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Embedded Optical Sensor System for Bisphenol A Detection

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Abstract

In recent days, the growing presence of microplastics and bisphenol A (BPA) in water and land environments raises serious concerns for both ecosystems and human health. There is a pressing need to create portable, fast and affordable ways to detect these substances, as a result. This study introduces an optical sensor designed to detect microplastics and BPA. This study uses principles like spectroscopy and fluorescence. This sensor includes an optical transducer that has been chemically modified and works with micro plastics whose surfaces have been altered to improve sensitivity. For identifying microplastics, the sensor uses light scattering and Fluorescence spectra to determine the type of microplastics and the size of the particles. To detect BPA, the sensor relies on the absorbance responses of the sample, using molecularly imprinted polymers (MIPs) to specifically recognize BPA. This sensor was tested using standard solutions and actual water samples from water bodies to check its accuracy, selectivity and how quickly it responds. The early findings of this study shows that the sensor can detect

BPA at low concentrations in the nano molar range and can distinguish micro plastics as mall as a few micro meters. These results align well with those from traditional methods that has been carried out in early evolution stage of detection like high performance liquid chromatography (HPLC) and Fourier transform (FT-IR) spectroscopy. The optical sensor is portable, inexpensive and suitable for real time, onsite monitoring of microplastics and BPA pollution. This research supports the development of optical sensing technologies for environmental monitoring and offers a scalable solution for detecting BPA in water systems.

Keywords: Bisphenol A (BPA), Fluorescence, Concentration, Microplastics, Light Dependent Resistor (LDR), and Light Emitting Diode (LED).

1. Introduction

In recent decades, the use of plastic materials has excessively created a major global environmental problem because of plastic pollutants keep building up and staying in natural ecosystems for a long time. Among the plastic pollutants, microplastic particles smaller than 5mm have a lot of attention drawn because, they are found in the oceans, rivers, on land and almost everywhere. These plastic particles do not easily break down because of their molecular bonds and might carry harmful substances such as toxic elements, lead, heavy metals and other pollutants that remain in the environment over a long time. When it is subjected to aquatic ecosystems, animals might eat these microplastics, it can cause a threat to the aquatic ecosystems and also to human health because, these pollutants may pass into human bodies through the food chain and gets into people who consume contaminated seafood.

Along with microplastics, bisphenol A (BPA) a synthetic organic chemical that is often used in making of polycarbonate (PC), Thermoplastic and epoxy resin has become a most significant environmental concern factor in recent decades. BPA disrupt the endocrine system and interfere with hormone function in both humans and animals, causing a toxic harm. The BPA often gets leaked from plastic containers, food packages and industrial waste resulting in the presence of BPA in water, soil and the water we consume. If the exposure to BPA is for a long term, it might result with issues such as reproductive problems, metabolic disorders and developmental issues. There are many Conventional methods used to identify Bisphenol A (BPA). Like Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy and High Performance Liquid Chromatography (HPLC) are known for their accuracy and ability to detect small amounts of these substances. But, these techniques have a drawback of taking a lot of time to calculate the

BPA, skilled personnel are required and the procedure depends on complex equipment, which makes these traditional or conventional methods unsuitable for fast or remote onsite testing in testing area or environment. There is a crucial need for new, efficient, reliable, portable and easily affordable technologies that can detect these BPA pollutants from the microplastics faster and at low levels, as a result. Optical sensing technology represents a promising alternative sensing technology because it is cooperated with several advantages like high sensitivity, resulting faster, non- destructive testing and ability to be made small and portable. These optical sensors can be designed to utilize different optical effects such as absorbance and fluorescence.

2. Literature Review

Bisphenol A (BPA) is an endocrine-disrupting chemical widely used in polycarbonate plastics and epoxy resins, and its leaching into food, water, and the environment has raised serious health concerns, necessitating sensitive and rapid detection methods [1]. Conventional analytical techniques such as high-performance liquid chromatography and gas chromatography provide accurate BPA quantification but suffer from drawbacks including high cost, complex sample preparation, and lack of portability, limiting their suitability for on-site monitoring [1,2]. To overcome these limitations, optical sensors have gained significant attention due to their advantages of real-time detection, simplicity, high sensitivity, and potential for miniaturization [3]. Various optical sensing strategies have been reported for BPA detection, including photonic crystal-based sensors that exploit refractive index changes or diffraction shifts upon BPA binding, enabling label-free and visually observable detection [2,4]. Optical fibre sensors functionalized with polymers such as chitosan have also demonstrated enhanced sensitivity by increasing BPA adsorption on the sensing surface and translating molecular interactions into measurable optical signals [3]. Furthermore, molecularly imprinted polymer (MIP)-based optical sensors have shown excellent selectivity toward BPA by providing specific recognition sites, and when combined with photonic crystal or fluorescent platforms, they enable highly sensitive and selective detection even at trace levels [4,5]. Recent developments integrating optical sensors with smartphone-based readout systems further highlight the potential of optical sensing technologies for portable, low-cost, and user-friendly BPA monitoring in environmental and food safety applications [4,6].

3. Methodology

Red Laser source with a wavelength of 385nm, serves as light source for generating fluorescence and absorbance readings. LDR or photodiode, functions to measure the light that passes through or emitted by the sample. The sample holder or cuvette chamber, constructed to contain liquid sample that has microplastic in it and that allows consistent light transmission through the sample that is obtained by the LDR. Microplastic particles such as polystyrene, polypropylene and polystyrene with controlled size ranges (1-100µm). Ethanol, Methanol, Acetone and buffer solutions for sample preparation and cleaning. Arduino Uno/Raspberry Pi micro controller. Wi-Fi module ESP32 for IOT connectivity. LCD display for onsite readings and cloud interface Thing Speak for remote monitoring. The hardware design integrates the optical sensing unit, signal processing unit and data transmission unit into a single efficient system. The sensing part mainly includes UV LED that operates at the range of 385nm as input light source, then a water sample containing micro plastic is hold by a container and the light that passes through or is emitted by the sample is detected by the LDR. The arrangement of Light source and photodiode are in a straight line on opposite sides of the container to maximize light transmission and reduce any loss of light.

The Arduino Uno functions as the main processor, gathering voltage signals from the photodiode and transforming them into digital data that shows the level of light or the presence of contaminants. The system is powered by a 5V DC power source and an LCD screen is connected to display real time measurements like light intensity or contaminants levels.

4. Flow Map

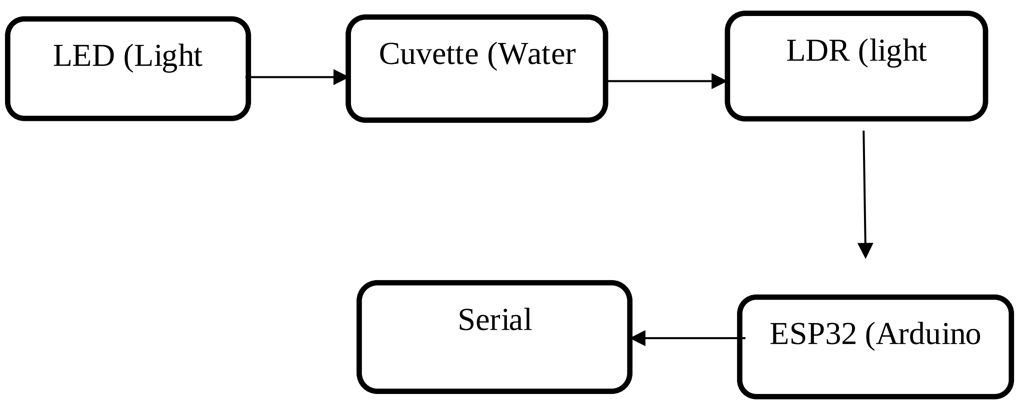


Figure.1. Block diagram of optical sensor for BPA detection.

The above depicted flow map Fig (1) shows the optical sensing based microplastics detection setup that works on the principle of light absorption and scattering. The system consists of a light source, sample holder, optical detector, processing unit, and output display. The LED acts as a stable and continuous light source for the system. It emits monochromatic or near-monochromatic light directed toward the sample. The intensity of the emitted light remains constant throughout the experiment to ensure reliable measurements. The cuvette holds the water sample containing microplastics. When the LED light passes through this medium, microplastic particles interact with the light.

As the concentration of microplastics increases, the amount of transmitted light decreases. This variation in transmitted light intensity forms the basis for microplastics detection. The LDR is positioned directly opposite the LED to detect the transmitted light emerging from the cuvette. The resistance of the LDR varies inversely with the intensity of incident light.

High transmitted light → Low LDR resistance
Low transmitted light → High LDR resistance

This resistance change is converted into a voltage signal using a voltage divider circuit. The resulting analog voltage represents the optical attenuation caused by microplastics in the sample. To support real time monitoring and data recording, the optical sensor is connected with IoT technologies. The ESP32 Wi-Fi module, which is a part of the node MCU, is connected to the Arduino using serial communications to allow wireless access. This module sends the optical data to an internet based IoT platform. The sensor data is sent to platforms like Think Speak or Blynk, where it is stored, processed and displayed in chart. This lets the users view real time information such as optical absorbance, BPA levels or the presence of microplastics from any device with internet access.

Users can track pollution levels continuously through the IoT interface, examine patterns and download data for additional analysis. The system is also setup to send warnings or messages when pollutant levels go beyond defined limits. The signals from the LDR detector were converted into digital data and analyzed to measure the amount of BPA present. Important factors like lowest detectable level, how sensitive the sensor is and how quickly it responds were determined. The sensors accuracy was checked by comparing its findings with result from traditional techniques like FTIR and HPLC. Statistical methods proved that the system consistently gives reliable, selective and trustworthy results for monitoring the environment.

5. Experimental Setup

The goal is to create and build an optical sensor that uses a Laser light source, LDR and a sample holder to detect Bisphenol A (BPA) in water. The sensing surface will be modified with nanomaterials and molecularly imprinted polymers (MIPs) to enhance the sensors sensitivity and ability to distinguish between different substances. As the Red Laser source passes the sample holder that consists of micro plastics, the absorbance is done by the micro plastics. The transmitted light is detected by the LDR sensor or UV Photodiode. With these both parameters and the molar absorbance and path length we can determine the concentration of the sample that consists of the micro plastic.

With the concentration the BPA range is found out and the output is given the result. The sensor will be calibrated and tested using standard solutions of BPA samples with known sizes and concentrations. The performance of the sensor will be analyzed and confirmed by comparing the results with those obtained from traditional laboratory techniques like FT-IR and HPLC.

All experimental procedures were designed to ensure environmental safety, with proper disposal of chemical reagents, BPA solutions following laboratory waste management guidelines. The project avoids the release of microplastics or harmful chemicals into natural water bodies during testing, using controlled laboratory environments only. Data integrity and transparency were maintained by accurately recording, analysing and reporting all experimental results without manipulation or bias. Standard Bisphenol A (BPA) solutions were made at different concentrations, ranging from 0.1µm to 100µm, using deionized water. Similarly, microplastics suspensions with defined particle sizes, between 1 and 100µm were created by carefully dispersing the particles and using ultrasound to ensure even mixing. The optical sensor was tested with pure deionized water first to measure the baseline absorbance or fluorescence intensity.

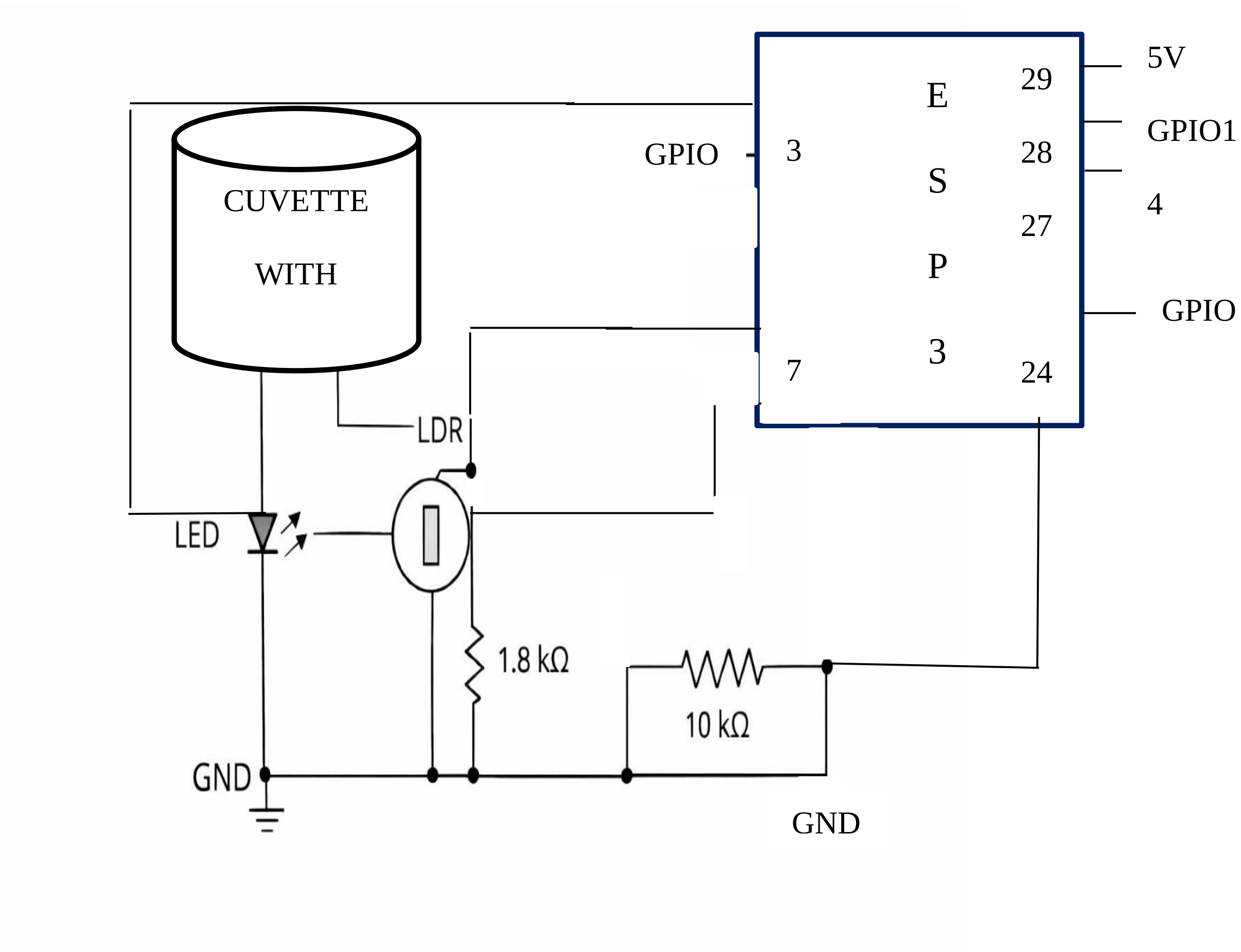


Figure.2. Circuit schematic diagram

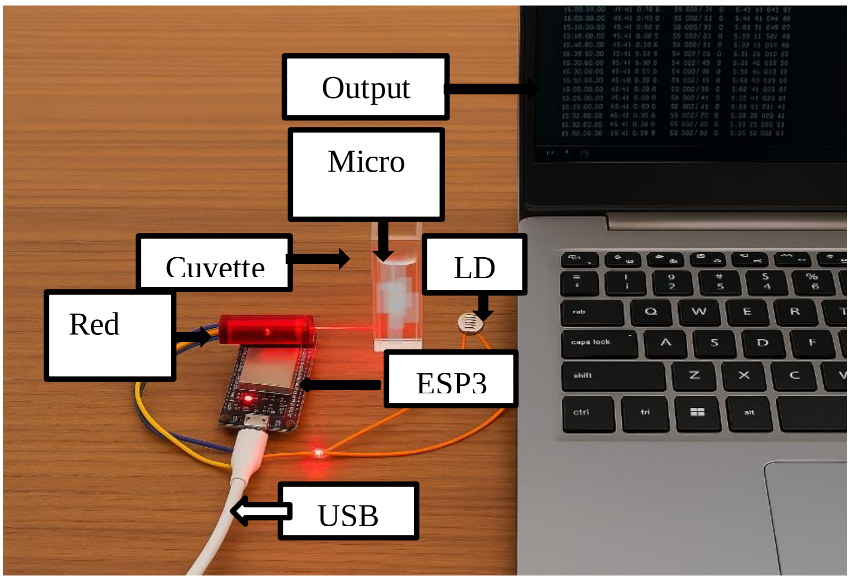


Figure.3. Experimental setup

Each BPA and microplastic standard was placed into the sample holder and the optical response such as absorbance, scattering was measured using the Light source and LDR detector and UV photodiode. Check that the Light source, sample holder and LDR detector are properly align and that all electrical connections are secure.

6. Sensor Placement and Configuration

In the developed optical sensor for BPA detection, the sensing element is placed directly in the sample interaction zone to ensure effective contact between the analyte and the BPA-selective sensing layer, typically within a cuvette or flow cell for liquid samples. The sensor is aligned along a defined optical path where a UV or visible light source illuminates the functionalized sensing surface, and the transmitted or emitted light is collected by a photodetector positioned opposite the source. The sensing region is enclosed to minimize interference from ambient light and environmental variations. The overall configuration comprises an appropriate optical source, a BPA-selective sensing layer, and a detector connected to a signal processing unit, where optical changes resulting from BPA binding are converted into electrical signals and quantified using calibration curves.

Table.1. Combined Measurement of Red Laser Transmission and BPA Detection in Microplastics

Type of Microplastic	Red Laser Transmission (%) at 650 nm	Measured BPA Concentration (µg/L)	Observation
Polyethylene (PE)	85 ± 3	0.5 – 1.2	High transmission, low BPA presence
Polypropylene (PP)	82 ± 4	0.4 – 1.0	Acts mainly as BPA carrier
Polystyrene (PS)	68 ± 5	2.0 – 4.5	Moderate transmission, elevated BPA
Polyethylene terephthalate (PET)	78 ± 4	1.5 – 3.0	BPA traces from additives/recycling
Polyvinyl chloride (PVC)	50 ± 6	4.0 – 7.5	Low transmission, high BPA leaching
Polyamide (Nylon) (PA)	72 ± 4	1.0 – 2.5	Moderate optical loss, moderate BPA
Polycarbonate (PC)	90 ± 2	8.0 – 15.0	High transmission, major BPA source

Standard BPA solutions ranging from 0.1 to 100 micro molar and microplastic suspensions, with particle sizes between 1 and 100µm were made using deionized water. The optical sensor system consists of a Light source emitting at 385 nm, a sample holder, LDR detector positioned directly opposite to the laser. The Light source was turned ON and allowed to stabilize for 2 to 3 minutes before taking any measurements. The sample holder was cleaned with Ethanol and deionized water to prevent any contaminations. A pure water account for any background interference. Each sample was introduced into the system and the optical intensity was detected and recorded. The analog signal from the detector was converted into digital data using an Arduino microcontroller, displayed on an LCD screen and sent to an IoT platform through an ESP32 module. Each concentration level was measured 3 times to ensure consistent and reliable results. The optical sensor showed a clear increase in detector response with increasing BPA concentration and microplastic particle density, indicating good sensitivity. Smaller microplastic particles(1-100µm) caused less scattering compared to large particles. But, the sensor could still detect the reliability.

7. Results

The result is based on the Arduino IDE coding that takes the transmittance and absorbance to calculate the concentration. With the concentration rate we can determine the range of BPA present in the sample solution.

$$A = \varepsilon * b * c$$

Where , Absorbance(A)

Molar absorptivity(ε)

Path length of the cuvette(b)

Concentration of the solution(c)

Here the length(b) is constant that is 2cm and molar absorbance(ε) is 100mm with this the absorbance(A) is found out. Concentration is found by,

$$c = A / (L \times \mathcal{E})$$

The concentration is found out by the absorbance of the microplastics to the constant path length, molar absorbance and transmittance.

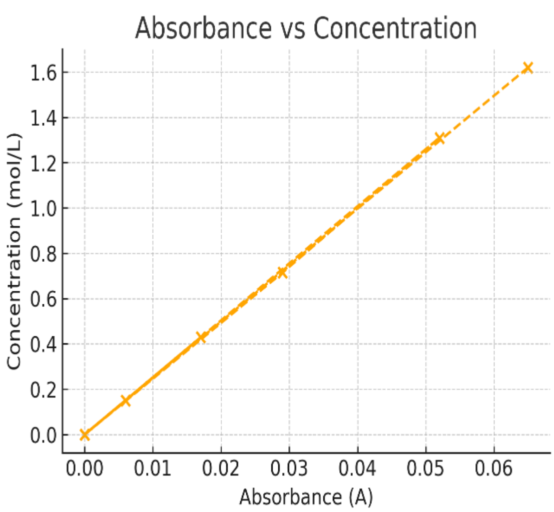
Table.2. Transmittance, Absorbance and Concentration Values

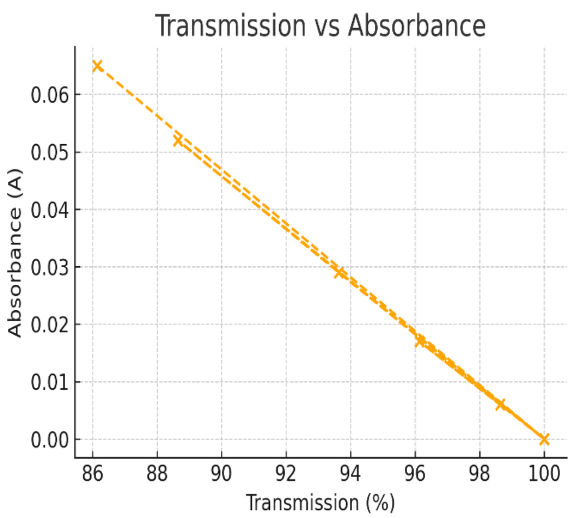
Port	Intensity	Transmittance(t%)	Absorbance	Concentration (mol/L)
16:18:09.644	I1: 69.00	86.14	0.065	1.619585
16:18:11.602	I1: 81.00	100.00	0.000	0.000000
16:18:13.616	I1: 75.00	93.63	0.029	0.714281

16:18:15.626	I1: 71.00	88.64	0.052	1.309354
16:18:17.602	I1: 84.00	100.00	0.000	0.000000
16:18:19.602	I1: 87.00	100.00	0.000	0.000000
16:18:21.615	I1: 77.00	96.13	0.017	0.428544
16:18:23.642	I1: 79.00	98.63	0.006	0.150135

7.1 Sensor Response to BPA

The optical sensor showed a proportional increase in detector output with increasing BPA concentration. Calibration curve for BPA exhibited linear behaviour over the range 0.1-100µm. Repeated measurements showed high repeatability with standard deviation (<5%). As the concentration increases the amount of BPA also increases with accordance to the constant length and molar absorbance.





In the as the absorption increases by the microplastics when the light source passes through it, the concentration also increases. As the concentration increases, we will be able to measure the BPA range. Some concentration ranges for microplastic is given below. With the concentration level, we will be able to calculate the amount of BPA present in the sample. Higher the concentration of the sample, higher the BPA content. In the it is the basic principle which is absorbance inversely proportional to transmission. Sensor readings were successfully transmitted in real time to the Thing Speak/Blynk cloud platform. Remote monitoring enabled instant detection of BPA.

7.2 Validation with Standard Methods

Sensor readings for environmental water samples were compared with FT-IR and HPLC results. Differences were minimal (<7%) indicating high accuracy and reliability of the developed optical sensor.

Table.3. Parameters Values

Microplastic Type	Red Laser Transmission (%) at 650 nm	BPA Concentration (µg/L)	Optical Observation	BPA Inference
Polyethylene (PE)	85 ± 3	0.8 ± 0.2	High transparency, low scattering	Negligible BPA presence
Polycarbonate (PC)	90 ± 2	12.0 ± 1.5	High transmission, stable signal	Major BPA source

The combined optical and chemical measurements demonstrate a clear distinction between microplastics with negligible BPA involvement and those that act as significant BPA sources. Polyethylene (PE) exhibited high red laser transmission with minimal BPA concentration, indicating low additive content and limited interaction with BPA. In contrast, polycarbonate (PC) showed high optical transmission alongside markedly elevated BPA levels, confirming that optical transparency alone does not indicate chemical safety. The results validate the ability of the developed optical sensor to detect BPA independently of the optical clarity of the microplastic, highlighting its selectivity and sensitivity. BPA is a well-documented endocrine-disrupting chemical capable of mimicking estrogen and interfering with hormonal regulation even at low concentrations. The high BPA levels detected from polycarbonate microplastics are physiologically significant, as continuous exposure through food packaging, drinking water, or environmental contamination can contribute to hormonal imbalance, reproductive disorders, and developmental effects. The low BPA levels associated with polyethylene suggest comparatively reduced physiological risk, emphasizing the importance of polymer-specific assessment rather than generalized plastic evaluation.

The observed high BPA release from polycarbonate aligns with previously reported studies identifying PC as a primary BPA-based polymer, while polyethylene is consistently reported as BPA-free or exhibiting only trace adsorption from external sources. The measured BPA concentrations fall within ranges reported in environmental leaching and food-contact studies, supporting the reliability of the developed optical sensing approach. Furthermore, the use of red laser transmission as a complementary optical parameter agrees with existing optical characterization techniques used for polymer identification and microplastic analysis. The red laser transmission measurements primarily reflect the optical properties of the microplastics, including surface roughness, internal scattering, and polymer structure, whereas BPA detection relies on selective molecular interaction at the sensing layer. The lack of direct correlation between transmission and BPA concentration, particularly in polycarbonate, demonstrates the necessity of integrating chemical sensing with optical characterization. The stability of the transmission signal and the reproducibility of BPA measurements indicate proper sensor placement, alignment, and effective functionalization of the sensing surface, validating the robustness of the sensor configuration. The findings highlight the importance of combined optical and chemical sensing for comprehensive microplastic assessment. The developed system can be effectively applied for environmental monitoring, food safety evaluation, and screening of plastic materials for BPA contamination. By distinguishing between optically transparent but chemically hazardous plastics and safer alternatives, this approach supports informed material selection and regulatory decision-making. Additionally, the sensor's portability and optical simplicity make it suitable for real-time and in-situ BPA detection, offering a practical tool for mitigating BPA-related health risks.

8. Limitations and Future Scope

The current system exhibits reduced detection efficiency for microplastic particles smaller than 1 µm due to limited light scattering, and optical measurements may be affected by interference from organic compounds and suspended particulates present in water. Sensor performance and calibration stability are also influenced by environmental factors such as temperature, pH, and turbidity. Additionally, the use of small sample volumes may limit the representativeness of larger environmental water bodies. Future enhancements will focus on improving sensitivity for smaller particles, minimizing interference effects, enhancing environmental robustness, enabling larger sample analysis, and adopting safer alternatives or improved handling protocols for hazardous chemicals such as BPA**.**

Future work will focus on enhancing sensor sensitivity and selectivity through advanced sensing materials and nanostructures to enable accurate detection of smaller microplastics and trace BPA levels. Miniaturization of the system can support portable, on-site monitoring, while integration with IoT and AI-based analytics can enable real-time data acquisition, automated reporting, and predictive pollution assessment. Additionally, extending the sensor for multipollutant detection and deploying it in commercial and industrial water monitoring applications can broaden its environmental impact and support regulatory compliance**.**

9. Conclusion

The development of optical sensor for the detection of BPA represents a significant step towards a rapid, sensitive and reliable environmental monitoring. The sensor uses optical principles such as Fluorescence, absorbance or refractive changes to detect contaminants in water with high specificity. Experimental results indicate that it can identify low concentrations of BPA, which are otherwise difficult to measure using conventional methods like chromatography. This approach offers advantages such as faster response time, minimal sample preparation and potential for continuous monitoring. Overall, the study confirms that optical sensing can be an effective tool for addressing pollution caused by BPA, which are major threat to ecosystem and human health.

This project demonstrates the potential of optical sensing techniques for the effective detection of Bisphenol A (BPA) in water, offering a sensitive, reliable, and cost-effective approach for environmental monitoring. With further optimization in sensor design, material selection, and system integration, the developed sensor can be advanced into a robust tool for real-time water quality assessment and broader environmental protection applications. The proposed optical sensor provides a promising platform for addressing growing concerns related to BPA contamination in water sources. By improving detection limits, enhancing stability under varying environmental conditions, and enabling portable and smart monitoring capabilities, the system can contribute significantly to sustainable water management and public health protection.

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Conflict of Interest/Competing Interests
No conflict of interest.

Data Availability
The raw data supporting the findings of this research paper will be made available by the authors upon a reasonable request.

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