voltage output
- Filters electrical noise
- Matches signal range with ESP32 ADC input (0–3.3 V)

Typical design elements include:

- Low-noise operational amplifier
- Feedback resistor and capacitor
- Power regulation filtering
- Analog grounding layout

Proper circuit shielding and dark chamber placement are essential to minimize ambient light and electromagnetic interference.

VI. SOFTWARE AND CLOUD PLATFORM

A. *Arduino IDE – Firmware Programming and Data Acquisition Control*

The Arduino Integrated Development Environment (IDE) is used as a major tool for firmware development, hardware configuration, and ESP32 microcontroller control in the proposed Internet of Things (IoT)-based optical sensing system. The Arduino IDE provides a simplified programming environment based on the C/C++ programming language, which can be used to develop firmware for embedded systems in an efficient manner. In the proposed optical sensing system, the Arduino IDE is used to initialize various hardware modules, set up input/output pins, and enable communication between the sensing devices and the microcontroller.

The ESP32 microcontroller samples analog voltage levels generated by the photodiode using the analog-to-digital converter (ADC) module. The analog signal is processed in the firmware to enable noise reduction and averaging, thereby allowing the microcontroller to read a stable signal value. The analog signal is converted into a digital intensity value that represents the intensity of the received optical power. In addition, a threshold value detection algorithm is implemented in the firmware to compare the intensity value with a predefined baseline value. The microcontroller compares the intensity value with a predefined threshold value, and any variation in the intensity value above a specified threshold value indicates the presence of microplastics in the environment.

The firmware in the proposed optical sensor is used to manage wireless communication protocols using various libraries, thereby allowing the sensor to communicate securely with cloud computing systems. The proposed sensor can operate in power-saving mode, making it a suitable candidate for use in long-term monitoring applications in various environments.

B. *IoT Dashboard ThingSpeak/Blynk Platform*

The IoT dashboard acts as the cloud-based interface that receives, stores, visualizes, and manages the sensor data received from the ESP32 device. ThingSpeak and Blynk are examples of such IoT platforms that allow for the real-time interaction between the devices and the users through the Internet. After the transmission of the sensor readings from the embedded system, the cloud-based platform processes the received data streams and visualizes them using the graphical visualization tool. These visual tools allow for the observation of the changes that occur in the optical intensity measurements in real time, thereby providing immediate feedback on the quality of the water.

The remote monitoring is achieved through cloud connectivity, which allows access to the information on the device from a smartphone, tablet, or computer irrespective of the location. This feature allows for the monitoring of environmental conditions without the need to physically touch the device. Furthermore, the device has the feature to log the received information. This feature enables the device to analyze the received information and provide results to validate the information gathered for research purposes. This information can be exported and analyzed using various tools such as Excel, MATLAB, and Python.

VII. CONCLUSION

This paper proposes a conceptual framework for the development of an Internet of Things (IoT)-based optical sensing system for the early detection of microplastics in water systems. The proposed framework combines the principles of optical sensing with IoT to overcome the limitations of conventional laboratory-based detection techniques, which are expensive, complicated, and impractical for monitoring water systems. From the analysis of the secondary experimental results obtained from the literature, the variations in the optical scattering and absorption of light caused by the presence of suspended microplastics can be effectively monitored using simple photodiode-based sensing architectures.

The proposed system architecture consists of a UV/blue light source, silicon photodiode-based detection, signal conditioning circuitry, and an ESP32 microcontroller for the acquisition and transmission of environmental data. In the proposed model, the threshold-based intensity analysis can be considered an effective early warning system for the detection of potential contaminant events. In the proposed model, the integration of cloud-based dashboards can be considered an extension of the system functionality to support the development of a distributed environmental surveillance system.
While the present work is conceptual in nature and based on secondary data analysis, the results clearly imply the possibility of employing low-cost optical sensing as a supplementary tool for the detection of microplastics using conventional methods. Such a system has the potential to be employed for community-level research initiatives, education-oriented research projects, and environmental screening applications, especially in regions where access to advanced analytical facilities is not readily available.

Future work will be directed towards the physical prototype, its calibration, and validation under different turbidity and environmental conditions. Possible refinements can also be made through the use of multiple wavelengths, the application of machine learning algorithms for better accuracy, and the addition of other water quality parameters such as turbidity, pH, and temperature. It has the potential for development into a smart system that can be useful for the conservation of the environment.

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