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Lateral offset Displacement Fiber Optic Sensor for Detecting Adulteration of Pure Olive Oil with Palm Oil

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Abstract: An optical fiber sensor was developed to detect the adulteration of pure olive oil with palm oil using a lateral offset displacement technique. Pure olive oil is a high-quality cooking oil often used in cooking, but its quality degrades due to adulteration. This study employed a single-mode fiber (SMF) displacement sensor, employing lateral offset distances of 1 µm, 2 µm, and 3 µm, to analyze the sensor's response to varying concentrations of palm oil in olive oil, ranging from 10% to 50%. The refractive indices of pure olive and palm oil were initially measured at 1.4698 and 1.4431, respectively, with a proportional decrease in refractive index observed as the concentration of palm oil increased. The maximum sensitivity of 0.888 dBm/% was achieved with a 3 µm lateral offset distance, highlighting the correlation between offset distance and the sensor sensitivity. The power loss increased consistently with higher concentrations of palm oil and greater offset distances, with the highest power loss of -5.2 dBm recorded at 50% adulteration and 3 µm offset. These results underscore the sensor's accuracy and sensitivity in detecting and quantifying adulteration, making it a valuable tool for quality control and ensuring the authenticity of high-value edible oils in the food industry.

Keywords: Fiber optic sensor, olive oil, adulteration, lateral offset, single-mode fiber

1. Introduction

Over the past decades, advancements in optical fiber technology have been remarkable, significantly impacting various fields, including sensing and measurement. The foundational discovery by Kao and Hockham in 1965, which demonstrated that impurity removal in glass could reduce light attenuation below 20 dB/km, laid the groundwork for developing low-loss optical fibers (Xie, 2022). Since then, continuous research and innovation have propelled the evolution of fiber optic sensors, which are now extensively used in detecting adulteration in various oils (Ansari et al., 2024; Srinivasulu & Rao, 2019).

Fiber optic sensors, known for their high sensitivity and accuracy, have been widely studied for identifying adulterants in oils such as lard in olive oil (Puspita et al., 2021), kerosene in petrol and diesel (Chauhan & Singh, 2022), and kerosene in petrol (Ferdous et al., 2022). These sensors typically rely on changes in refractive index or spectral shifts to detect adulteration levels. For example, a heptagonal photonic crystal fiber-based sensor using terahertz signals has demonstrated high sensitivity and low loss in detecting kerosene adulteration in petrol (Chauhan & Singh, 2022). Similarly, a multimode fiber optic sensor has effectively detected and quantified traces of palm oil adulterant in coconut oil by measuring wavelength shifts due to refractive index changes (Jadhav et al., 2022). These advancements underscore the potential of fiber optic sensors in ensuring the quality and authenticity of edible oils.

In this paper, we propose a novel lateral offset displacement approach in fiber optic sensors for detecting adulteration in pure olive oil (POO). Lateral offset in fiber optic cables involves deliberately misaligning or displacing optical fibers sideways, enhancing the sensor's capabilities by improving sensitivity and accuracy. This technique has been successfully applied to various sensing applications, including detecting hydrogen concentration (Zhang et al., 2022), chemical concentrations (Tian et al., 2022), curvature, and temperature changes (Liu et al., 2018).

Olive oil, derived from olives, is highly valued for its health benefits, including reducing the risk of cardiovascular diseases and inflammation due to its rich content of monounsaturated fats, phenolic compounds, and vitamin E (Guasch-Ferré et al., 2014; Nocella et al., 2017; Aparicio & Harwood, 2013). Its widespread use extends beyond culinary applications (Boskou, 2009) to cosmetics (Rodrigues et al., 2015), medicines (Caramia et al., 2012), and soaps (Girgis, 2003), making it a versatile product (Stanciu, 2023). However, olive oil is often adulterated with lower-quality oils such as palm (Rohman & Man, 2010), paraffin

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(Bunaciu et al., 2022), and used cooking oil (Li et al., 2018), driven by economic incentives to increase profits.

Detecting adulterants like palm oil in olive oil is crucial for maintaining pure olive oil's quality, authenticity, and health benefits. Palm olein oil, a cost-effective liquid fraction derived from palm oil (Elaeis guineensis), is commonly used in the food industry due to its high yield and low cost (Padial-Jaudenes et al., 2020; Deffense, 1985; Mamat et al., 2005). However, concerns regarding its high saturated fat content (Imoisi et al., 2015), environmental impact (Beyer et al., 2020), and associated social issues highlight the importance of reliable detection methods.

Previous studies have shown the potential of fiber optic sensors for detecting adulteration in edible oils. However, many of these methods rely on complex setups, focus on specific types of adulterants, or struggle to detect a broad range of concentrations. They often lack the sensitivity needed for identifying low levels of adulteration and face challenges regarding real-time applications.

As mentioned earlier, the novelty of this study lies in its lateral offset displacement technique, which enhances sensor sensitivity and precision. This method offers a linear, repeatable response to adulteration levels with minimal environmental interference and without complex sample preparation. Additionally, the sensor's reliance on straightforward refractive index measurements and power loss analysis makes it practical for industrial applications. This approach not only demonstrates superior sensitivity compared to earlier multimode fiber systems but also enables simpler implementation with minimal sample preparation and lower operational complexity.

This study aims to establish a robust, efficient tool for quality control, addressing the unmet need for reliable, cost-effective, and real-time detection of edible oil adulteration within the global food industry.

2. Methodology

2.1 Sample Preparation

The olive and palm oil needed for the experiment were bought from a nearby supermarket. To preserve the integrity of the samples, they were stored in a dark location before the experiment to prevent exposure to conditions that might alter their composition. Adulterated olive oil samples were prepared by mixing pure olive oil with palm oil in varying concentrations of 10%, 20%, 30%, 40%, and 50%. Table 1 summarizes the sample volumes used for each concentration.

Table 1: Volume of The Sample.

Concentration (%)	Volume of Pure Olive Oil (ml)	Volume of Palm Oil (ml)
0	50	0
10	45	5
20	40	10
30	35	15
40	30	20
50	25	25
100	0	50

2.2 Instrumentation

The Sumitomo Electric Type-82C HD Core Aligning Fusion Splicer was employed to splice the optical fibers with high precision, ensuring minimal signal loss and optimal alignment of the fiber cores. This splicer is renowned for its robust core alignment technology, which is critical for maintaining the integrity of the optical signals. The EXFO's ELS-50 was used as the light source. This device, known for its high stability and accuracy, provides a controlled light beam through optical fibers. It operated at a wavelength of 1550 nm, which was selected due to its low attenuation in SMF and its suitability for refractive index-based sensing applications. The EXFO FPM-22A Optical Power Meter was utilized to measure power loss, offering high sensitivity and precision in detecting changes in power levels. This meter's capability to accurately measure optical power loss is crucial for determining the sensor's response to different sample concentrations.

2.3 Determination of Refractive Indices

The refractive index of a material depends on various factors, including its chemical composition, density, and temperature. Different materials have different refractive indexes, and this property is critical in numerous optical applications, such as lenses, prisms, fiber optics, and waveguides. A refractometer will be used to test the sensor's refractive index. The refractive indices of pure olive oil and palm oil were measured, with variations recorded for each concentration of adulterated oil. Refractive indices were determined using the refractometer Atago PAL–BX/RI Digital Hand–Held Pocket Dual Scale Refractometer. The changes in refractive index with varying adulteration levels provided additional confirmation of sensor performance.

2.4 Adulteration Detection

The fiber is stripped, cleaned, and cleaved for a standard splice. It is then placed into the HD Core Aligning Fusion Splicer Type-82C from Sumitomo Electric, which typically aligns the fibers automatically. Next, the fibers are laterally adjusted using the splicer's fine adjustment controls or an external micro-positioner to achieve the desired offset. The fusion splice is performed, ensuring the offset remains intact. Finally, the splice is visually inspected, and the optical performance is tested to confirm the desired effect. The splicer's built-in imaging system was used to capture each splice, and the lateral displacement was measured from these images by determining the distance between the fiber core centers in the captured frame. The splicing procedure was repeated on separate samples for each offset value to confirm reproducibility.

Figure 1 depicts the experimental setup used in this study, consisting of a single-mode fiber (SMF), an optical light source, and an optical power meter. The sensor in this research is the laterally offset SMF. Light from the optical source travels through

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the first fiber, leaking into the cladding and exciting high-order cladding modes. The second fiber then couples the light back into the core, creating an interference pattern. The fiber's cross-section is intentionally arranged so that the cores of the fibers do not overlap, resulting in power loss during light transmission.

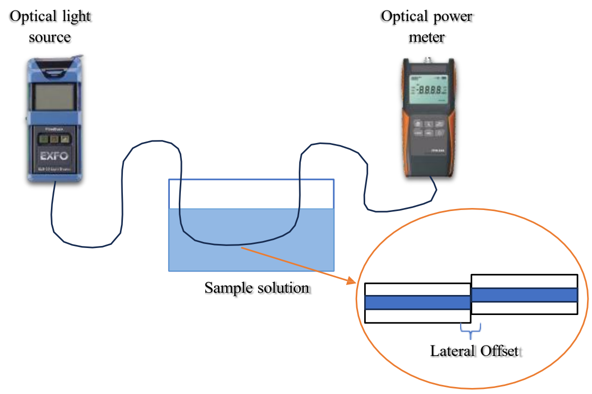

Figure 1. Experimental Setup for Adulteration Sensing

Detection is established as the cladding modes interact, with light dispersing across both the core and cladding. The lateral offset distance is varied at 0 µm, 1 µm, 2 µm, and 3 µm to analyze their effect on power loss and sensitivity. Finally, an Optical Power Meter measures the sensor's response in terms of optical signal loss.

The samples were prepared and tested under identical conditions, strictly following measurement protocols. Each measurement was repeated to verify consistency, and outliers were identified and excluded. The power loss data were then analyzed to quantify the relationship between adulteration levels, offset distance, and sensor performance. All measurements were performed at room temperature (25 ± 2°C) to minimize temperature effects, which are expected to be negligible within this range. Future work will focus on evaluating and compensating for potential temperature-induced variations to ensure consistent sensor performance under different environmental conditions.

3. Results and discussion

In this research, the refractive indices of the test samples were measured first. Table 2 displays the correlation between the percentage concentration of adulterants and the refractive index of pure olive oil compared to adulterated olive oil with palm oil. The refractive index of the olive oil analyzed in this study was 1.4698, which is consistent with the reported range of 1.4677 to 1.4705 for olive oil as specified by Codex Stan 33-1981 (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization [WHO], 1981).

Table 2: Refractive Index Value of Olive Oil Adulteration.

Concentrations	Refractive Index
POO	1.4698
10%	1.4701
20%	1.4698
30%	1.4693
40%	1.4691
50%	1.4688
PO	1.4431

On the other hand, the refractive index value for palm oil obtained in this study was 1.4431, which falls outside the range specified by Codex Stan 210–1999, which is 1.459 to 1.460 (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization [WHO], 1999). This deviation may be attributed to the degradation of palm oil. Over time, oils can degrade, leading to changes in their chemical composition due to oxidation and hydrolysis, which can alter the fatty acid profile and, consequently, the refractive index (Andrew et al., 2012).

The following table presents the findings from blending olive and palm oil at various concentrations. When combined with 50% adulterant, the refractive index for olive oil adulteration was ≤1.4688. At 40%, the refractive index was ≤1.4691. A 30% concentration resulted in a refractive index of ≤1.4693. For the 20% combination, the refractive index was ≤1.4698. Finally, with a concentration of 10%, the obtained value was ≤1.4701. The refractive index showed a small increase at 10% palm oil concentration because, at low concentrations, the saturated fatty acids in palm oil can occupy small gaps between the unsaturated molecules of olive oil, making the mixture a bit denser and increasing the refractive index. Such non-ideal mixing behavior and molecular packing effects have been reported in vegetable oil systems, where differences in fatty acid composition influence both density and optical properties (Amos-Tautua & Onigbinde, 2013). As the palm oil content increases further, the mixture becomes increasingly dominated by palm oil, resulting in a gradual decrease in the overall refractive index. Thus, it suggests that the refractive index can be a valuable indicator of the quality of edible oils.

Figure 2 illustrates the refractive index (RI) values for various olive oil-palm oil mixture concentrations, depending on the volume of adulterants added to the olive oil. The RI decreased proportionally with the increasing amount of palm oil adulterant. Pure olive oil has a refractive index of 1.4698. The addition of

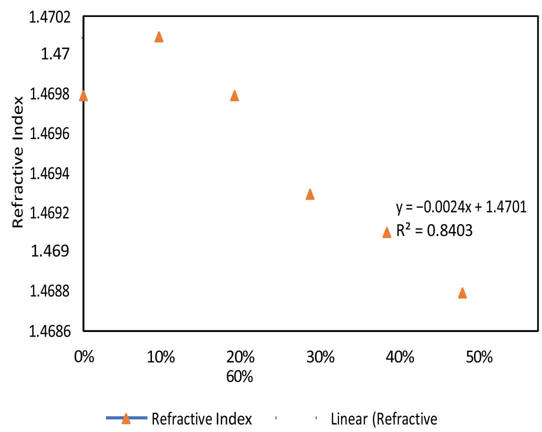

Figure 2. Refractive Index (RIU) Vs Concentration of Palm Oil in Olive Oil.

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palm oil altered the RI value of the mixture. The slope of the line in the graph represents the fiber's sensitivity to different concentrations of adulteration. A steeper slope indicates greater sensitivity of the fiber sensor (Tian et al., 2022). According to the graph, the sensitivity of the fiber sensor to palm oil is 0.8403 RIU/%.

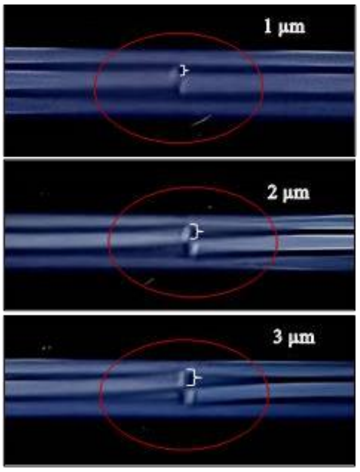

Figure 3. Captured image from the fusion splicer for 1, 2, and 3 µm offset.

Figure 3 shows the images of the spliced offset fiber from the splicing machine, as recorded from the fusion splicer.

Table 3. Power Loss for Olive Oil Adulteration with Palm Oil

Concentration (%)	Power Loss (dBm)			
	0 µm	1 µm	2 µm	3 µm
0	-3.69	-4.1	-4.56	-5.13
10	-3.73	-4.08	-4.58	-5.14
20	-3.75	-4.09	-4.59	-5.16
30	-3.76	-4.1	-4.63	-5.17
40	-3.77	-4.12	-4.67	-5.19
50	-3.79	-4.14	-4.63	-5.2

The relationship between the concentration of palm oil and the power loss was measured at different offset distances. The data shows that as the offset distance increases, the power loss also increases for all concentrations, indicating a greater degree of signal attenuation with larger offset gaps. For example, at 50% concentration, the power loss values are -3.79 dBm at 0 µm, -4.14 dBm at 1 µm, -4.63 dBm at 2 µm, and -5.2 dBm at 3 µm. This trend is consistent across all concentrations, suggesting that even a small physical gap can cause additional signal attenuation. Furthermore, there is a noticeable increase in power loss with higher concentrations of palm oil at each offset distance. At 3 µm offset, the power loss progresses from -5.13 dBm for 0% concentration to -5.2 dBm for 50% concentration, demonstrating that adulteration affects the optical properties of the oil mixture, likely due to changes in refractive index or other optical characteristics (Bodurov et al., 2013).

However, there is a slight inconsistency in the power loss trend at offsets of 1 µm and 2 µm. This can be attributed to most of the light remaining confined within the fiber core, resulting in weaker mode coupling and lower sensitivity to refractive index changes. Small differences in alignment or the sample condition may also slightly affect the measurements, causing the power loss to appear inconsistent. In contrast, at a 3 µm offset, stronger coupling between the core and cladding modes enhances light interaction with the surrounding oil, giving a more stable and linear response as the palm oil concentration increases.

To ensure the consistency and reliability of the sensor's performance, statistical process control (SPC) was applied to the measured power loss data across varying levels of adulteration (0%, 10%, 20%, 30%, 40%, 50%, and 100% palm oil). SPC was employed through the development of control charts to monitor the process behavior and identify any potential variations that might indicate inconsistencies in sensor output. Upper Control Limit (UCL) and Lower Control Limit (LCL) were calculated based on the data's mean and standard deviation, following standard SPC methods. The plotted data show that all power loss measurements fell within the UCL and LCL across the tested adulteration levels. This confirms that the sensor operated within statistical control limits, and no significant outliers or trends indicating process shifts or deviations were observed, reinforcing the sensor's reliability under experimental conditions.

The findings highlight that both the offset distance and the concentration of palm oil adulteration significantly impact power loss. Larger offsets lead to higher power loss, emphasizing the importance of maintaining minimal offsets in experimental setups to reduce signal degradation. Additionally, higher concentrations of palm oil in olive oil result in increased power loss, providing a potential method for detecting and quantifying adulteration in olive oil by measuring power loss. This can be attributed to the changes in the optical properties of the oil due to the presence of palm oil, as supported by the work of Bodurov et al., 2013 and Khosroshahi, 2018. These results are critical for ensuring the integrity and quality of olive oil, as they offer a quantitative approach to identifying adulteration.

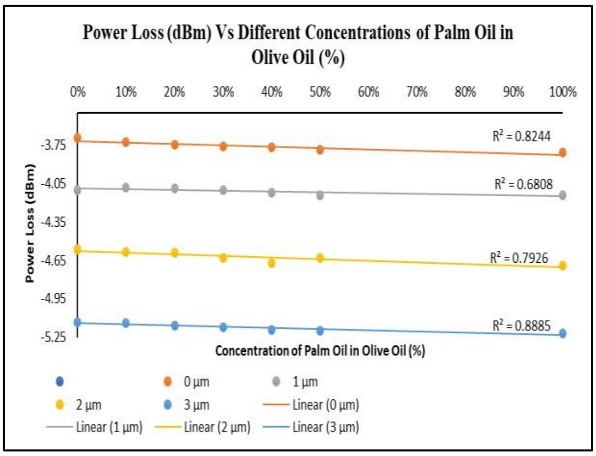

Figure 4. Power Loss (dBm) Versus Different Concentrations of Palm Oil in Olive Oil.

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Figure 4 illustrates the relationship between power loss (dBm) and the concentration of palm oil in olive oil (%). The sensitivities observed for offsets of 0 µm, 1 µm, 2 µm, and 3 µm were 0.824 dBm/%, 0.680 dBm/%, 0.792 dBm/%, and 0.888 dBm/%, respectively. The data reveal a clear trend: as the lateral offset increases, the power loss increases for the same level of adulteration. This indicates that a larger offset results in greater sensitivity and more pronounced detection of adulterants. The sensitivity values at the 3 µm lateral offset distance showed a stable trend within control limits, confirming the repeatability and accuracy of the sensor's responses. The increase in sensitivity with greater offset distance suggests that the sensor's ability to detect changes in the refractive index due to palm oil adulteration improves as the offset widens. A greater lateral offset enhances coupling between the fiber core and cladding modes, allowing more light to leak into the cladding and interact with the surrounding oil medium. This enhanced light-sample interaction makes the sensor more responsive to changes in refractive index, resulting in higher sensitivity. Additionally, the observed linear decrease in output intensity with increasing offset highlights the impact of misalignment on sensor performance, emphasizing the importance of optimizing offset distances for effective adulteration detection.

Compared to previous studies about edible oil detection sensors that use fiber grating, U-bent fiber, or multimode interference, the lateral offset displacement sensor achieves a comparable or higher sensitivity using only standard SMFs and fusion splicing. This straightforward design removes the need for complex spectral analysis and enables direct, real-time power loss measurement with minimal calibration requirements.

4. Conclusion

This study successfully developed and demonstrated an optical fiber sensor based on the lateral offset displacement approach for detecting adulterated pure olive oil with palm oil. Utilizing the SMF-SMF displacement sensor, the research effectively analyzed the sensor's responses to varying concentrations of adulterants in olive oil. The experimental setup utilized sensing probes with offset distances at 1 µm, 2 µm, and 3 µm. The initial refractive indices for pure olive and palm oil were measured at 1.4698 and 1.4431, respectively.

Key findings revealed that the sensor achieved its highest sensitivity at a 3 µm lateral offset distance, with a sensitivity value of 0.888 dBm/%. This finding highlights the positive correlation between increased offset distance and enhanced sensor sensitivity. The sensor demonstrated high accuracy in detecting even small quantities of palm oil in olive oil, underscoring its potential as a reliable tool for quality control in the food industry. This study addresses several research gaps by optimizing the lateral offset displacement to improve sensitivity and precision while minimizing sample preparation and environmental interference.

Furthermore, the reliance on straightforward refractive index measurements and power loss analysis enhances the sensor's practicality for real-time applications. By integrating the benefits of high sensitivity, operational simplicity, and broad applicability, this study provides a robust solution to current challenges in edible oil adulteration detection. The lateral offset displacement approach demonstrates significant potential for ensuring product authenticity, enhancing quality control, and safeguarding consumer safety in the food industry. Future work could explore extending the technique to other high-value edible oils and further refining the sensor's performance for lower levels of adulteration.

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