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A Portable IoT-Based Colorimetric Sensor for Microplastic Detection in Water Using RGB Spectral Response

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ABSTRACT-
Microplastic contamination is one of the major environmental concerns for both water and oceanic ecosystems worldwide. The detection of microplastic contamination has been achieved by employing Raman spectroscopy, Fourier Transform Infrared Spectroscopy, and scanning electron microscopy, which provide accurate results for identifying microplastic contamination; however, the detection of microplastic contamination is limited by the high costs of the equipment, the complex setup, and the expertise of the personnel. Therefore, there is a need for the development of innovative detection tools for microplastic contamination.

In this study, a portable Internet of Things-based colorimetric sensor system for the early detection of microplastic contamination of water samples has been proposed, which employs RGB-based color changes for microplastic detection. The system employs white light-emitting diodes, a TCS34725 RGB color sensor, and an ESP32 microcontroller for measuring changes in reflected light intensity caused by microplastic particles suspended in water samples. The feasibility of the proposed system has been validated by employing optical scattering theory and comparing the results obtained with the existing literature on microplastic contamination of water samples. The intensity of the reflected light changes significantly with increasing microplastic contamination, showing significant changes in the green and blue colors, which can be used for the detection of microplastic contamination of water samples.

Keywords — *IoT, Microplastic Detection, Colorimetric Sensing, RGB Sensor, ESP32, Water Quality Monitoring.*

I. INTRODUCTION

Plastic pollution is one of the most critical environmental challenges facing today's society. Microplastics, which are described as plastic particles smaller than five millimeters, are derived from the deterioration of larger plastic objects, synthetic fibers, personal care products, and different manufacturing processes. Because of the chemical inertness of these particles, they can persist in aquatic systems, thereby posing ecological and health hazards. Conventional techniques for detecting microplastics include laboratory-based analytical techniques. Spectroscopic techniques, such as Raman spectroscopy and FTIR spectroscopy, have the advantage of identifying different polymers with high accuracy but are limited by the need for specialized equipment that can function optimally at specific conditions. Other techniques, including scanning electron microscopy and fluorescence microscopy, have the advantage of high resolution but are not practical for monitoring systems. Therefore, the monitoring of water systems for microplastics is not practical. Advances in electronic technology have made it possible to develop Internet of Things (IoT)-based monitoring systems. Optical techniques have the advantage of detecting microplastics, as these particles have different optical properties from natural water or sediment. RGB color sensors have the advantage of detecting changes in the spectrum of light. This paper presents a conceptual design of an IoT-based colorimetric sensing system for detecting microplastics.

II. LITERATURE REVIEW

A. *Optical Detection of Microplastics*

Previous studies have shown that optical scattering and fluorescence methods can help in differentiating between microplastics and organic materials. The multispectral technique has shown positive results in the classification of microplastics, although it is influenced by turbidity.

B. *Imaging and AI-Based Methods*
Camera technology that utilizes artificial intelligence, as well as smartphone-based microscopy, has been explored for the detection of microplastics. This technology increases the accuracy of microplastic identification; however, it requires image processing capabilities.

C. *Low-Cost Monitoring Systems*
Several researchers have proposed microscopes and monitoring systems; however, these proposed microscopes are mostly restricted to the lab and cannot be used for real-time monitoring.

D. *IoT-Based Environmental Monitoring*
The paradigm of the Internet of Things (IoT) using the ESP32 platform, along with sensor devices, has been utilized in agricultural and water monitoring systems, resulting in the effective monitoring of water quality.

From the above literature, it is quite evident that the development of microplastic detection systems is in the nascent stage, which has led the authors to propose the framework that can be utilized in the development of the prototype in the near future as well as the implementation of machine learning-based systems for the assessment of water quality.

III. LIMITATIONS OF EXISTING SYSTEMS

The existing techniques for the detection of microplastics are limited in many aspects, including the cost of the equipment, the need for expertise, portability, and time. These limitations have highlighted the need for cost-effective Internet of Things technology.

IV. PROPOSED MODEL

A. *System Architecture*
The proposed system consists of:

- ESP32 microcontroller
- White LED illumination source
- TCS34725 RGB color sensor
- Optical measurement chamber
- IoT cloud dashboard (ThingSpeak/Blynk)

Light reflected from water samples is analyzed using RGB spectral measurements.

B. *Working Principle*

- LED emits controlled illumination into water sample.
- Microplastic particles scatter incident light.
- RGB sensor captures reflected spectral intensity.
- ESP32 reads sensor data via I²C interface.
- Normalized RGB values are calculated.
- Threshold algorithm determines contamination status.
- Data uploaded to cloud dashboard.

C. *Detection Algorithm*
Step1:Initialize RGB sensor and Wi-Fi connection
Step2:Acquire R, G, B, Clear intensity values
Step3:Normalize readings

$$R_n = \frac{R}{C}, G_n = \frac{G}{C}, B_n = \frac{B}{C}$$

Step4:Compare with baseline reference
Step5:Trigger alert if deviation exceeds threshold
Step6:Upload data to cloud platform
Step7: Repeat sensing cycle

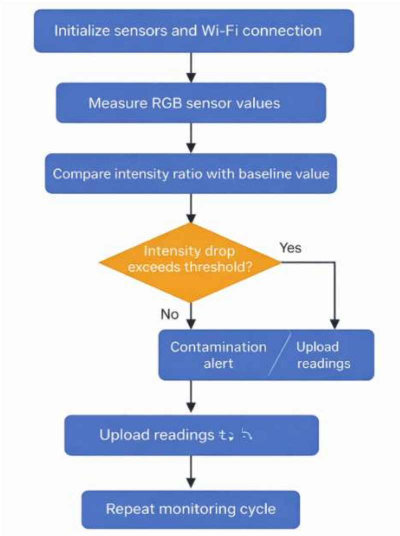

Fig 1. Flowchart of the Proposed system

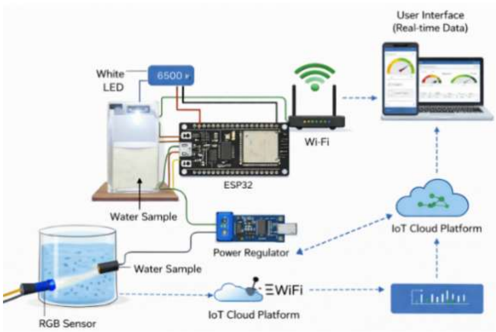

Fig 2. Working model of the system

V. COMPONENT DESCRIPTION

A. *ESP32 Microcontroller*
The ESP32 microcontroller acts as the central processing and communication element of the proposed optical sensing system based on the IoT technology. The ESP32 microcontroller, developed by Espressif Systems, is

equipped with a dual-core processor, 12-bit ADC, wireless communication, and power management.

The primary roles of the ESP32 microcontroller within the proposed system include the following:
- The ESP32 microcontroller is used for the acquisition of analog signals from the photodiode using the 12-bit ADC.
- The ESP32 microcontroller is used for the processing of sensor data and detection.
- The ESP32 microcontroller is used for the transmission of sensor data to the cloud server.

ESP32 microcontroller supports the following operating modes:
- Active mode
- Modem sleep mode
- Deep sleep mode

ESP32 microcontroller is also equipped with a TCP/IP stack, which eliminates the necessity of including a communication module within the system. This reduces the system's complexity, making it less expensive.

Fig 3. ESP32 Node MCU Board

B. *RGB Color Sensor (TCS34725)*

The TCS34725 RGB color sensor is a digital optical sensor designed to measure spectral intensity in red, green, blue, and clear colors with high precision. The device works by employing silicon photodiodes with microscopic color filters that respond to different colors in the visible spectrum. As the sensor detects incident light, photons interact with the semiconductor junction to generate electron-hole pairs, producing a photocurrent proportional to the detected optical power. The device then uses an integrated 16-bit analog-to-digital converter to amplify the analog signal and detect changes in optical intensity with high precision. The clear channel in the sensor allows it to detect changes in luminance without any color filtering effects, which is necessary to compensate for changes in brightness due to changes in lighting or environmental factors. As the level of microplastics in water increases, the amount of scattered light detected by the sensor also increases, allowing it to detect microplastics in water through threshold-based analysis. The sensor works with low computational requirements due to its ability to produce digital output rather than images, making it suitable for IoT device integration in monitoring microplastics in water. Although it does not have the capability to detect polymers like spectroscopic instruments do, it has been found to be useful in detecting microplastics in water at the early stages through colorimetric optical analysis.

Fig 4 RGB Color Sensor Board

C. *White LED Illumination Source*

The white LED illumination source acts as the main optical excitation source in the proposed colorimetric microplastic detection method. It supplies a constant and consistent light spectrum to interact with the water sample and particles, thus allowing accurate optical measurement to take place. The white LED with a correlated color temperature close to 6500 K has been used in this study since it effectively emulates natural outdoor lighting conditions and has a broad spectral distribution in the visible region of the electromagnetic spectrum. The broad spectral distribution ensures that sufficient energy is provided in all regions of the red, green, and blue colors to allow accurate color measurement with the RGB color sensor.

As the photons travel through the sample chamber after being emitted by the LED, they travel through the water sample and interact with the suspended particles in the water sample. In the case of clean water, most of the photons travel through the medium without any significant scattering effect, thus providing constant intensity readings to the sensor. However, in the presence of microplastic particles in water, scattering and absorption of photons take place due to the difference in refractive indices between plastic polymers and water..

D. *Optical Chamber*

The optical chamber is an essential constituent of the proposed colorimetric sensor system and is meant to provide a controlled environment for measurement in order to enable accurate optical measurement. The primary function of the optical chamber is to shield the sensor region from external light sources and environmental factors that could interfere with the sensor readings. Considering that an optical sensor is highly vulnerable to external light sources and their reflections, as well as shadows, the optical chamber is designed to ensure that only light from a specific light source is directed to the water sample and then to the RGB sensor.

VI. SOFTWARE AND CLOUD PLATFORM

The Arduino Integrated Development Environment (IDE) is utilized as a fundamental tool in the development of firmware, hardware setup, as well as the management of the ESP32 microcontroller in the proposed Internet of Things (IoT) technology-based optical sensing system. The Arduino IDE provides a simplified development environment that relies on the C/C++ programming language, which can be utilized to develop firmware for the proposed optical sensing system in an efficient manner. In the proposed optical sensing system, the IDE can be utilized to set up different hardware components as well as to facilitate the communication of the sensing devices with the microcontroller.

The microcontroller of the proposed optical sensing system can be utilized to sample the analog voltage levels generated by the photodiode through the analog-to-digital converter module. The analog signal can be processed to reduce noise as well as to perform averaging, thus enabling the microcontroller to attain a stable value of the analog signal. The analog signal can be converted into a digital intensity value that represents the intensity of the optical power that is being sensed by the optical sensing system. Moreover, a threshold detection algorithm can be utilized to determine the presence of microplastics in the environment by comparing the intensity value of the optical signal with a predefined value in the firmware of the optical sensing system. The microcontroller of the optical sensing system can detect the presence of microplastics in the environment by determining a variation in the intensity value that exceeds a predefined threshold value.

The firmware of the optical sensing system can be utilized to manage the wireless communication protocols of the optical sensing system through different libraries, thus enabling the optical sensing system to communicate securely with cloud computing systems. The optical sensing system can be utilized in a power-saving mode, thus rendering it suitable for usage in different environments.

B. *IoT Dashboard ThingSpeak/Blynk Platform*

The role of the IoT dashboard is to act as an interface that receives, stores, visualizes, and manages the sensor information transmitted by the ESP32 device. ThingSpeak and Blynk can be cited as examples of IoT systems that allow real-time interaction among different devices through the internet. After the transmission of the sensor information by the embedded system, the IoT platform processes the incoming information streams, providing graphical visualization of the same. The graphical visualization of the information allows real-time observation of the changes in the optical intensity measurements, thus providing immediate feedback regarding the quality of the water.

The remote monitoring of the device can be achieved through the cloud interface, which provides access to the information of the device from anywhere in the world through smartphones, tablets, or computers. This allows the user to monitor the environmental conditions without the need to touch the device. The device also has the ability to perform data logging, which enables it to analyze the information it receives and provide the results to verify the information it has collected for the purpose of research.

VII. CONCLUSION

The present study proposes a conceptual framework for IoT-enabled colorimetric sensing for the early detection of microplastics in aquatic systems, using RGB spectral response analysis. The proposed framework, which combines colorimetric sensing and IoT technology, has been developed to mitigate some of the limitations of traditional microplastic detection methods in laboratories, including high operational costs, limited portability, and time delays in obtaining results. The results of this study have demonstrated the effectiveness of colorimetric sensing in detecting microplastics in aquatic systems, where the presence of microplastics in the water column affects the scattering of light and, in turn, the normalized RGB intensity value of the color sensed by the color sensor. The proposed framework, which has been developed to detect microplastics in aquatic systems, has been demonstrated to be effective in detecting microplastics in water, and the spectral response variations have been found to be accurate indicators of contamination trends, which in turn enables the detection of microplastics in water using a threshold-based detection method.

The proposed framework, which has been developed to detect microplastics in water, has been demonstrated to be effective in detecting microplastics in water, and the proposed architecture has been developed to ensure the accessibility and scalability of the proposed framework, which has been achieved by using affordable components in the proposed framework, including IoT technology, which enables the transmission of data and results to the cloud for real-time visualization and monitoring of the environment, and the proposed framework has been demonstrated to be effective in detecting microplastics in water, and the proposed architecture has been developed to support the concept of decentralized surveillance of the environment, where multiple sensors have been deployed in the water to track the level of pollution in the water.

Even though the identification of the polymers is not as detailed as that achieved by Raman spectroscopy or FTIR, the colorimetric method has the advantage of serving as an effective preliminary screening technique that can greatly reduce the number of samples that require detailed laboratory investigation. As such, the system can be seen as an early warning system in the overall monitoring strategy, thus improving efficiency without significantly increasing the complexity of the operation. The RGB measurements, when normalized, can also reduce the impact of varying illumination levels, thus improving the stability of the measurements in a controlled environment.

The future work will be to transform the conceptual strategy into a fully developed hardware prototype that can be subjected to laboratory calibration as well as field testing in different environmental conditions. Some of the improvements that can be achieved in the system include the incorporation of different colored light sources, the development of adaptive calibration strategies, as well as the application of machine learning-based classification techniques to enhance the system's sensitivity as well as reduce false alarms resulting from the presence of turbidity or organic matter in the water samples. The incorporation of other water quality sensors such as turbidity, temperature, conductivity, as well as pH sensors can also greatly enhance the interpretation of the optical measurements in the system. As such, the proposed IoT-based colorimetric sensing technique has the potential to develop into a smart system that can be utilized in the long-term preservation of the environment as well as the management of water resources in a sustainable manner, as well as in the development of water pollution monitoring initiatives by the community at large.

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