NASE
Natural Sciences and Engineering Bulletin
November 2024, 1(2)
**Received:** 04/07/2024
**Accepted:** 27/09/2024

**RESEARCH ARTICLE**
http://dergipark.gov.tr/nase

# Sensitive Microwave Sensor for Adulteration Detection in Olive Oil

**Hüseyin KORKMAZ**[1*], **Uğur Cem HASAR**[1]

**Keywords**
*Microwave sensing,*
*Dielectric constant,*
*Quality factor,*
*Figure of merit,*
*Low cost*

**Abstract –** A novel reflection-based microwave sensor that is reproducible, feasible, and sensitive to changes in dielectric parameters has been specifically developed, fabricated, and analyzed to detect sunflower oil mixed with olive oil. The proposed sensor is built on an FR-4 dielectric substrate and shows a magnitude of -47.19 dB at a resonance frequency of 9.48 GHz. An electric field distribution analysis of the sensor was performed, and it was determined that the electric field was significantly concentrated in the upper regions of the resonator. Olive oil was mixed with sunflower oil at the rates of 10%, 20% and 30%. The prepared samples were placed directly on the sensor and the performance of the sensor in simulation and experimental environments was tested. Based on the measured dielectric constants, the results of the experiments and simulations were observed to be consistent. The proposed sensor demonstrated superior performance compared to other sensors proposed in the literature in experimental measurements with a Q-factor of 4635, normalized sensitivity value of 3.62%, a Figure of Merit of 6581, and resonance frequency shift of 62 MHz occurred between the pure olive oil and the 10% sunflower oil adulterated olive oil sample. The proposed sensor can be preferred in industrial and liquid chemical detection applications due to its high sensitivity, high-quality factor, low cost, and small amount of sample required.

## 1. Introduction

Food quality and composition are key parameters of critical importance in all processes of the food manufacturing industry. However, some manufacturers increase the adulteration of foods for profit maximization purposes (Göğüş et al., 2009). It is emphasized that olive oils are richer in composition and quality than other oils in daily use. However, due to differences in the production processes of these oils, the price range may vary from low-quality to high-quality oils. This can cause complexities in the marketing process when low-quality oils are mixed with high-quality oils (Osman et al., 2014). Extra virgin olive oil and other valuable oils are often mixed with more economical oils such as sunflower, corn, palm, and cottonseed (Gunstone, 2011). Such adulterations may utilize methods to conceal changes that make them difficult to detect by normal human senses or basic tools (Meenu et al., 2019). Infrared combined with traditional methods such as gas chromatography (GC) (Hashempour et al., 2024) and High-Performance Liquid Chromatography (HPLC) (Menegoz and Moret, 2024) as well as modern spectroscopic techniques such as thin layer chromatography (TLC) (Khursheed et al., 2024) and differential scanning calorimetry (DSC) (Islam et al., 2022a). Methods such as (IR) (Yılmaz-Düzyaman et al., 2024), ultraviolet (UV) (Musa, 2024) and fluorescence spectroscopy (Rueda et al., 2024) are also used in the analysis of oil samples. Although these analysis techniques are often criticized for being time-consuming, complex, and requiring high-cost facilities. Metamaterials (MMs) are defined as human-created materials with extraordinary exotic properties. One of the properties of metamaterials (MM) is that they can control and direct electromagnetic waves (Wu et al., 2024). Following experimental verification of the structures of metamaterials, significant research has been conducted in this field. One of the most striking features of this structure is the concept known as the "Invisibility Cloak", which is quite interesting (Ergin et al., 2010). Additionally, this structure allows energy absorption in wide band gaps (Krödel et al., 2015). Advances in absorber applications

---

[1*] **Corresponding Author.** Gaziantep University, Graduate School of Natural and Applied Sciences, Department of Electrical and Electronics Engineering, 27310 Gaziantep, Turkiye. E-mail: muh.huseyinkorkmaz@gmail.com OrcID: 0000-0002-3518-1943
[2] Gaziantep University, Faculty of Engineering, Department of Electrical and Electronics Engineering, 27310 Gaziantep, Turkiye. E-mail: uchasar@gantep.edu.tr OrcID: 0000-0002-6098-7762

**Citation:** Korkmaz, H., and Hasar, U. C. (2024). Sensitive microwave sensor for adulteration detection in olive oil. *Natural Sciences and Engineering Bulletin*, 1(2), 27-37.

have created opportunities for various studies on energy harvesting (Korkmaz and Hasar, 2021; Korkmaz et al., 2023; Obaidullah et al., 2021). Every year, new types of sensors are developed thanks to advances in micro and nanotechnology and electronics, photonics, and materials science (Hasar et al., 2024b; Shi et al., 2020). Recent research has focused on the development of sensors with high accuracy, compact size, and high sensitivity (Alahnomi et al., 2021). Microwave (MW) sensors use the electromagnetic field for sensing and generally have operating frequencies in the range of 300 MHz to terahertz (Mehrotra et al., 2019). The advantages of MW sensors compared to other options include features such as low cost, compact structure, high accuracy, easy production, and testability. Due to these obvious advantages, MW sensors play an important role in various fields of life, such as healthcare (Korostynska et al., 2014), the food industry (Hasar et al., 2024a), the defence sector (Hudec et al., 2009), and industry (Nyfors, 2000). MW sensors can generally be classified into two basic types: Broadband sensors and resonance-based sensors. Resonance-based sensors typically function with high sensitivity over a narrow frequency range and generally use a limited and intense electric field for sensing. The resonance frequency is extremely sensitive to dielectric loading in this region, and any instantaneous change can lead to a significant shift in the resonance frequency (Bhatti et al., 2022). In recent years, researchers have conducted a series of studies to detect adulteration with MW sensors. The use of MTM sensors in detecting various oils is demonstrated by (Bakır et al., 2019). For example, while the resonance frequency is 70 MHz in dirty and clean transformer oils, this value is reduced to 50 MHz in olive and corn oils. A high-efficiency portable sensor is mentioned to detect branded and unbranded fuel samples (Tümkaya et al., 2018). While the resonance frequency shift for branded and unbranded diesel was determined as 72 MHz, this frequency shifted by 12 MHz for branded and unbranded gasoline. A transmission line-based MTM sensor has been introduced to identify original and adulterated gasoline samples (Tamer et al., 2018). This sensor can discriminate between original and adulterated diesel samples with a frequency shift of 50 MHz. Reviews of the literature reveal that metamaterial-based sensors can be used over a wide frequency range (Bakır et al., 2019; Tümkaya et al., 2018; Tamer et al., 2018; Lee et al., 2017) and for a variety of materials from solid dielectrics to liquids, gases, and biomolecules (Vélez et al., 2017; Mohd Bahar et al., 2019; Lee and Yook, 2008). A sensitive MTM sensor has been introduced to discriminate between original and adulterated fuel samples (Tümkaya et al., 2017). The resonance frequency is shifted to 100 MHz. Rhombus MTM sensor was considered for flow sensing (Tümkaya et al., 2019), but the sensitivity and quality factors were low in this study. Another study proposed that a curved line metamaterial-based sensor used for polypropylene detection exhibited moderate performance (Islam et al., 2021). A sensor inspired by the MTM absorber has been proposed to detect liquid chemicals with changing electrical properties (Abdulkarim et al., 2019). The quality factor and sensitivity of the sensor were found to be inadequate. An omega-shaped sensor has been introduced for industrial applications (Altıntaş et al., 2020). The sensor operates in the 8–12 GHz frequency range and is designed with a 70 MHz frequency shift for clean and waste transformer oils. Additionally, another MTM sensor has been introduced to detect liquid chemicals (Abdulkarim et al., 2020c). In the study, quality factors and sensitivity are average. As a result of our literature research, it was determined that the sensitivity, quality factor (Q-factor), and Figure of Merit (FoM) of the proposed sensors are important performance parameters and that these parameters are potential limitations and disadvantages for the sensors proposed in the literature (Khalil et al., 2023). As a solution to the mentioned limitations and disadvantages, this study proposes a microwave (MW) sensor that is repeatable, feasible, and sensitive to changes in dielectric parameters to detect adulterations in olive oil. The proposed sensor is capable of successfully detecting adulteration in sunflower oil mixed with olive oil at 10%. The proposed sensor exhibits superior performance compared to other sensors reported in the literature. The proposed sensor operates at a frequency of 9.481 GHz with a maximum sensitivity of 3.62%, a quality factor value of 4635, and a FoM value of 6581. In addition, the proposed sensor or system is considered an important candidate for sensing applications. It has advantages such as high sensitivity, compact design, low manufacturing and measurement costs, small size, easy use, low sample consumption, and low cost. The rest of the manuscript is as follows. The design of the proposed sensor, analysis, and preparation of samples are presented in detail in the Materials and Methods section. In the next section, dielectric constant measurement and adulteration processes of sunflower oil mixed with olive oil were examined in detail. Additionally, the proposed sensor's Q-factor, FoM, and sensitivity analyses are presented in detail in the Results and Discussion section. In the last section, the conclusions obtained from the study are given.

## 2. Materials and Methods

### 2.1. Design and analysis

In this section, the proposed MW sensor developed and examined within the scope of this study will be explained in detail. The optimal design was obtained by meticulously adjusting the proposed dimensions, and its final version for the detection of liquid foods (especially oils) using MW techniques is shown in Figure 1a. The proposed design is presented in Figure 1a, and simulations were carried out using the finite integration technique (FIT)-based Computer Simulation Technology MW Studio (CST) program. The designed sensor consists of a resonator at the top, an FR-4 dielectric layer in the middle, and a copper grounding layer at the bottom. In the proposed design, the loss tangent value of FR-4 was determined to be 0.025, its relative permeability was 4.3, and its thickness was 1 mm. Considering the durability, cost analysis, market availability, and reproducibility of the study, FR-4 material can be considered as a more suitable material for this study. The total size of the sensor is 22.86x10.16 mm² (compatible with X-band waveguide) and is designed to operate in the 8-12 GHz frequency range. The $|S_{11}|_{dB}$ value of the reflection-based sensor (without sample) designed in the CST program is seen as -47.19 dB around 9.481 GHz in the graph in Figure 2b. To demonstrate the accuracy and repeatability of the designed sensor, the proposed sensor was fabricated in compliance with the X-band waveguide, and the $|S_{11}|_{dB}$ (reflectance) parameter was measured (without samples) as shown in Figure 1b. As shown in Figure 2b, as a result of the measurement using the VNA device, when there is no sample on the proposed reflection resonance sensor, the $|S_{11}|_{dB}$ value of the sensor is approximately -42.35 dB at the frequency of 9.467 GHz. In addition, effect of four strips that forming resonator of the proposed sensor to response of the $|S_{11}|_{dB}$ value shown in Figure 2b. The $|S_{11}|_{\mathrm{dB}}$ value of the sensor is approximately -29.96 dB at the frequency of 9.493 GHz in the case without using the four strips in the design. It is evident that the four strips surrounding the main resonator induce a deeper reflection response and increase the response's quality.

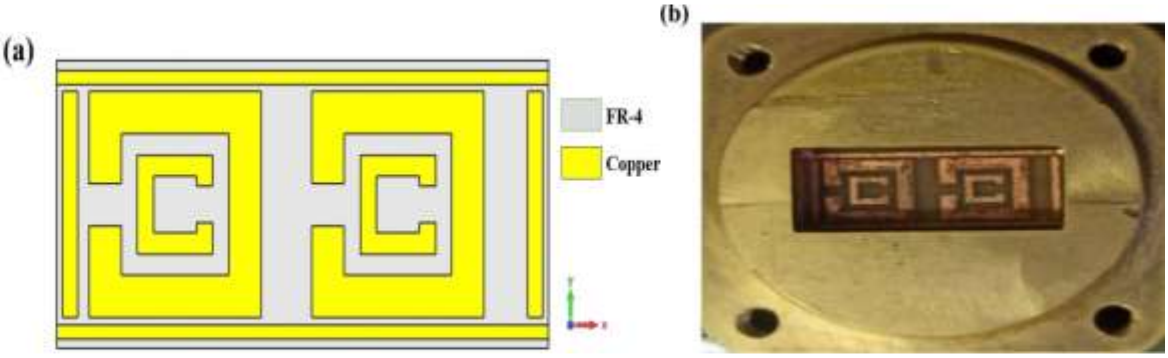

**Figure 1**. Proposed MW sensor (a) main structure in CST (b) front view of the fabricated sensor

Electric field distributions were examined to understand the working principle of the proposed sensor. Changes in the electric field provide information about the amount of energy the sensor can store (Islam et al., 2022b). The electric field distributions of the proposed sensor were simulated without samples at the resonance frequency of 9.48 GHz. As seen in Figure 2c, the electric field intensity is higher in the components that make up the resonator. Figure 2d represents the surface current distribution of the proposed sensor at the resonance frequency. Surface current distribution is observed to be concentrated on and around the elements forming the resonator. As a result, the proposed structure is capable of detecting even the smallest changes in the electrical properties of the sample. The proposed sensor has a design where the input port is provided at 1, the output port is measured at 2, and a two-port network is used to power the sensor, as the setup is shown in Figure 2a. When the electromagnetic wave was transmitted through port 1, most of the energy was stored in the sensing section during resonance. This energy then interacted with the dielectric properties of the tested oil sample, which were different from those of air, changing the resonance frequency. The resonance frequency was determined with the reflection coefficient $|S_{11}|_{dB}$. As a result of our market and literature research, we determined that sunflower oil is one of the oil types most commonly mixed with olive oil. Based on this observation, pure sunflower and olive oil purchased from the supermarket were adulterated at different rates. Maintaining the properties of all the oils we supply is important for the accuracy of the study. Therefore, all samples were stored in the refrigerator, protected from sunlight, in closed, dark glass bottles at approximately 5°C. Some samples were prepared to determine whether the designed MW sensor could detect oils or determine minimum adulteration rate capacity. These samples consist of pure olive oil, pure sunflower oil, and pure sunflower oil (mixed with olive oil at 10%, 20%, and 30% rates).

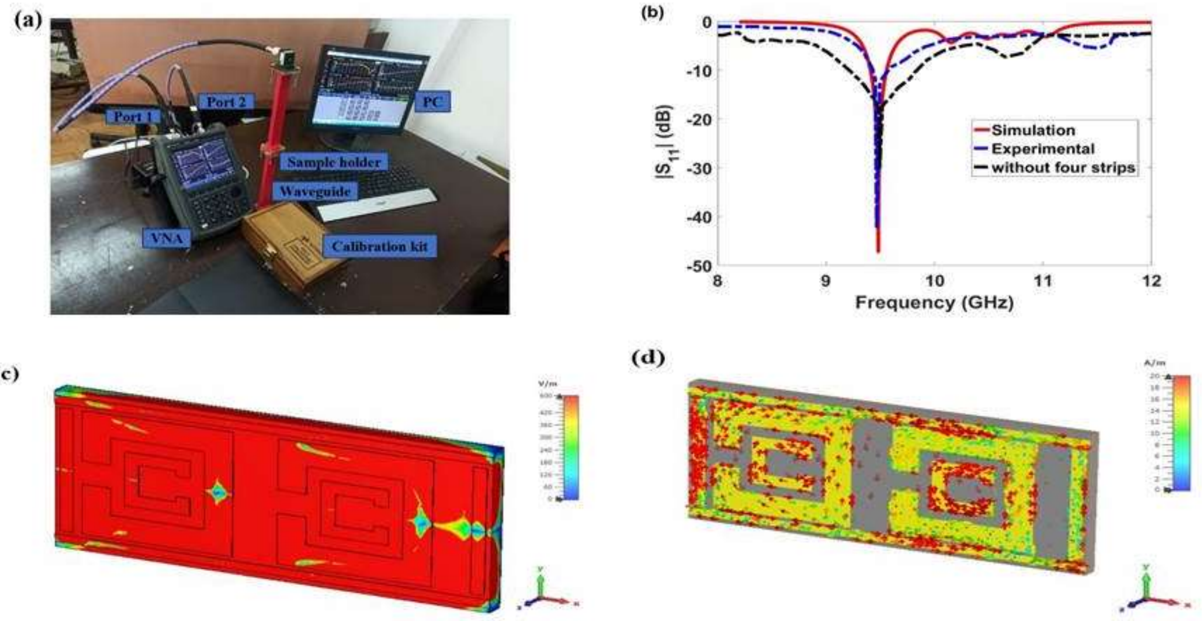

**Figure 2**. (a) Experimental setup for sample measurements with proposed sensor (b) experimental and simulated scattering parameter $|S_{11}|_{dB}$ of the proposed sensor in the air and $|S_{11}|_{dB}$ response without four strips (c) E-field and (d) surface current distribution of the proposed sensor at 9.481 GHz

## 3. Results and Discussion

The dielectric properties of all samples should be determined to simulate the response of the proposed sensor to samples prepared at different percentages and compared with experimental studies. For this purpose, the dielectric constants of the samples were determined in the 8-12 GHz frequency range using the dielectric probe measurement setup shown in Figure 3a. Dielectric constants of the prepared samples were determined using Keysight Technologies' open-ended coaxial dielectric probe kit (Model number: N1501A) with calibration steps such as short, clear, and distilled water and a calibrated VNA. The complex dielectric coefficient of the samples can be calculated using the formula given in (1).

$$\epsilon = \epsilon' - j\epsilon'' \tag{1}$$

Here $\varepsilon'$ represents the real component of permittivity, and $\varepsilon''$ represents the imaginary component of the permittivity. Figure 3b shows the graph of the real dielectric constants of pure olive oil, pure sunflower oil, and olive oil-sunflower oil mixture samples at different ratios. It can be seen from Figure 3b that the real dielectric constant value of sunflower oil is greater than that of olive oil. Additionally, the real dielectric constant of the samples shows a linear decrease between 8 GHz and 12 GHz. The real dielectric constants measured at the resonance frequency of the samples for pure olive oil, sunflower oil mixed with 10%, 20%, and 30% olive oil, and pure sunflower oil are 2.53, 2.68, 2.73, 2.77, and 2.89, respectively.

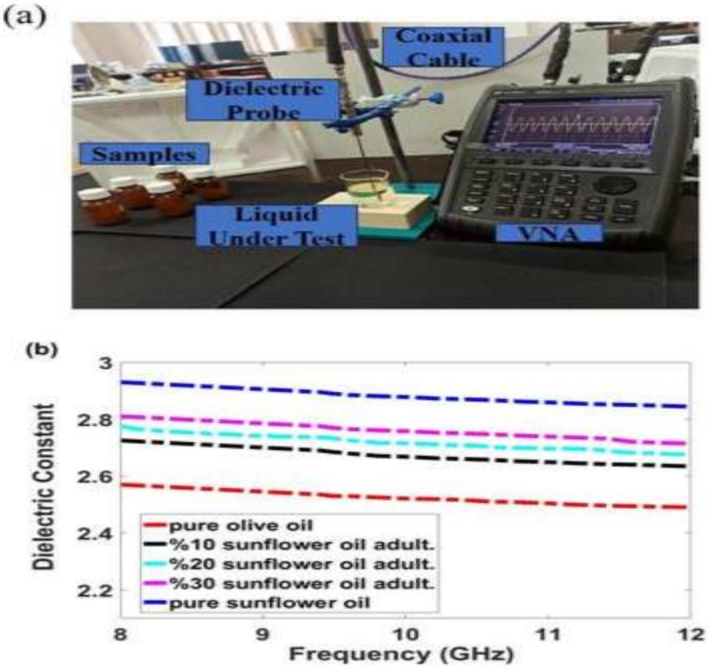

**Figure 3**. (a) Measurement set up for determining the dielectric constant of different samples using N1501A dielectric probe kit (b) dielectric constant curves for pure olive oil-sunflower oil adulteration

We stated that the dielectric properties of all prepared samples should be determined to simulate the response of the designed MW sensor to samples prepared at different percentages and compare it with experimental studies. The dielectric properties of the samples were determined using the dielectric probe assembly shown in Figure 3a, and the results are shown in Figure 3b. The measured dielectric constants were transferred to the CST simulation program and added to the CST library. All samples whose dielectric properties were determined and whose data were transferred to the CST library were simulated by placing them on the resonator. In this context, the response of the proposed sensor to samples prepared at different percentages was evaluated in a simulation environment.

### *3.1. Adulteration and analysis of olive oil with sunflower oil*

In this section, the process of the proposed MW reflection resonance sensor to analyze the adulteration of olive oil and sunflower oil at different rates with simulation and experimental setups is examined. The proposed sensor was modeled in a simulation environment in the frequency range of 8 GHz to 12 GHz, using the dielectric property data of pure olive oil, pure sunflower oil, and 10%, 20%, and 30% sunflower oil-olive oil mixtures. Pure olive oil and pure sunflower oil samples were added to the CST library. The simulation results of adulteration of sunflower oil and olive oil are shown in Figure 4a. As observed in Figure 4a, the proposed reflection resonance sensor responds to different resonance frequencies and changing reflection magnitudes with the change of the sunflower oil ratio added to the olive oil. For the proposed sensor, the observed resonance frequency in the simulation environment (without samples) was found to be approximately 9.481 GHz and the $|S_{11}|_{dB}$ value was -47.19 dB. When pure olive oil is placed at the top of the resonator, the observed resonance frequency is approximately 9.274 GHz and the $|S_{11}|_{dB}$ magnitude is -35.23 dB, under conditions where all simulation parameters are kept same. In this case, changes were observed in the resonance frequency and $|S_{11}|_{dB}$ value of the proposed sensor when there was no sample in the simulation environment and pure olive oil was placed as a sample. In the simulation for the proposed sensor, according to the result obtained using pure sunflower oil dielectric constant data, the resonance frequency was observed to be approximately 8.824 GHz, and the $|S_{11}|_{dB}$ value was observed to be -23.13 dB. Simulation results (resonance frequency and magnitude) of 10% sunflower oil and pure olive oil mixture, 20% sunflower oil and pure olive oil mixture, and 30% sunflower oil and pure olive oil mixture were obtained as (-32.13 dB and 9.112 GHz), (-30.03 dB and 9.050 GHz), and (-28.83 dB and 8.980 GHz), respectively. The experimental results of adulteration of olive oil and sunflower oil are presented in Figure 4b. When Figure 4b is examined, it is observed that the $|S_{11}|_{dB}$ values of the proposed reflection resonance sensor vary at different resonance frequencies, and in various samples.

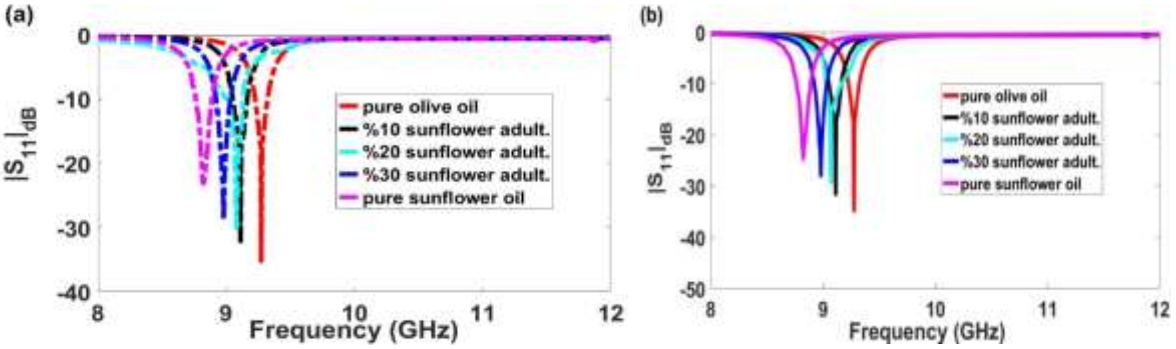

**Figure 4**. $|S_{11}|_{dB}$ graph for pure olive oil, pure sunflower oil, and pure olive oil- sunflower oil adulteration in different percentages (a) simulated result and (b) measured result

It has been observed that the experimental measurement results (magnitude and resonance frequency) for pure olive oil, 10% sunflower oil olive oil mixture, 20% sunflower oil olive oil mixture, 30% sunflower oil olive oil mixture, and pure sunflower oil samples are (-34.76 dB and 9.263 GHz), -31.57 dB and 9.101 GHz, (-29.17 dB and 9.042 GHz), (-27.97 dB and 8.971 GHz), (-22.73 dB and 8.811 GHz), respectively. Experimentally observed changes in the resonance frequency of the sensor were recorded as the ratio of sunflower oil mixed with olive oil increased. Figure 5a and Figure 5b show the resonance frequencies obtained from olive oil and sunflower oil mixtures in experimental and simulation setups and how these frequencies change compared to pure olive oil. According to the experimental measurement results, the resonance frequencies of pure olive oil, pure sunflower oil, and adulterated samples were determined. As a result of experimental measurements, the resonance frequency shifts of the samples compared to pure olive oil were determined as 0 MHz, 62 MHz, 221 MHz, 292 MHz, and 452 MHz, respectively. Additionally, in the simulation results, the resonance frequency shifts of the samples compared to pure olive oil were observed as 0 MHz, 62 MHz, 224 MHz, 294 MHz, and 450 MHz, respectively. According to the experimental and simulation results presented above, as the amount of sunflower oil added to pure olive oil increases, the resonance frequency decreases, and resonance frequency shifts increase. Table 1 shows the experimental and simulation results of olive oil-sunflower oil adulteration, including the resonance frequencies of the samples, $|S_{11}|_{dB}$, ε′ values, and the resonance frequency shifts of the samples compared to pure olive oil.

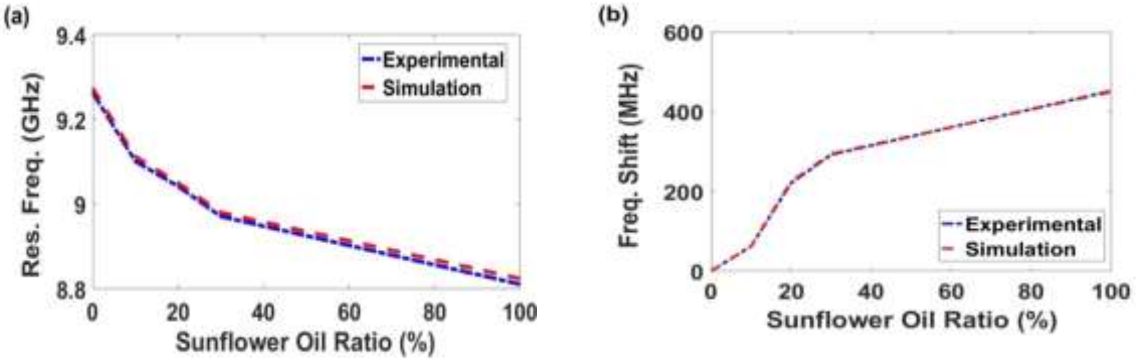

**Figure 5**. (a) Measured and simulated linearity plot of the resonant frequency versus sunflower oil concentration, (b) Measured and simulated linearity plot of the frequency shift versus sunflower oil concentration

When Table 1 is examined, the following inferences can be made regarding Figure 4a, Figure 4b, Figure 5a and Figure 5b. When the real dielectric constant values of the samples were listed from smallest to largest, an order was observed as pure olive oil, olive oil mixture containing 10% sunflower oil, olive oil mixture containing 20% sunflower oil, olive oil mixture containing 30% sunflower oil, and pure sunflower oil. In both simulation and experimental measurements, it is observed that the resonance frequency decreases as the ratio of sunflower oil mixed with pure olive oil increases. However, it is observed that as the sunflower oil ratio increases, the resonance frequency shifts of the samples increase compared to pure olive oil. Additionally, when Figure 5a and Figure 5b are examined, it is observed that an almost linear graph is obtained. When Figure 5a and Figure 5b are examined, it is possible to estimate the resonance frequency of the olive oil sample to which a certain amount of sunflower oil is added and the frequency shift compared to pure olive oil. When we look at the $|S_{11}|_{dB}$ values according to the experimental and simulation results of olive oil-sunflower oil adulteration, it is observed that $|S_{11}|_{dB}$ values decrease as the amount of sunflower oil added to pure olive oil increases in both cases. Finally, when the resonance frequency and $|S_{11}|_{dB}$ values for olive oil and sunflower oil adulteration are examined, it is understood that the experimental and simulation results are compatible and are ranked according to the dielectric constant values.

**Table 1**. Resonance frequency, $|S_{11}|_{dB}$ value, ε′ values, and resonance frequency shifts compared to pure olive oil for samples of olive oil-sunflower oil adulteration

| **Samples** | **Res. Freq. (sim)** | **Res. Freq. (exp)** | **$|S_{11}|_{dB}$ (sim)** | **$|S_{11}|_{dB}$ (exp)** | **ε′** | **Freq. Shift (sim)** | **Freq. Shift (exp)** |
|---|---|---|---|---|---|---|---|
| Pure olive oil | 9.274 GHz | 9.263 GHz | -35.23 dB | -34.76 dB | 2.53 | 0 MHz | 0 MHz |
| 10% sunflower oil adulteration | 9.112 GHz | 9.101 GHz | -32.13 dB | -31.57 dB | 2.68 | 62 MHz | 62 MHz |
| 20% sunflower oil adulteration | 9.050 GHz | 9.042 GHz | 30.03 dB | 29.17 dB | 2.73 | 224 MHz | 221 MHz |
| 30% sunflower oil adulteration | 8.980 GHz | 8.971 GHz | -28.83 dB | -27.97 dB | 2.77 | 294 MHz | 292 MHz |
| Pure sunflower oil | 8.824 GHz | 8.811 GHz | -23.13 dB | -22.73 dB | 2.89 | 450 MHz | 452 MHz |

### *3.2. Sensitivity, quality factor, and figure of merit analysis*

The performance of the sensor is generally determined by dimensionless sensor parameters such as sensitivity, quality factor, and FoM. The expressions in (2) and (3) were used to calculate the quality factor (Q-factor) and bandwidth frequency of the proposed sensor. Here $f_c$, $f_b$, $f_h$, and $f_l$ represent center resonance frequency, bandwidth frequency, and higher and lower frequencies within -3 dB of the center frequency, respectively. As can be understood from (2), the bandwidth frequency has a critical effect on the Q-factor value.

$$Q = \frac{f_c}{f_b} \tag{2}$$

$$f_b = f_h - f_l \tag{3}$$

When the proposed sensor is tested in the region where the electric field is strongest by loading the sample, the resonance frequency changes depending entirely on the permeability of the tested material. This relationship shows that any change in relative permittivity ($\Delta\epsilon_r$) causes a linear change in resonance frequency ($\Delta \mathrm{f}_r$). Therefore, sensitivity ($S$), an important parameter of the proposed sensor, can be determined by using (4).

$$S = \frac{\Delta f_r}{\Delta\epsilon_r} = \frac{f_{empty} - f_{\epsilon_r}}{\epsilon_r - 1} \tag{4}$$

Here, $\epsilon_r$ represents the dielectric constant of the sample, $f_{empty}$ is the empty state resonance frequency of the proposed sensor, $f_{\epsilon_r}$ is the resonance frequency of the sensor in the state where the sample is placed. $S(\%)$ is the normalized sensitivity of the proposed sensor (Alahnomi et al., 2021). The normalized sensitivity of the proposed sensor can be determined by using expression (5).

$$S(\%) = \frac{f_{empty} - f_{\epsilon_r}}{f_{empty}(\epsilon_r - 1)} \times 100 \tag{5}$$

Within the scope of this study, the Q-factor and sensitivity values of olive oil and sunflower oil samples tested on the proposed sensor were calculated. The Q-factors of olive oil and sunflower oil are 4635 and 465, the sensitivity values are 1.42% and 3.62%, respectively. Additionally, the FoM value of the proposed sensor can be determined by using expression (6).

$$FoM = S \times Q - factor \tag{6}$$

Based on expression (6), the FoM values of olive oil and sunflower oil were calculated as 6581 and 1683, respectively. Olive oil, with a Q-factor value of 4635, and sunflower oil, with a normalized sensitivity value of 3.62%, have the highest values. The proposed sensor was evaluated based on the Q-factor, material detection, operating frequency, resonance frequency shift, and FoM criteria presented in Table 2 for comparison with other proposed sensors in the literature. When Table 2 is examined, it is seen that the proposed sensor in this study has the highest values with a Q-factor value of 4635 and FoM of 6581.

When we examine (2), it is understood that the bandwidth frequency is inversely proportional to the Q-factor value. The bandwidth of the proposed design at the ringing frequency is quite low compared to other studies in the literature. Therefore, the Q-factor value is expected to be higher. In addition, since the FoM value is directly proportional to the Q-factor (6), it is clear that the FoM value of the proposed sensor is higher compared to other studies in the literature. Our proposed sensor offers higher sensitivity, better quality factor, and higher FoM value compared to other studies published in the literature. Therefore, these results indicate that the proposed sensor is a suitable choice for practical applications.

**Table 2**. Comparison of the proposed sensor with other sensors available in the literature

| **References** | **Material Sensing** | **Operating Frequency (GHz)** | **Resonance Frequency Shift (MHz)** | **Q-factor** | **FoM** |
|---|---|---|---|---|---|
| (Altintaş et al., 2019) | Transformer oil | 2-6 | 40 | 60 | 34 |
| (Abdulkarim et al., 2020b) | Oil | 1-8 | 63 | 90 | 32 |
| (Tamer et al., 2020) | Diesel | 8-12 | 60 | 110 | 37 |
| (Abdulkarim et al., 2020a) | Diesel | 8-12 | 120 | 105 | 41 |
| (Bakır et al., 2019) | Transformer oil | 8-12 | 70 | 100 | 48 |
| (Tümkaya et al., 2018) | Diesel | 10-12 | 72 | 90 | 52 |
| (Tamer et al., 2018) | Diesel | 8-12 | 100 | 95 | 38 |
| (Tümkaya et al., 2019) | Diesel | 8-12 | 92 | 105 | 43 |
| (Islam et al., 2022b) | Olive and corn oils | 8-12 | 100 | 135 | 76 |
| **This work** | **Olive and sunflower oils** | **8-12** | **450** | **4635** | **6581** |

## 4. Conclusion

Olive oil is a highly preferred food due to its healthy ingredients. Olive oil may be exposed to impurities during the production process due to high costs. This study proposes an MW sensor that is reproducible, feasible, and sensitive to changes in dielectric parameters to detect sunflower oil adulterated with olive oil. Simulation and experimental measurement results of the proposed reflection-based MW sensor were determined as -47.19 dB at 9.481 GHz frequency and -42.35 dB at 9.467 GHz frequency, respectively. When the simulation and experimental results are examined, it is observed that both measurements of the proposed sensor are consistent. In addition, the electric field and surface current distribution analyses of the proposed sensor were performed, and it was observed that the electric field was more intense in the parts forming the resonator. On the other hand, the dielectric constants of olive oil and sunflower oil were measured and analyzed using a dielectric measurement probe setup. Although the dielectric constants for olive oil and sunflower oil are close to each other, a resonance frequency shift of 62 MHz occurred between the pure olive oil and the 10% sunflower oil adulterated olive oil sample. The dielectric constants of the determined oils were significantly effective in frequency shift and magnitude interpretations in the simulation environment and experimental measurements. Olive oil and sunflower oil were mixed in certain proportions, and the response of the samples prepared using the proposed reflection-based sensor was examined in both simulation and experimental environments. Finally, the performance of the proposed sensor is analyzed. Accordingly, the Q-factor, sensitivity, and FoM values of the proposed sensor were calculated. It has been observed that the proposed sensor performs better than other sensors published in the literature, with a Q-factor value of 4635, a normalized sensitivity value of 3.62%, and a FoM value of 6581. In conclusion, based on simulation, experimental data, and performance analysis, it was observed that the proposed MW sensor could detect sunflower oils added to olive oil at rates of 10% and above by using the frequency shift properties. For these reasons, the proposed sensor or system can be preferred in various applications, such as industrial and liquid chemical detection, with advantages such as high sensitivity, high-quality factors, superior performance, low cost, and little sample consumption.

### Acknowledgment

The author Hüseyin Korkmaz acknowledges the Scientific and Technological Research Council of Turkey (TÜBİTAK) BIDEB 2211/C and Council of Higher Education (YÖK) 100/2000 Doctoral Scholarship program for supporting his studies.

## Ethics Permissions

This paper does not require ethics committee approval.

### Author Contributions

Hüseyin Korkmaz and Uğur Cem Hasar conducted the simulations and experiments; Hüseyin Korkmaz and Uğur Cem Hasar performed conceptualization analysis; Hüseyin Korkmaz and Uğur Cem Hasar prepared illustrations (visualization); Hüseyin Korkmaz and Uğur Cem Hasar analyzed the results; and Uğur Cem Hasar supervised the study.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### References

Abdulkarim, Y. I., Deng, L., Karaaslan, M., and Unal, E. (2019). Determination of the liquid chemicals depending on the electrical characteristics by using metamaterial absorber based sensor. *Chemical Physics Letters*, 732, 136655.

Abdulkarim, Y. I., Deng, L., Karaaslan, M., Dalgaç, Ş., Mahmud, R. H., Ozkan Alkurt, F., Muhammadsharif, F. F., Awl, H. N., Huang, S., and Luo, H. (2020a). The detection of chemical materials with a metamaterial-based sensor incorporating oval wing resonators. *Electronics*, 9(5), 825.

Abdulkarim, Y. I., Deng, L., Karaaslan, M., Altıntaş, O., Awl, H. N., Muhammadsharif, F. F., Liao, C., Unal, E., and Luo, H. (2020b). Novel metamaterials-based hypersensitized liquid sensor integrating omega-shaped resonator with microstrip transmission line. *Sensors*, 20(3), 943.

Abdulkarim, Y. I., Deng, L., Luo, H., Huang, S., Karaaslan, M., Altıntaş, O., Bakır, M., Muhammadsharif, F. F., Awl, H. N., Sabah, C., and Al-badri, K. S. L. (2020c). Design and study of a metamaterial based sensor for the application of liquid chemicals detection. *Journal of Materials Research and Technology*, 9(5), 10291-10304.

Alahnomi, R. A., Zakaria, Z., Yussof, Z. M., Althuwayb, A. A., Alhegazi, A., Alsariera, H., and Rahman, N. A. (2021). Review of recent microwave planar resonator-based sensors: Techniques of complex permittivity extraction, applications, open challenges and future research directions. *Sensors*, 21(7), 2267.

Altintaş, O., Aksoy, M., Ünal, E., and Karaaslan, M. (2019). Chemical liquid and transformer oil condition sensor based on metamaterial-inspired labyrinth resonator. *Journal of the Electrochemical Society*, 166(6), B482.

Altıntaş, O., Aksoy, M., and Ünal, E. (2020). Design of a metamaterial inspired omega shaped resonator based sensor for industrial implementations. *Physica E: Low-dimensional Systems and Nanostructures*, 116, 113734.

Bakır, M., Karaaslan, M., Karadag, F., Dalgac, S., Ünal, E., and Akgöl, O. (2019). Metamaterial sensor for transformer oil, and microfluidics. *The Applied Computational Electromagnetics Society Journal (ACES)*, 799-806.

Bhatti, M. H., Jabbar, M. A., Khan, M. A., and Massoud, Y. (2022). Low-cost microwave sensor for characterization and adulteration detection in edible oil. *Applied Sciences*, 12(17), 8665.

Ergin, T., Stenger, N., Brenner, P., Pendry, J. B., and Wegener, M. (2010). Three-dimensional invisibility cloak at optical wavelengths. *Science*, 328(5976), 337-339.

Göğüş, F., Özkaya, M. T., and Ötleş, S. (2009). Zeytinyağı. *Ankara: Eflatun Yayınevi*.

Gunstone, F. D. (2011). Production and trade of vegetable oils. Vegetable oils in food technology: Composition, properties and uses, 2, 1-24.

Hasar, U. C., Hasar, H., Ozturk, H., Korkmaz, H., Kaya, Y., Ozkaya, M. A., Ebrahimi, A., Barroso, J. J., Nayyeri, V., and Ramahi, O. M. (2024a). Simple and inexpensive microwave setup for industrial based applications: Quantification of flower honey adulteration as a case study. *Scientific Reports*, 14(1), 8847.

Hasar, U. C., Ozturk, H., Korkmaz, H., Nayyeri, V., and Ramahi, O. M. (2024b). De-embedding method for a sensing area characterization of planar microstrip sensors without evaluating error networks. *Scientific Reports*, 14(1), 10062.

Hashempour-baltork, F., Zade, S. V., Mazaheri, Y., Alizadeh, A. M., Rastegar, H., Abdian, Z., Torbati, M., and Damirchi, S. A. (2024). Recent methods in detection of olive oil adulteration: State-of-the-Art. *Journal of Agriculture and Food Research*, 16, 101123.

Hudec, P., Raboch, J., Randus, M., Hoffmann, K., Holub, A., Svanda, M., and Polivka, M. (2009, September). Microwave radar sensors for active defense systems. *In 2009 European Radar Conference (EuRAD)* (pp. 581-584). IEEE.

Islam, M. T., Islam, M. R., Islam, M. T., Hoque, A., and Samsuzzaman, M. (2021). Linear regression of sensitivity for meander line parasitic resonator based on ENG metamaterial in the application of sensing. *Journal of Materials Research and Technology*, 10, 1103-1121.

Islam, M., Bełkowska, L., Konieczny, P., Fornal, E., and Tomaszewska-Gras, J. (2022a). Differential scanning calorimetry for authentication of edible fats and oils–What can we learn from the past to face the current challenges?. *Journal of Food and Drug Analysis*, 30(2), 185.

Islam, M. R., Islam, M. T., Bais, B., Almalki, S. H., Alsaif, H., and Islam, M. S. (2022b). Metamaterial sensor based on rectangular enclosed adjacent triple circle split ring resonator with good quality factor for microwave sensing application. *Scientific reports*, 12(1), 6792.

Khalil, M. A., Yong, W. H., Islam, M. T., Hoque, A., Islam, M. S., Leei, C. C., and Soliman, M. S. (2023). Double-negative metamaterial square enclosed QSSR for microwave sensing application in S-band with high sensitivity and Q-factor. *Scientific Reports*, 13(1), 7373.

Khursheed, M., Ahmad, A., Noor, S. E., García del Moral, L. F., and Martos Núñez, V. (2024). Chromatographic Techniques for the Detection and Identification of Olive Oil Adulteration.

Korkmaz, H., and Hasar, U. (2021). Wide band metamaterial absorber with lumped element. *The International Journal of Materials and Engineering Technology*, 4(1), 61-66.

Korkmaz, H., Hasar, U. C., and Ramahi, O. M. (2023). Thin-film MXene-based metamaterial absorber design for solar cell applications. *Optical and Quantum Electronics*, 55(6), 530.

Korostynska, O., Mason, A., and Al-Shamma'a, A. (2014). Microwave sensors for the non-invasive monitoring of industrial and medical applications. *Sensor Review*, 34(2), 182-191.

Krödel, S., Thomé, N., and Daraio, C. (2015). Wide band-gap seismic metastructures. *Extreme Mechanics Letters*, 4, 111-117.

Lee, H. J., and Yook, J. G. (2008). Biosensing using split-ring resonators at microwave regime. *Applied Physics Letters*, 92(25).

Lee, Y., Kim, S. J., Park, H., and Lee, B. (2017). Metamaterials and metasurfaces for sensor applications. *Sensors*, 17(8), 1726.

Meenu, M., Cai, Q., and Xu, B. (2019). A critical review on analytical techniques to detect adulteration of extra virgin olive oil. *Trends in Food Science & Technology*, 91, 391-408.

Menegoz Ursol, L., and Moret, S. (2024). Evaluation of the impact of olive milling on the mineral oil contamination of extra-virgin olive oils. *European Journal of Lipid Science and Technology*, 126(3), 2300123.

Mehrotra, P., Chatterjee, B., and Sen, S. (2019). EM-wave biosensors: A review of RF, microwave, mm-wave and optical sensing. *Sensors*, 19(5), 1013.

Mohd Bahar, A. A., Zakaria, Z., Md. Arshad, M. K., Isa, A. A. M., Dasril, Y., and Alahnomi, R. A. (2019). Real time microwave biochemical sensor based on circular SIW approach for aqueous dielectric detection. *Scientific Reports*, 9(1), 5467.

Musa, I. (2024). Investigation the optical properties of Palestinian olive oils for different geographical regions by optical spectroscopy technique. *Food Chemistry Advances*, 4, 100584.

Nyfors, E. (2000). Industrial microwave sensors—A review. *Subsurface Sensing Technologies and Applications*, 1(1), 23-43.

Osman, S. B., Korostynka, O., Mason, A., Cullen, J. D., and Al-Shamma'a, A. I. (2014). Application of microwave spectroscopy analysis on determining quality of vegetable oil. International *Journal on Smart Sensing and Intelligent Systems*, 7(5), 1-4.

Obaidullah, M., Esat, V., and Sabah, C. (2021). Multi-band (9, 4) chiral single-walled carbon nanotube based metamaterial absorber for solar cells. *Optics & Laser Technology*, 134, 106623.

Rueda, M. P., Domínguez-Vidal, A., Llorent-Martínez, E. J., Aranda, V., and Ayora-Cañada, M. J. (2024). Monitoring organic matter transformation of olive oil production residues in a full-scale composting plant by fluorescence spectroscopy. *Environmental Technology & Innovation*, 103695.

Shi, Q., Dong, B., He, T., Sun, Z., Zhu, J., Zhang, Z., and Lee, C. (2020). Progress in wearable electronics/photonics-moving toward the era of artificial intelligence and internet of things. *InfoMat,* 2(6), 1131-1162.

Tamer, A., Alkurt, F. O., Altintas, O., Karaaslan, M., Unal, E., Akgol, O., Karadag, F., and Sabah, C. (2018). Transmission line integrated metamaterial based liquid sensor. *Journal of the Electrochemical Society*, 165(7), B251.

Tamer, A., Karadağ, F., Ünal, E., Abdulkarim, Y. I., Deng, L., Altintas, O., Bakır, M., and Karaaslan, M. (2020). Metamaterial based sensor integrating transmission line for detection of branded and unbranded diesel fuel. *Chemical Physics Letters*, 742, 137169.

Tümkaya, M. A., Dinçer, F., Karaaslan, M., and Sabah, C. (2017). Sensitive metamaterial sensor for distinction of authentic and inauthentic fuel samples. *Journal of Electronic Materials*, 46, 4955-4962.

Tümkaya, M. A., Karaaslan, M., and Sabah, C. (2018). Metamaterial-based high efficiency portable sensor application for determining branded and unbranded fuel oil. *Bulletin of Materials Science,* 41, 1-8.

Tümkaya, M. A., Ünal, E., and Sabah, C. (2019). Metamaterial-based fuel sensor application with three rhombus slots. *International Journal of Modern Physics B,* 33(24), 1950276.

Vélez, P., Su, L., Grenier, K., Mata-Contreras, J., Dubuc, D., and Martín, F. (2017). Microwave microfluidic sensor based on a microstrip splitter/combiner configuration and split ring resonators (SRRs) for dielectric characterization of liquids. *IEEE Sensors Journal*, 17(20), 6589-6598.

Wu, B., Jiang, W., Jiang, J., Zhao, Z., Tang, Y., Zhou, W., and Chen, W. (2024). Wave manipulation in intelligent metamaterials: recent progress and prospects. *Advanced Functional Materials*, 2316745.

Yılmaz-Düzyaman, H., de la Rosa, R., Velasco, L., Núñez-Sánchez, N., and León, L. (2024). Oil quality prediction in olive oil by near-infrared spectroscopy: Applications in olive breeding. *Agriculture*, 14(5), 721.