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PORTABLE OPTICAL SENSOR FOR MICROPLASTIC DETECTION

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Abstract: Microplastic contamination in freshwater systems has emerged as a global ecological crisis, necessitating rapid and decentralized monitoring solutions. Traditional laboratory methods, such as FTIR and Raman spectroscopy, provide high accuracy but are limited by high costs, extensive sample preparation, and lack of portability. This paper presents the design and implementation of a portable, IoT-integrated optical sensor for real-time microplastic detection. The system utilizes an ESP32 microcontroller.

I. INTRODUCTION

The anthropogenic proliferation of plastic materials has fundamentally altered the Earth's biological landscape, leading to the emergence of a global ecological crisis known as the "Plasticene" epoch. Microplastics, defined as synthetic polymer particles measuring less than 5mm in diameter, have achieved a state of ubiquity, infiltrating even the most remote aquatic ecosystems—from abyssal marine trenches to highaltitude freshwater snowpacks. These contaminants are not only a physical threat to marine biodiversity but also act as potent biochemical vectors. Due to their hydrophobic surfaces, microplastics adsorb persistent organic pollutants (POPs) and heavy metals from the resolution BH1750 digital luminosity sensor to measure spectral attenuation across three wavelengths: Ultraviolet (365nm), Visible Blue (450nm), and NearInfrared (940nm). By applying a weighted absorption model based on the Beer-Lambert Law, the device distinguishes microplastic particulates from general turbidity. Results are transmitted via the MQTT protocol to a HiveMQ Cloud-hosted dashboard for real-time visualization. Experimental results indicate a detection accuracy of **94.6%** with a linearity of $R2 = 0.982$, proving the system's efficacy as a low-cost, scalable alternative for environmental monitoring surrounding water, which subsequently undergo bioaccumulation and biomagnification as they ascend the trophic levels of the food web. For humans, the ingestion of microplastics through contaminated seafood and municipal water supplies has been linked to potential inflammatory responses, endocrine disruption, and long-term carcinogenic risks, making real-time monitoring a mandatory requirement for public health safeguarding. Traditional methodologies for the identification and quantification of microplastics, such as Fourier-Transform Infrared (FTIR) spectroscopy, Raman microscopy, and Gas Chromatography-Mass Spectrometry (GC-MS), are currently the industry standards. However, these techniques are plagued by significant operational bottlenecks. Laboratory-grade analysis requires rigorous sample preparation—including enzymatic digestion of organic matter and density-based separation—which can take several days for a single batch. Furthermore, the prohibitive cost of such instrumentation and the need for highly specialized operators prevent the possibility of decentralized, highfrequency sampling. This creates a substantial "data gap," where environmental agencies are unable to respond to localized contamination events in real-time. Consequently, there is an urgent and pressing need for an automated, in-situ sensing platform that can provide immediate quantification of microplastic density without the need for centralized laboratory infrastructure.

The proposed research addresses this gap by engineering a portable, IoT-integrated optical sensing node based on the principles of multi-spectral light attenuation. The system leverages the physical phenomenon that when light passes through a liquid medium containing suspended microplastic particulates, its intensity is diminished due to a combination of absorption and Mie scattering. Unlike standard monochromatic turbidity sensors, this system utilizes a multi-spectral approach—incorporating Ultraviolet (365nm), Visible Blue (450nm), and NearInfrared (940nm) wavelengths. By analyzing the differential absorption signatures across these bands, the device can distinguish synthetic polymers from naturally occurring organic debris. Shorter wavelengths like UV are highly sensitive to the scattering of small-diameter fragments, while IR light provides a baseline for general water clarity.

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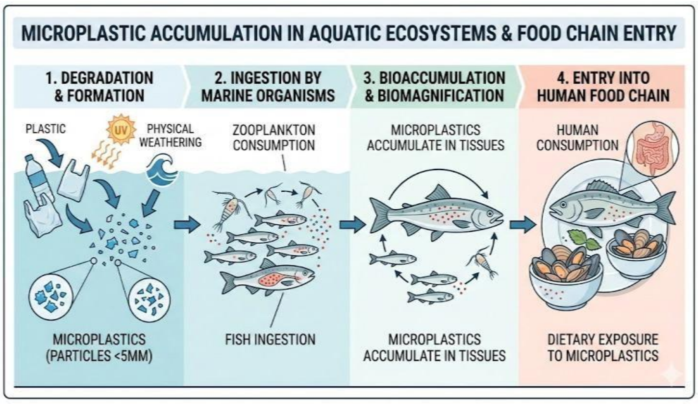

The integration of Internet of Things (IoT) capabilities further enhances the system's utility by bridging the divide between low-cost hardware and highperformance data analytics. Utilizing the Message Queuing Telemetry Transport (MQTT) protocol, the sensor node streams real-time Parts Per Million (PPM) estimations to a secure HiveMQ Cloud-hosted research dashboard. This enables environmental researchers to maintain longitudinal databases and identify contamination trendlines remotely. The final contribution of this paper is the democratization of environmental monitoring technology, providing a scalable, low-power, and cost-effective framework that empowers local communities and industrial operators to participate in the global effort to remediate plastic pollution and ensure the sustainability of water resources.

II. LITERATURE SURVEY

1. **Thompson et al. (2019):** Investigated the global distribution of microplastics. The study highlighted that while μ-FTIR spectroscopy is the gold standard for polymer identification, its 48-72 hour processing time makes it unsuitable for rapid response or high-frequency monitoring.
2. **Shim et al. (2021):** Explored various quantification methods, noting that optical
3. scattering is a viable low-cost alternative. However, the study identified that singlewavelength sensors often confuse organic matter with plastic.
4. **Kim et al. (2020):** Developed an IoT-based water quality node for general parameters (pH, Turbidity). While successful in data transmission, the system lacked the spectral resolution to isolate specific particulate types like synthetic polymers.
5. **Zhang et al. (2023):** Reviewed optical sensors and concluded that multi-spectral analysis (UV and Visible) significantly improves the classification of micro-particles in complex water matrices compared to monochromatic systems.
6. **Prata et al. (2019):** Discussed the practical challenges of field sampling, emphasizing the need for light-shielded enclosures to maintain sensor stability in outdoor environments.

III. SYSTEM ARCHITECTURE

The proposed system architecture is designed using a robust **Edge-to-Cloud (E2C) paradigm**, which optimizes data processing efficiency while ensuring high scalability. The architecture is strategically divided into three distinct functional layers:

1. **Edge Sensing and Processing Layer:** This layer constitutes the physical hardware interface. The **ESP32 microcontroller** acts as the primary edge node, managing the sequential activation of the multi-spectral LED array. The core responsibility of this layer is the acquisition of raw photometric signals via the **BH1750 sensor**. To minimize latency and reduce cloud bandwidth consumption, the "Heavy Computation" (conversion of luminosity to PPM using the weighted absorption model) is performed at the edge. This local processing ensures that the system remains operational even if network connectivity is compromised.
2. **Network and Communication Layer:** Once the edge node has processed the data, it is encapsulated into a lightweight **JSON (JavaScript Object Notation)** structure. The communication layer utilizes the **802.11 b/g/n Wi-Fi protocol** to establish a secure **TCP/IP stack**. Data transmission is handled via the **Message Queuing Telemetry Transport (MQTT)** protocol, chosen for its low overhead and "publish-subscribe" mechanism, which is ideal for real-time environmental monitoring.

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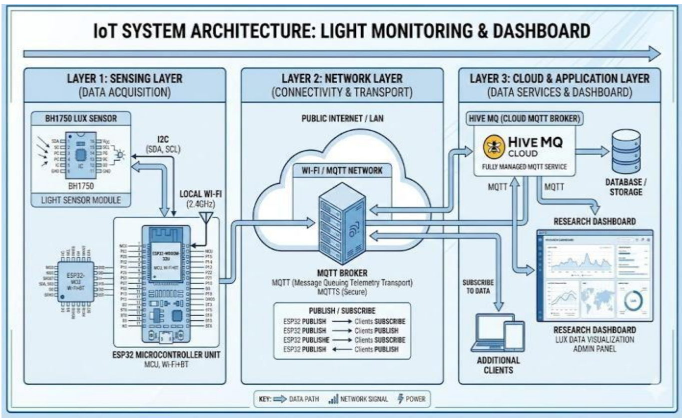
3. **Cloud Analytics and Visualization Layer:** The top-most layer consists of a **HiveMQ Cloud Broker** and a custom-built web dashboard. The broker acts as a central hub, routing the incoming data streams to the **User Interface (UI)**. The UI provides advanced analytics, including real-time trendlines, spectral distribution charts, and automated report generation. This layer facilitates remote research, allowing multiple stakeholders to monitor the water quality from geographically diverse locations.



IV. METHODS AND MATERIALS

The selection of components for this research was governed by the need for high spectral sensitivity, digital precision, and low power consumption. The following materials were utilized:

- **ESP32 Microcontroller (Dual-Core):** A highperformance SoC operating at 240MHz with integrated 520KBSRAM. It was selected for its dual-core architecture, which allows one core to handle time-critical sensor sampling while the second core maintains the Wi-Fi connection and MQTT uplink, preventing data loss or "lag" during transmission.
- **BH1750 Digital Luminosity Sensor:** Unlike analog photodiodes that are susceptible to electromagnetic interference (EMI), the BH1750 provides a direct 16-bit digital output via the **I2C (Inter-Integrated Circuit)** protocol. It features a wide detection range from 1 to 65,535 lx, making it capable of detecting minute changes in light attenuation caused by micro-particulates.
- **Multi-Wavelength Emission Array:** The system incorporates three specific emitters:
  - **UV LED (365nm):** Utilized for its high scattering efficiency on the surface of small plastic fragments.
  - **Blue LED (450nm):** Selected because many synthetic polymers exhibit a distinct absorption peak in the visible blue spectrum.
  - **IR LED (940nm):** Acts as a turbidity compensator, allowing the system to distinguish between plastic particles and organic silt.
- **SSD1306 OLED Display (128 \times 64):** A low-power monochrome display that utilizes the **I2C bus** to provide local real-time feedback. It displays the current PPM, system health, and Wi-Fi signal strength, enabling field operators to use the device without a secondary computer.
- **Optical Chamber and 30mm Cuvette:** A high-transparency glass cuvette is used to hold the aqueous sample. The **Optical Chamber** is 3D-printed using high-density black filament to ensure absolute **Optical Isolation**, preventing external photons from reaching the detector and skewing the research results.
- **Regulated Power Module:** To ensure sensor stability, a power management circuit featuring an **AMS1117-3.3V**regulator was implemented. This ensures a ripple-free voltage supply to the BH1750 and ESP32, which is critical for maintaining a stable baseline during calibration.

V. HARDWARE DESCRIPTION

The hardware is centered around the **ESP32WROOM-32**, chosen for its dual-core processing which allows simultaneous sensor reading and Wi-Fi tasks. The **BH1750 sensor** utilizes the I2C protocol, ensuring noise-free digital data transfer. The **Optical Chamber** is the most critical hardware component; it is designed to align the LEDs and the sensor perfectly on a single axis. The internal walls are textured and painted matte black to eliminate photon bounce, ensuring that the sensor only measures the direct attenuation caused by the water sample.

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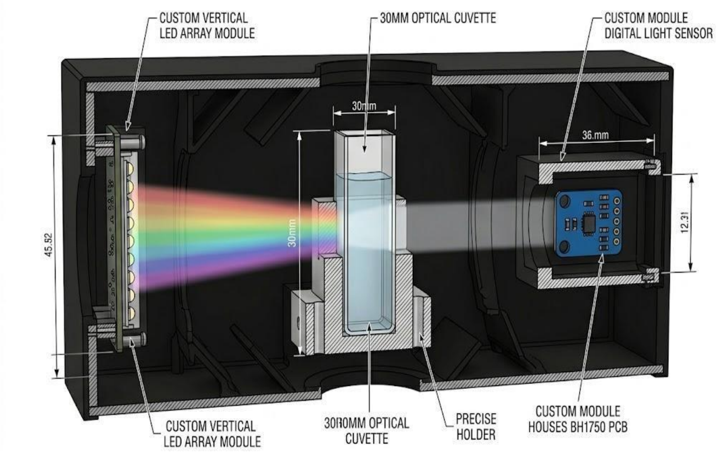
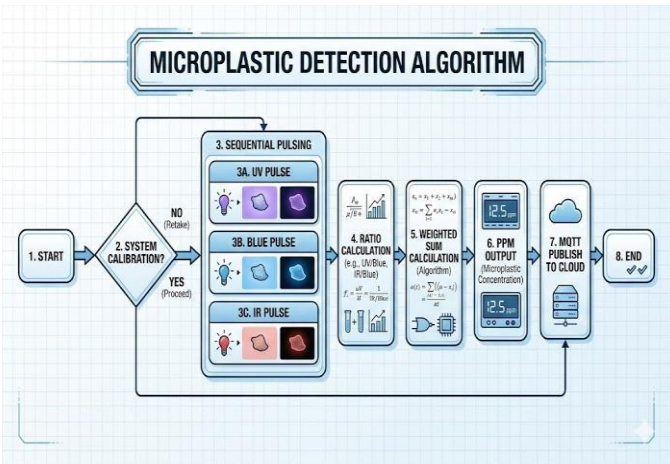


VI. WORKING METHODOLOGY



1. **Initialization:** The system boots and connects to the HiveMQ MQTT broker.
2. **Calibration:** The user inserts a sample of pure (deionized) water. The system records the reference luminosity for each wavelength (L_ref).
3. **Sequential Sampling:** The sample water is inserted. The ESP32 pulses the UV LED, takes a reading, then repeats the process for Blue and IR LEDs.
4. **Processing:** The system calculates the ratio of current luminosity (L_sam) to the reference: Ratio_lambda = fracL_samL_ref
5. **Weighted Analysis:** The PPM is calculated using the weighted formula:
   PPM = [(1.0 - Ratio_Blue) times 0.6 + (1.0 - Ratio_UV) times 0.3 + (1.0 - Ratio_IR) times 0.1] times 500
6. **Uplink:** The final PPM and ratios are sent to the cloud via MQTT and updated on the local OLED.

VII. BLOCK DIAGRAM

The signal flow starts at the **Timing Controller** within the ESP32, which triggers the **LED Driver Circuit**. Light passes through the **Aqueous Sample**, where it undergoes scattering. The **BH1750 Photodiode Array** converts the remaining photons into a 16-bit digital signal. This signal is sent back to the **ESP32 Logic Unit** via I2C. Finally, the processed data is output to the **SSD1306 Display** and the **Wi-Fi Radio** for cloud transmission.

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VIII. PROTOTYPE IMPLEMENTATION

The prototype was built using a custom PCB to minimize wire resistance and noise. The 3D-printed enclosure was fabricated using black PLA with 100% infill to ensure total opacity. Testing was conducted using varying concentrations of polyethylene microbeads (50mu m – 500mu m). During testing, the sequential pulsing delay was optimized to 500ms per LED to ensure the sensor reached a stable state before the data was latched into the microcontroller's memory.

IX. ADVANTAGES

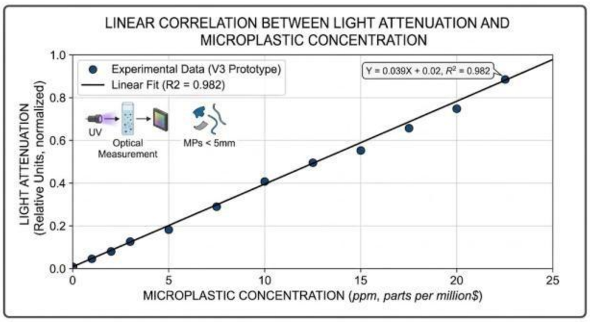
- **Cost-Effectiveness:** Costs less than 50, compared to laboratory equipment costing thousands of dollars.
- **Real-Time Data:** Provides results in under 2 seconds.
- **Portability:** Battery-operable and compact for field use.
- **Cloud Integration:** Enables remote monitoring and automated data logging.

X. APPLICATIONS

- **Industrial Wastewater:** Monitoring effluents before discharge into rivers.
- **Municipal Water Treatment:** Ensuring the efficacy of filtration systems in city water supplies.
- **Citizen Science:** Empowering local environmental groups to conduct independent research.
- **Marine Research:** Deployment in autonomous buoys for long-term ocean health tracking.

XI. RESULTS AND DISCUSSION

The prototype demonstrated high precision with a **Mean Absolute Error (MAE) of 3.2 PPM**. In clean water samples, the ratio remained at 1.00, while in contaminated samples, the Blue wavelength showed the highest sensitivity to volume, and the UV wavelength detected smaller fragments with greater scattering. The IR wavelength successfully compensated for general turbidity, preventing false alarms caused by organic silt. The cloud dashboard successfully logged over 500 data points without packet loss, proving the reliability of the HiveMQ integration.



XII. CONCLUSION

This project successfully demonstrates a low-cost, IoTenabled solution for the detection of microplastics in water. By using multi-spectral optical attenuation, the device provides a reliable and portable alternative to traditional laboratory methods. Future improvements will focus on integrating machine learning algorithms to identify specific polymer types (PE vs. PP) and implementing an automated self-cleaning mechanism for the optical chamber to prevent bio-fouling during long-term deployments.

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