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Development of a Chitosan-Coated Fiber Optic Sensor for the Detection of Cadmium Ions in Palm Oil

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***Abstract*- A U-shaped Plastic Optical Fiber (POF) sensor coated with chitosan was successfully developed for detecting cadmium (Cd^{2+}) ions in palm oil. While previous optical fiber sensors primarily focused on aqueous media, this study represents an initial investigation into heavy-metal detection in a non-aqueous, viscous medium. The sensor utilizes evanescent-wave absorption to detect refractive index changes caused by Cd^{2+} binding to the chitosan coating. A 660 nm light source (BF4R) was coupled into the U-shaped POF, and the transmitted signal was converted to voltage readings using a photodetector, an Arduino Nano, and an LCD interface. Palm oil samples with Cd^{2+} concentrations ranging from 0.05 ppm to 0.20 ppm were tested. The chitosan-coated sensor exhibited improved sensitivity of −7.49 ppm^{-1} compared to −2.87 ppm^{-1} for the uncoated fiber, achieving an average accuracy of 95%. This work is an early study of a chitosan-coated POF sensor using palm oil as the medium. Future work will aim to enhance coating uniformity, extend detection range, and explore sol–gel optimization or multiplexed sensing for broader applications in food safety monitoring.**

***Index Terms*- Plastic optical fiber, U-shaped, Chitosan coating, Cadmium, Palm oil, Evanescent wave**

I. INTRODUCTION

Palm oil is one of the most widely produced and consumed vegetable oils globally [1,2]. Its widespread use in the food industry raises concerns regarding the safety and quality of the final product [3,4]. The safety of palm oil is influenced by various factors, including agricultural practices, processing conditions, and storage environments. On of the safety standards for palm oil is maintaining a low concentration of cadmium ions (Cd^{2+})

Cd^{2+} is a highly toxic heavy metal that causes severe health problems, including renal dysfunction, skeletal damage, and carcinogenic effects [5,6]. Contamination of palm oil with Cd^{2+} may occur during cultivation using phosphate fertilizers, or during processing and storage due to contact with contaminated equipment or containers [7,8]. Therefore, developing a sensitive, reliable, and rapid detection method for Cd^{2+} in palm oil is critical for ensuring food safety and protecting public health.

Some methods for detecting Cd^{2+}, such as atomic absorption spectroscopy (AAS) [9,10], inductively coupled plasma mass spectrometry (ICP-MS) [11], and anodic stripping voltammetry (ASV) [12], provide high sensitivity and specificity. However, these methods are expensive, complex, and unsuitable for real-time or in situ analysis. In contrast, optical fiber sensors offer a promising alternative, with advantages including a compact form, resistance to electromagnetic interference, chemical resistance, and the capability for remote and real-time sensing [13,14].

Among various fiber-optic configurations, the U-shaped fiber excels at sensing due to its enhanced evanescent-field interaction [15]. Bending the fiber increases radiation loss, thereby strengthening the interaction between the guided light and the target analyte. A tighter U-shape increases light leakage to the cladding–medium interface, thereby boosting the interaction [16-18].

Optimal sensitivity is achieved when the ratio of the bending radius to the fiber core radius is less than approximately seven [19].

To further enhance the selectivity and sensitivity of the fiber-optic sensor toward Cd^{2+}, chitosan is used as the coating material [20]. Chitosan, a natural polysaccharide, is known for its strong affinity toward heavy metals due to the amino (-NH_2) and hydroxyl (-OH) groups that serve as chelation sites [21]. These functional groups enable the selective binding of Cd^{2+}. Additionally, chitosan can be easily coated onto optical fibers using simple techniques such as dip-coating or layer-by-layer deposition [22, 23].

Although chitosan-based and U-shaped POF sensors have been widely explored for heavy metal detection in aqueous media, the implementation in non-polar or semi-solid matrices, such as palm oil, remains limited [24-26]. The high viscosity and composition of palm oil challenge conventional sensing approaches. Building on this foundation, this study introduces Cd^{2+} detection in palm oil, offering novelty in both the sensing medium and the design, with improved adaptability and enhanced Cd^{2+} binding. This supports real-time, field-deployable monitoring for food safety and public health protection.

A previous, separated simulation-based study using a chitosan-coated straight optical fiber demonstrated that coating thickness affects Cd^{2+} sensitivity via light confinement and propagation loss [27] but lacked experimental validation. To address this, this study adopts a U-shaped fiber configuration that enhances evanescent-field interaction and enables practical deployment in viscous environments, such as palm oil.

This study develops a U-shaped chitosan-coated fiber-optic sensor for sensitive and selective Cd^{2+} detection in palm oil. The optical and chemical enhancements are evaluated through sensitivity and accuracy, demonstrating potential for quality assurance in the palm oil industry.

II. PRINCIPLE OF DETECTION

The detection mechanism of the developed sensor relies on evanescent wave absorption in a U-shaped optical fiber coated with a chitosan-based sol-gel layer, enabling selective detection of Cd^{2+}. In a conventional optical fiber, light propagates through the core via total internal reflection at the core–cladding interface, generating an evanescent field that extends into the cladding. Although this evanescent field decays exponentially, it allows partial interaction between the guided light and external analytes present near the fiber surface [28].

To enhance this interaction, the fiber is bent into a U-shaped configuration with a bending radius of 0.45 cm. Such geometry leads to increased radiation losses and modal-field distortion, thereby significantly increasing the intensity and depth of the evanescent field [15,29]. This structural modification allows for greater interaction between the evanescent wave and the surrounding medium—in this case, palm oil containing Cd^{2+}—resulting in improved detection sensitivity.

$$\frac{V_1}{V_0} = e^{-kC} \tag{1}$$

where V_0 is the initial voltage measured in air, V_1 is the voltage after immersion in the Cd^{2+}-containing sample, C is the Cd^{2+} concentration in ppm, and k is a sensitivity constant dependent on the fiber geometry, wavelength, and analyte properties [30]. For ease of interpretation, particularly in signal attenuation analysis, the sensor response can also be expressed in decibel (dB) loss, calculated as

$$Loss\ (dB) = -20\ log_{10}\left(\frac{V_1}{V_0}\right) \tag{2}$$

This formulation is widely used in optical fiber sensing to assess signal strength degradation and is adopted in this study alongside the voltage ratio

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to evaluate sensor performance over varying Cd^{2+} concentrations.

III. MATERIALS AND METHODS

A. Preparation of Chitosan Sol-Gel Coating

The chitosan sol–gel was synthesized to achieve uniform film formation of the sensing layer. Initially, 1 g of chitosan 75% was dissolved in 85 mL of distilled water and 15 mL of acetic acid (CH_3COOH), then stirred for about 2 hours at room temperature. From this stock, 10 mL was diluted with 30 mL of distilled water to prepare the working solution. Subsequently, 5 mL of Acetic acid ($NaHCO_3$) solution was added, and the mixture was stirred for 10 minutes to ensure uniformity. In parallel, 4 g of polyvinyl alcohol (PVA) was dissolved in 100 mL of distilled water and stirred for approximately 3 hours. Then, 6 mL of the PVA solution was incorporated into the chitosan mixture and stirred until a viscous, stable sol–gel was obtained.

B. Fabrication of U-Shaped Optical Fiber Sensor

A Plastic Optical Fiber (POF) with an 800 µm diameter was used as the sensing medium. A section of the fiber was stripped of its cladding to expose the core, then gently bent into a U-shape with a bending radius of about 0.45 cm using a heat-assisted method. The fiber was clamped and heated with a heat gun to form the curvature, thereby enhancing evanescent-field interaction by increasing radiation losses and strengthening light–analyte interaction.

After POF formed into a U-shape, it was coated with a chitosan sol–gel solution to serve as the new functional cladding layer. The coating was performed using a dip-coating method, in which the fiber was immersed vertically in the chitosan sol–gel for 5 seconds, then dried in an oven at a controlled temperature below 70 °C. This process was repeated three times to ensure uniformity and sufficient thickness of the sensing layer. Adequate drying time was provided between each coating cycle to stabilize the structure and prevent cracking or peeling

C. Preparation of Cd^{2+} Test Samples in Palm Oil

Pure palm oil was used as the sample for Cd^{2+} detection. 5000 ppm of Cd^{2+} concentration was obtained by dissolving $Cd(NO_3)_2 4H_2O$ in palm oil as a base solution. Because of the polarity difference between Cd^{2+} and palm oil, Polyoxymethylene sorbitan monooleate (Tween 80) was added as an emulsifier to promote stable dispersion of Cd^{2+} within the oil matrix. Tween 80 reduces interfacial tension and facilitates the formation of a uniform and stable emulsion [31]. The mixing process was carried out using a magnetic stirrer to ensure thorough homogenization and consistent distribution of Cd^{2+} throughout the palm oil samples. Base solution diluted into 100 ppm, 1 ppm, and finally to 0.05 ppm, 0.1 ppm, 0.15 ppm, and 0.20 ppm as a sample.

D. Characterization

The experimental setup for the fiber optic sensor system is illustrated in Figure 2. A U-shaped, unclad POF coated with a chitosan-based sol–gel layer was immersed in palm oil samples spiked with Cd^{2+}. A 660 nm laser source, integrated into the Autonics BF4R fiber optic amplifier unit, served as the light source. The light was launched into one end of the fiber, and a constant voltage source of 12–24 V was used to power the emitter. This wavelength was chosen not only for its low cost and excellent compatibility with POF [32], but also because it corresponds to wavelengths commonly used in similar optical fiber sensing studies, as shown in Table 2, thereby making it appropriate for this initial proof-of-concept work. However, the impact of different wavelengths on sensitivity was not investigated. Future work should explore a spectral analysis to determine the optimal wavelength for Cd^{2+} detection, which may further enhance sensor performance.

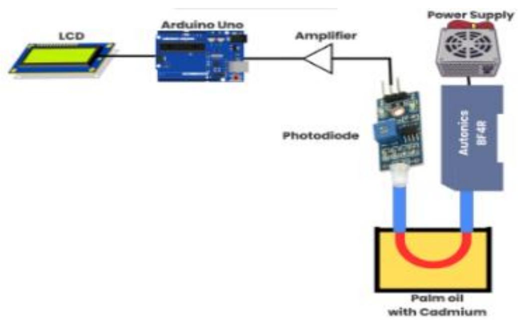

Fig. 2. Schematic diagram of the fiber optic sensor instrumentation system.

As light propagated through the U-shaped sensing region, part of the guided optical power interacted with the surrounding medium via evanescent-wave coupling.

The transmitted light was detected at the fiber's output using a photodiode module, which converted the optical signal into a voltage. This analog signal was then amplified and sent to an Arduino Uno microcontroller, which processed the data and transmitted it to an LCD in real time. The displayed voltage values represent the optical intensity detected after transmission through the sample and serve as a proxy for the Cd^{2+} concentration in the palm oil.

IV. RESULT AND DISCUSSION

Figure 3 shows the relationship between the voltage ratio and Cd^{2+} concentration in palm oil, fitted with an exponential decay model. For the uncoated fiber, the response is expressed as:

$$y = e^{-2.87x+1.45} \tag{3}$$

while for the chitosan-coated fiber, the response is:

$$y = e^{-7.49x+2.32} \tag{4}$$

The equations for uncoated and coated fibers yielded R-squared values of 0.988 and 0.985, respectively. These equations follow the same exponential form as the Beer–Lambert law (1), where the exponent coefficient k can be directly interpreted as the sensor's sensitivity, x represents the Cd^{2+} concentration, and y denotes the voltage ratio in the chitosan-coated sensor. The chitosan-coated sensor has a greater sensitivity of -7.49 ppm^{-1}. The coated sensor exhibits enhanced sensitivity, attributed to the interaction between Cd^{2+} and the $–NH_2$/–OH functional groups of chitosan, which increases refractive index changes and light attenuation [26]. Consequently, higher Cd^{2+} concentrations result in stronger absorption and a lower output voltage.

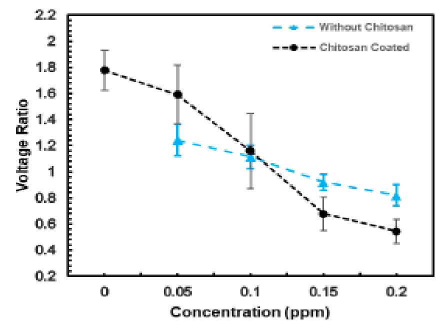

Fig. 3. Voltage ratio (V_1/V_0) as a function of Cd^{2+} concentration in palm oil

Table 1. Accuracy of sensors

Actual Concentration	Predicted concentration		Accuracy (%)	
	With chitosan	Without chitosan	With chitosan	With chitosan
0.05	0.054	0.053	99	93
0.1	0.092	0.091	92	91
0.15	0.163	0.157	91	95
0.2	0.193	0.198	97	99
average			95	95

The performance of the sensor and the analytical model was validated by comparing the results from the analytical equations directly against the experimental data. Table 1 provides this direct comparison. The 'Actual Concentration' represents the experimental sample, while the 'Predicted Concentration' was calculated by inputting the sensor's experimental voltage readings into the analytical model, as outlined in Equations 3 and 4.

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By comparing the actual and predicted concentrations, the average accuracy of the sensor is about 95% for both chitosan-coated and uncoated sensors, as shown in Table 1. The coated sensor showed superior accuracy at the lowest concentration 99% at 0.05 ppm, and the uncoated sensor at the highest concentration 99% at 0.2 ppm. This indicates a trade-off in performance, such that a chitosan layer improves sensitivity, as reflected by a steeper calibration slope, but slightly reduces linearity and stability. By comparing exponential equations to experimental data, the sensor's accuracy is quantitatively evaluated, thereby linking the Beer–Lambert law to actual sensor response.

The accuracy of the developed sensor is influenced by fabrication factors, including fiber stripping and chitosan coating. Inaccurate stripping alters the fiber core diameter and evanescent field depth, leading to inconsistent light interaction and sensitivity [33]. Uneven chitosan thickness causes refractive index irregularities and scattering losses, reducing measurement stability [34]. Therefore, maintaining precise stripping and uniform coating is essential for ensuring reliable sensor accuracy.

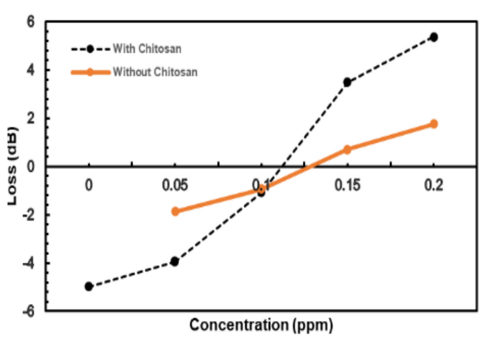

Fig. 4. Optical loss in decibels as a function of Cd^{2+} concentration for the chitosan-coated sensor.

The optical loss was also evaluated using Equation (2) to determine baseline attenuation. The stripping loss due to cladding removal was measured at 12.74 dB, and the bending loss due to U-shaped geometry with a 0.45 cm radius was 4.47 dB. The bending loss is notably lower than previously reported values of ~13.4 dB for a 5 cm radius [35], due to light redirection caused by the refractive index modification of the chitosan coating.

Figure 4 shows the optical loss (dB) versus Cd^{2+} concentration for the chitosan-coated sensor. Increasing Cd^{2+} levels result in higher optical losses, consistent with stronger analyte–coating interaction and enhanced attenuative effects. This trend supports prior finite-element and experimental models showing that Cd^{2+} binding to chitosan-coated sensing layers increases waveguide attenuation. The simulation sensitivity is highest at a reagent thickness of 0.5 cm, such as 1.63 [27].

Table 2. Comparison of chitosan-coated optical fiber sensors for heavy metal detection

Ref	Fiber Configuraton	Medium	Wave-length (nm)	Sensitivity	Detection Range
[25]	Concentric fiber bundle and flat mirror	Water	532	515 mV/ppm	0.005-0.04 ppm
[26]	U-shaped silica fiber and chitosan	Water	650	−0.283 dBm /ppm	2-5 ppm
[28]	Au-coated FO-SPR and BSA	De-ionized water	600 - 800	76.67 nm/µM	0-0.129 nM
[36]	U-shaped POF + PVA-borate-chitosan hydrogel	Water	660	88.69 dB/ppm	0.05 – 0.20 ppm
[37]	Stripped Plastic Optical Fiber (POF)	Palm oil	630	0.456 V/times	3 times
This study	U-shaped POF and Chitosan	Palm oil	660	-2.87 ppm^{-1} (uncoated) -7.49 ppm^{-1} (coated)	0.10–0.25 ppm

Table 2 revealed the novelty of this study, which introduces palm oil as a new sensing medium for optical fiber–based heavy metal detection. Unlike previous works such as Pujiyanto et al. [25] and

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Yulianti et al. [26], which operated in aqueous environments. This study demonstrates that an optical fiber sensor can effectively function in a non-aqueous, viscous medium with a higher refractive index. Compared with the stripped POF sensor by Khoiro et al. [37], which also used palm oil as a testing medium but focused on quality degradation through reuse cycles, the present work specifically targets Cd^{2+} detection using a U-shaped POF coated with chitosan. While the previous design measured physical quality changes in oil, this study extends the application toward chemical contamination monitoring, integrating both high linearity ($R^2 = 0.985$) and consistent sensitivity. This research establishes a new direction for fiber-optic sensing in non-aqueous media, showing potential for real-time, low-cost monitoring of metal contamination in edible oils.

VI. CONCLUSION

A U-shaped POF sensor coated with chitosan was successfully developed for detecting Cd^{2+} in palm oil. The U-shaped POF enhanced evanescent-wave interaction, while chitosan provided selective binding to Cd^{2+}. The detection range of both sensors is 0.05–0.2 ppm. The sensor showed improved sensitivity of -7.49 ppm^{-1} compared to -2.87 ppm^{-1} for the uncoated fiber. Both sensors had the same accuracy of 95%. This work demonstrates an initial study on the development of an optical fiber sensor for cadmium detection in palm oil. Future research may focus on improving coating uniformity, extending the detectable concentration range, and conducting a comprehensive spectral analysis to identify the optimal wavelength for Cd^{2+} detection, thereby further enhancing overall sensor performance through continued optimization of the sol–gel formulation.

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