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Development of a Non-Contact Microwave Sensor System Specifically for the Detection of Honey Adulteration with Syrup

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ABSTRACT: This article presents the microwave detection and analysis of honey adulteration. A study of the differences between pure and adulterated honey based on dielectric properties in the frequency range of 2 to 12 GHz was performed. A honey adulteration determination system using a free-space method with microwaves was developed. The transmitting section was responsible for generating a 2.4 GHz frequency signal using a high-frequency signal generator and radiating the signal power through a prototype transmitting antenna that propagated through the honey sample to the receiving antenna. All 72 honey samples were tested and categorized into six levels of adulteration. The average transmission power (S_{21}) for pure honey and adulteration levels of 10%, 20%, and 50% was found to be 2.356, 2.321, 2.297, and 2.222 mV, respectively, with a coefficient of determination R^2 of 0.969. The sensitivity of the detection was 0.027 mV/10% adulteration. The decision-making system was used to test the measurement of 144 honey samples. The sensor system achieved an accuracy of 95.83%, indicating that the non-contact microwave-based method for detecting honey adulteration is effective.

1. INTRODUCTION

Honey is a natural sweetener with high nutritional value [1, 2]. It has health benefits owing to its probiotic, antioxidant, and antibacterial properties, making it a superior sweetener compared to normal sugar. As a result, honey is widely consumed. However, the relatively high cost of pure honey has often led to adulteration by the addition of water or lower-cost sweeteners such as corn syrup, invert syrup, or high-fructose inulin syrup [3]. Adulteration causes a decrease in the nutritional and medicinal properties of honey [4]. Conventional methods for distinguishing pure honey consider its color, concentration, and viscosity. However, these techniques are difficult for inexperienced individuals. Recently, food quality assurance has become increasingly important in the food industry, and the development of rapid and efficient analytical methods for food quality assessment is crucial [5].

Chemical methods for honey quality analysis [6, 7] offer high accuracy. However, these methods involve complex procedures, including sample preparation, the use of expensive equipment, and the requirement for skilled personnel. In addition, they are contact-based methods and time-consuming. Consequently, researchers have explored and developed various tools for honey adulteration detection, which are user-friendly and capable of providing immediate results. Most of these tools are designed to be portable for field applications, such as electronic tongues [8] or techniques based on the measurement of impedance characteristics and Q-factor [9]. Nonetheless, these methods involve direct contact with honey. Near-infrared (NIR) spectroscopy has also been employed, offering high sensitivity and accuracy in a non-contact format [10]. However, NIR techniques are complex in terms of requiring large-scale data analysis to classify adulteration levels [11] and are sensitive to environmental light and interference. Microwave-based measurement techniques have gained increasing attention in recent years, using the free-space method, which is non-contact and suitable for measuring hazardous or high-temperature liquids [12, 13]. Because the dielectric properties of a medium are key electrical characteristics influencing microwave behavior, researchers have utilized these properties to detect honey adulteration based on variations in dielectric constants within the microwave frequency range. Measurement techniques include direct dielectric property analysis using coaxial probes and vector network analyzers (VNAs) [14, 15], as well as indirect methods that analyze related parameters to infer dielectric behavior [16–18]. However, these techniques require expensive equipment to be performed. Furthermore, indirect measurement approaches have been investigated, such as monitoring the resonant frequencies of antennas [19] and resonators [20–22]. Although these methods reduce sensor hardware costs, they still require high-end laboratory instruments. Some researchers have proposed using the waveguides integrated with metamaterials [23], which provides high sensitivity. However, the metamaterials used are specialized and not widely available. Other studies utilized reflection coefficient measurements from custom-designed sensors [24], but these sensors involve complex structures that require precise fabrication tools, and the method remains contact-based.

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Therefore, this study proposes a non-contact method for detecting honey adulteration using microwave frequency signals based on the analysis of the differences in the dielectric properties of honey. A simulation of the honey sensing system was conducted by adjusting the dielectric properties according to the level of adulteration. A prototype system was developed using the Free-Space Method combined with microwave frequencies owing to its simplicity, low cost, immediate result display, and suitability for field applications. The related theory is presented in Section 2. The dielectric properties of honey were measured using a vector network analyzer, and the values of ε_r' and ε_r'' at 2.4 GHz were considered in relation to adulteration levels shown in Section 3. The size and structure of the antenna were analyzed and used to simulate the honey detection system described in Section 4. The system simulation involved adjusting the dielectric property values of the honey model according to the adulteration level. A prototype antenna was developed based on this optimized structure. In Section 5, the structure of the proposed sensor system and the development of the system to operate at 2.4 GHz for non-contact testing of samples are described. Section 6 is the testing and reference threshold setting for the six levels of honey adulteration. The system was tested on 144 honey samples, and its performance was evaluated. The final section concludes the study.

2. RELATED THEORY

The dielectric properties are electrical characteristics that determine the storage and dissipation of energy between a medium and electromagnetic wave energy [25]. Permittivity (ε) is a dielectric property of a material that describes the effect of the medium on electric field energy [26]. The complex relative permittivity consists of the real part, dielectric constant (ε_r'), imaginary part, and the dielectric loss factor (ε_r''), as shown in Equation (1).

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' \tag{1}$$

The dielectric constant and dielectric loss factor are not constant; they vary depending on the temperature and frequency [27], which represent the energy of the electric field stored in the medium. The dielectric loss factor indicates the energy loss of an electric field within a medium. When the amplitude of the electric field E_0 oriented along the x-axis propagates through a medium along the z-axis and is incident at the interface between two media with different properties, a portion of the power is transmitted through the interface into the second medium. The amplitude of the transmitted wave changes according to the transmission coefficient (T), as described by Equation (2).

$$\bar{E}_t = \hat{x} T E_0 e^{-\gamma z} \tag{2}$$

where γ is the propagation constant. In the case of wave propagation from air, which has an impedance η_0 into a second medium with impedance η and relative permittivity ε_r, the transmission coefficient T is related to the impedance of the media, as shown in Equation (3) [28]. The impedance of the medium is related to the dielectric properties according to Equation (4):

$$T = \frac{2\eta}{\eta + \eta_0} \tag{3}$$

$$\eta = \eta_0 \sqrt{\mu_r / \varepsilon_r} \tag{4}$$

The value μ_r is the relative permeability of the medium, which is approximately equal to 1 for dielectric materials. Therefore, the amplitude of the transmitted wave changes with respect to the dielectric property ε_r of the second medium, as expressed in Equation (5).

$$\bar{E}_t = \frac{1}{1 + \sqrt{\varepsilon_r}} \hat{x} E_0 e^{-\gamma z} \tag{5}$$

The dielectric constant of a solution of two mixed substances changes according to the Lichtenecker mixing rule [29]. Therefore, in the case of honey adulterated with other sweeteners that have lower dielectric constants, the overall dielectric properties of honey decrease owing to a reduction in its ability to generate polarization. This resulted in a decreased dielectric constant [30]. Consequently, the transmitted power can be analyzed to differentiate between pure honey and adulterated honey.

3. DIELECTRIC PROPERTY OF ADULTERATED HONEY

To study the trends in the changes in dielectric properties resulting from syrup adulteration, dielectric measurements of adulterated honey were performed to analyze the possibility of using frequency to detect adulteration [31]. Adulterated honey samples were prepared by mixing pure honey with a syrup. The samples were divided into six adulteration levels and stored in acrylic containers for measurement. Sample group 1 consisted of pure honey (0% adulteration, ADT). Sample group 2 comprised 10%ADT syrup by weight. Sample groups 3 to 6 contained syrup adulteration at 20%ADT, 30%ADT, and up to 50%ADT. The sweetness of the adulterated honey samples was measured using a Brix refractometer. Subsequently, the dielectric properties of the adulterated honey were measured using an open-ended coaxial probe (Agilent 85070E) connected to a vector network analyzer (VNA; E5063A, Keysight Technologies). The equipment was calibrated before the measurements

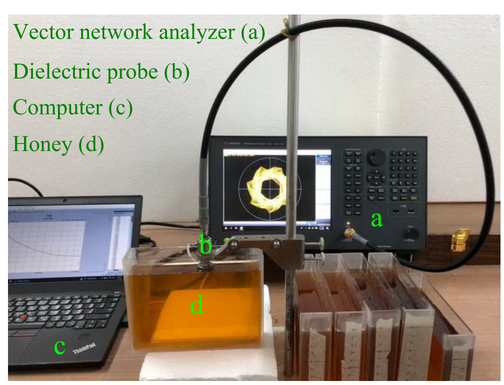

FIGURE 1. Dielectric properties of honey adulteration measurement.

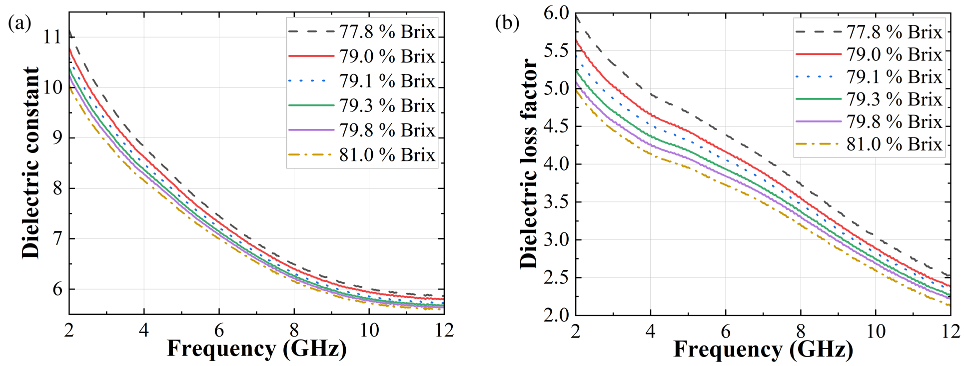

FIGURE 2. (a) Dielectric constant, (b) dielectric loss factor of adulterate honey.

were taken. The dielectric properties of the adulterated honey samples were measured in the frequency range of 2 to 12 GHz, as illustrated in Figure 1.

The measurement of the dielectric constant (ε_r') of pure honey (0%ADT) exhibited ε_r' values ranging from 5.60 to 10.04 with an soluble solid content (SSC) level of 81 %Brix; when increasing the level of adulteration, ε_r' increases, and sweetness level decreases. At the maximum adulteration level of 50%ADT, ε_r' ranged from 5.86 to 11.14 with a sweetness level of 77.8 %Brix, as illustrated in Figure 2(a). For the dielectric loss factor (ε_r''), the honey with 0%ADT adulteration exhibited values ranging from 2.12 to 4.98, and at 10%ADT, values ranged from 2.20 to 5.08, and similarly increased as the adulteration level increased. At the maximum adulteration level of 50%, the values ranged from 2.51 to 5.97, as illustrated in Figure 2(b).

As the frequency increased from 2 to 12 GHz, the values of ε_r' and ε_r'' for each honey sample decreased. When the level of adulteration increased, ε_r' and ε_r'' of each honey sample significantly increased. Consider a single frequency at 2.4 GHz to reduce the complexity of the processing and decision-making steps for adulteration level classification. The adulteration levels of 0%ADT and up to 50%ADT yielded dielectric properties at 2.4 GHz with ε_r' values of 9.51 to 10.49, respectively, and ε_r'' values of 4.73 to 5.66, respectively, as illustrated in Figure 3.

The dielectric properties of honey obtained from the measurements indicate distinguishable differences in ε_r' and ε_r'' at each level of adulteration, particularly at the frequency of 2.4 GHz. Therefore, an antenna was developed for a honey determination system.

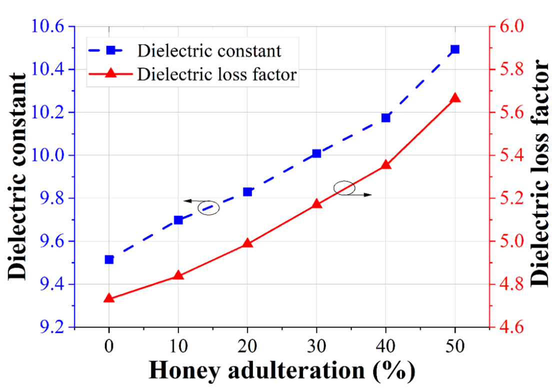

FIGURE 3. Dielectric property of adulterated honey at 2.4 GHz.

4. SIMULATION OF THE ANTENNA AND HONEY DETECTION SYSTEM

Adulteration affects the dielectric properties of honey, and when electromagnetic waves propagate through media with different ε_r', it results in wave absorption, energy accumulation, and conversion of electromagnetic energy into thermal energy [32]. Therefore, to detect adulteration, the free-space method is applied by utilizing a patch antenna for transmitting and receiving signal power. The antenna design process began with the calculation of dimensions and feed point position, which served as fundamental parameters for the simulation using Computer Simulation Technology (CST) Studio Suite. The dimensions were then adjusted to ensure that the antenna operated in the 2.4 GHz frequency band [33]. To ensure a compact fit for mounting on the sample holder, a low-profile octagonal microstrip antenna with a coaxial probe feed was fabricated on a double-sided FR4 printed circuit board. The substrate has a dielectric constant of 4.3 and a thickness of 1.414 mm. A coaxial probe feeding technique was employed, as illustrated in Figure 4(a). The dimensions of the radiating patch (w_1, h_1) were varied with diameters ranging from 32.0 to 33.2 mm, resulting in resonance frequencies of 2.56 to 2.33 GHz with the optimal patch size being 32.8 mm, corresponding to a resonance frequency of 2.4 GHz. Then, the feed point position (w_2) was adjusted, and the feed point distance was varied from 4.0 mm, 4.2 mm, to 4.6 mm, yielding S_{11} return loss values at 2.4 GHz of -19.02 dB, -23.75 dB, and -23.57 dB, respectively. The optimal feed position was 4.4 mm, providing an S_{11} of -33.37 dB, as illustrated in Figure 4(b).

Based on the simulation results, the optimal radiating patch dimensions were determined to be 32.8 mm for the patch and 4.4 mm for the feed point position. The overall antenna size was 70 × 70 mm, as shown in Table 1.

TABLE 1. Parameters of antenna.

Parameter	h, w	w_1, h_1	h_3	w_2	w_3	h_2
size (mm)	70.0	32.8	1.414	4.4	18.2	32.7

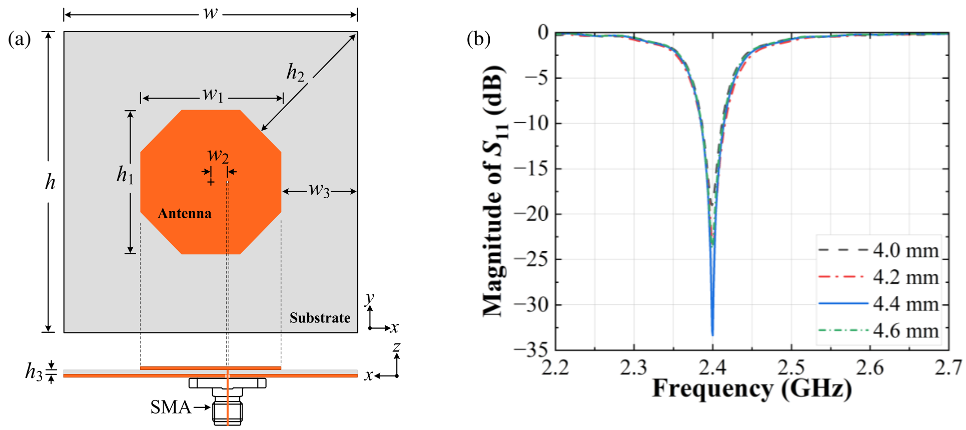

FIGURE 4. (a) Structure of octagonal microstrip antenna, (b) S_{11} with various feed point position.

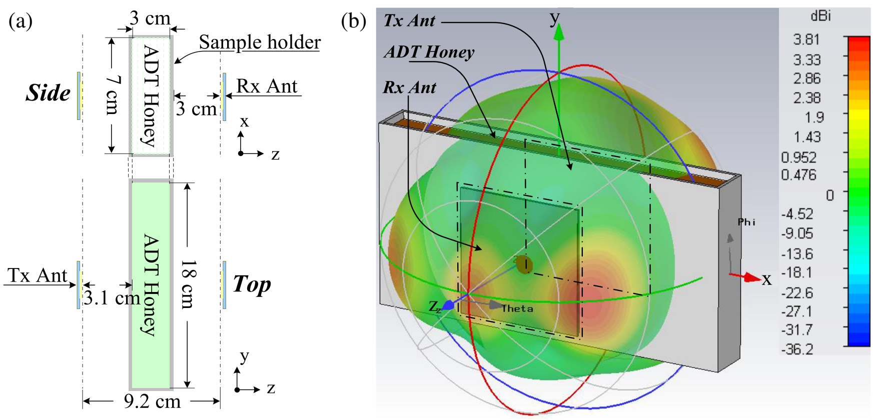

FIGURE 5. (a) Sample holder, (b) simulated system for adulterated honey detection.

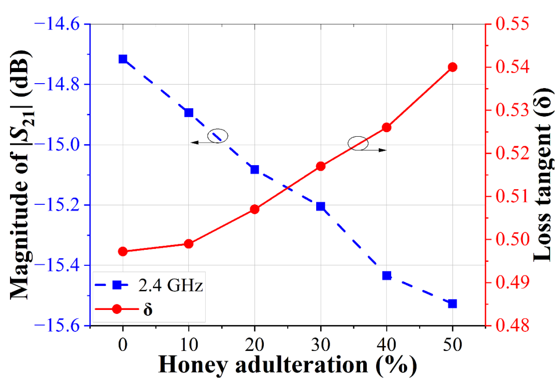

FIGURE 6. Simulated S_{21} parameter response to the loss tangent of adulterated honey.

Subsequently, a honey adulteration detection system was simulated using the CST Studio Suite. The developed antenna was used to transmit and receive the signal power through honey samples. The honey samples were placed in a sample holder made of acrylic (PMMA), which had a dielectric constant of 2.7. The holder dimensions were $3.2 \times 18.2 \times 7.2$ cm with a wall thickness of 1 mm. The sample holder was positioned centrally between the transmitting and receiving antennas, as illustrated in Figure 5(a). The dielectric properties of the honey model at 2.4 GHz were adjusted according to the adulteration levels of 0%ADT to 50%ADT. According to the level of adulteration, corresponding to the loss tangent values ($\varepsilon_r''/\varepsilon_r'$), the corresponding complex relative permittivities ($\varepsilon_r' - j\varepsilon''_r$) were $9.52-j4.73$, $9.70-j4.84$, $9.83-j4.99$, and $10.49-j5.66$, respectively. The complete detection system model is shown in Figure 5(b).

For adulteration levels of 0%ADT to 50%ADT, the corresponding loss tangent values were 0.497, 0.499, 0.507, 0.517, and 0.540, with transmitted power S_{21} values of -14.72 dB, -14.89 dB, -15.08 dB, -15.20 dB, and -15.53 dB, respectively. As the adulteration percentage increased, the loss tangent also increased, leading to a noticeable reduction in the transmitted power, as illustrated in Figure 6.

The simulation results indicated that adulteration affects S_{21}, suggesting the potential for detecting honey adulteration using microwave frequencies. Therefore, the antenna was developed and fabricated, as illustrated in Figure 7(a). The operating frequency range of the antenna was tested using a vector network analyzer (VNA), model FPC1500 by Rohde & Schwarz, within the frequency range of 2.2 to 2.65 GHz. The antenna provided optimized characteristics at 2.4 GHz, achieving S_{11} of -33.55 dB, as illustrated in Figure 7(b).

The developed antenna possesses suitable characteristics, as it operates well at a frequency of 2.4 GHz, provides a low return loss, is easy to fabricate, has a simple structure, and is suitable for application in a honey adulteration detection system.

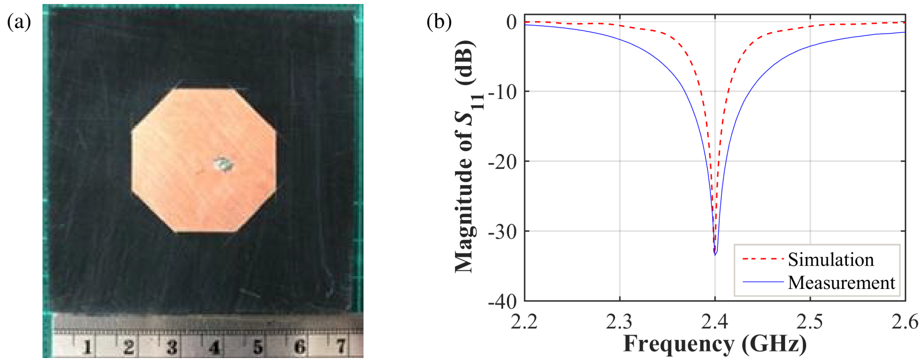

FIGURE 7. (a) Prototype antenna, (b) S_{11} of prototype antenna.

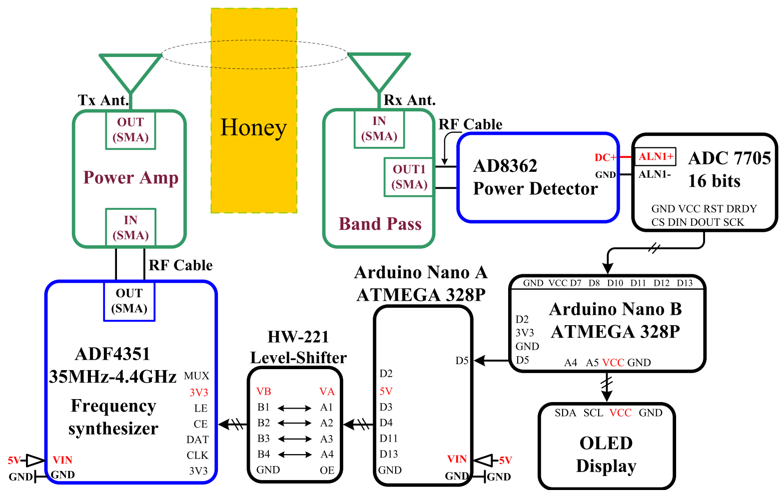

FIGURE 8. Proposed system operation diagram for honey detection.

5. PROPOSED SENSOR SYSTEM

In the transmitter section of the proposed sensor system, begin by generating a frequency signal using microcontroller board A connected to a frequency synthesizer to generate a 2.4 GHz signal. This signal was then transmitted through a radio frequency (RF) power amplifier to amplify the signal power and pass it to the transmitting antenna, which radiated the signal power through the honey samples. When the wave is incident on the honey sample, some of the energy is reflected; some is refracted; some propagates through, some is converted into heat energy; and some is absorbed by the sample. These changes result from the different dielectric properties of the materials [34, 35]. The power transmitted through the honey is detected by the receiving antenna. The received signal was filtered to isolate the desired frequency range and then passed to a power detector to convert the frequency signal into DC voltage. The DC signal was converted into a digital signal using an analog-to-digital converter (ADC). The data are sent to microcontroller board B for processing and displayed on a screen for decision-making, as illustrated in Figure 8.

The transmitter section of the prototype sensor system used an Arduino Nano A V3.0 with an ATMEGA328P chip to control a high-frequency signal generator, ADF4351 from Analog Devices, which can generate frequencies between 0.35 and 4.4 GHz. It was configured to generate a 2.4 GHz signal. The frequency power was then amplified using an RF power amplifier that could operate in the 0.02 to 3 GHz range with a gain of 20 dB. The amplified signal was transmitted via the prototype transmitting antenna to propagate the signal power through adulterated honey samples. The receiving antenna was placed on the same line as the transmitting antenna, with the honey sample positioned in between. The power transmitted through the honey sample was detected by the receiving antenna and filtered using a bandpass filter to eliminate unwanted signals, allowing only the 2.4 GHz frequency to pass through. The filtered signal was then sent to a power detector, AD8362 from Analog Devices, which accepted input from -52 to $+8$ dBm and provided an output in the range of 0.4 to 3.4 V. The frequency signal was converted into DC level and sent to an analog-to-digital converter (ADC), model AD7705 from Analog Devices, providing a 16-bit digital output. These data were then sent to Arduino Nano B, which controlled the entire sensor system, managed data storage and processing, and displayed the decision-making results on an OLED display, as illustrated in Figure 9.

6. EXPERIMENTAL RESULTS

The sensor system was calibrated using an empty sample holder to minimize the effects of the sample holder and environmen-

TABLE 2. Comparison of our method with other syrup-adulterated honey techniques.

Ref.	Method	Freq.	Sensor parameter	Equipment	Contact level	Accuracy	Material Cost
[19]	Self complementary dipole antenna	1.1–3.3 GHz	Resonant frequency shift	Antenna, VNA	Contact	N/A	Expensive laboratory equipment
[22]	Fluorescence + Dielectric	2 GHz	Resonant frequency shift	Circular complementary split-ring resonator (CSRR), VNA, microcontroller, computer	Contact	100%	Expensive laboratory equipment
[23]	metamaterial sensor	7.6–8 GHz	Resonant frequency shift	Sensor, waveguide, VNA	Non-contact	Error $< 0.4\%$	Expensive laboratory equipment
[36]	Transmission signal	1.85–3.25 GHz	Absorbance level	SDR	Non-contact	$R^2 = 0.81$	Medium cost
[37]	Raman spectra	-	Raman spectra	Raman Spectrometers	Non-contact	84.4%	Expensive laboratory equipment
[38]	Hyperspectral imaging	-	Hyperspectral images	Hyperspectral imaging camera	Non-contact	$> 95\%$	Expensive laboratory equipment
This work	**Free space/ microwave technique**	**2.4 GHz**	**Voltage of transmission signal**	**Antenna, microcontroller**	**Non-contact**	**95.83%** $\mathbf{R^2 = 0.969}$	**Low cost ($77)**

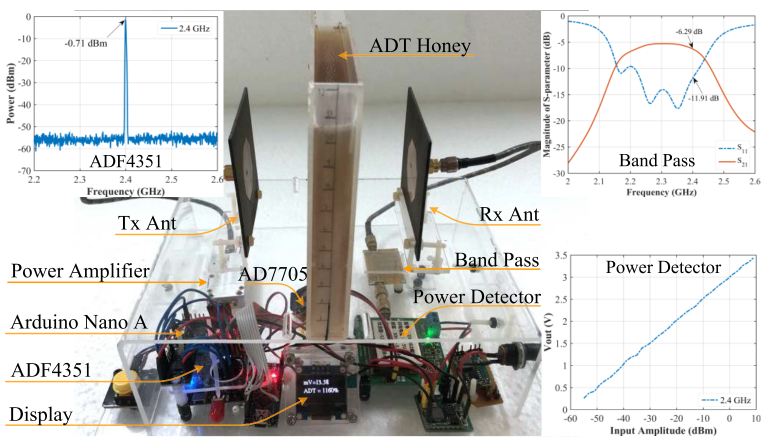

FIGURE 9. Prototype sensor system for honey adulteration detection.

tal conditions. Subsequently, the honey samples were tested and divided into six levels of adulteration. Each adulteration level consisted of 12 samples. Pure honey yielded DC voltage ranging from 2.34 to 2.36 mV. For adulteration levels of 10%ADT, 20%ADT, to 50%ADT, the values ranged from 2.32 to 2.29, 2.27 to 2.25, and 2.27 to 2.22 mV, respectively, with corresponding average values of 2.356, 2.321, and 2.297 to 2.222 mV, respectively. To assess the stability of the system, the measurement data at each percentage level of adulteration were analyzed by calculating the standard deviation (SD). At 0%ADT, 10%ADT, 20%ADT, and 50%ADT, the SD values were 1.39, 2.66, 3.1, and 2.94, respectively, indicating a slight fluctuation in the measurement data, particularly in the 40–50%ADT range, owing to the high levels of adulteration affecting the sensor response. The overall average SD was 2.37, which is within the acceptable range. This can be observed as the percentage of adulteration increased, and the transmission power decreased, which aligns with the simulation results and corresponds to a decrease in the transmission coefficient (T) as the dielectric properties of the adulterated honey increase, according to Equation (5) as shown in Figure 10.

The system uses a decision-making process based on linear regression to simplify data processing. The transmitted power corresponding to the adulteration level yielded an R^2 value of 0.969. The decision-making process of the sensor system utilized the equation $y = -2.54x + 2358$. Subsequently, the sensor system was tested on 144 randomly selected honey samples, which were divided into six levels of adulteration, with 24 sam-

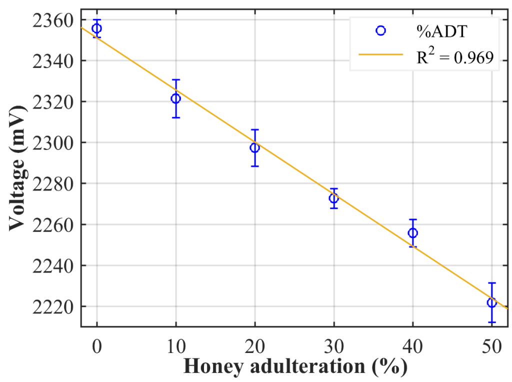

FIGURE 10. Measurement results of adulterated honey.

ples per level. At 0%ADT, 10%ADT, and 30%ADT, the system demonstrated high accuracy, and at 40% to 50%ADT, the data exhibited slight fluctuations, resulting in a minor decrease in accuracy. The sensor system classified the adulteration levels with an ADT accuracy of 95.83%. This indicates that honey adulteration can be identified effectively. A comparison of the performance of the proposed sensor with that of other methods for identifying honey adulteration with syrup is listed in Table 2.

7. CONCLUSION

The honey adulteration detection sensor system employs the free-space method, a non-contact measurement technique, to analyze the differences in the transmitted signal power level for adulteration level classification. The measurement utilized microstrip patch antennas to transmit and receive the microwave frequency signals. The dielectric constant and dielectric loss factor of honey samples with six adulteration levels were measured over the frequency range of 2 to 12 GHz. The values of ε_r' and ε_r'' were used to develop a honey model for simulating the detection system at 2.4 GHz. The honey model adjusted the adulteration levels with ε_r' ranging from 9.51 to 10.49 and ε_r'' from 4.83 to 5.66. Increasing adulteration levels led to a reduction in transmitted power ranging from -14.89 to -15.53 dB. The sensor system consisted of a transmitter and a receiver unit positioned opposite each other, with the honey sample placed between them. The transmitter used a 2.4 GHz high-frequency signal generator. The signal was amplified and radiated toward the honey sample using a prototype of the patch antenna. The transmitted signal was detected by a receiver, which consisted of a band-pass filter and a power detector. The measurement data were processed and analyzed in relation to the adulteration percentages. The measurements were performed on 72 samples across the six adulteration levels. The average transmission signal voltage ranged from 2.356 to 2.222 mV, with standard deviations of 1.39 to 2.94, respectively. The linear regression of S_{21} against the adulteration levels showed an R^2 value of 0.969. The system employed a low-complexity decision-making process based on the equation $y = -2.54x + 2358$. The sensor system for detecting adulterated honey was tested across six levels of adulteration, with a total of 144 samples. As the adulteration percentage increased, the measured data exhibited minor fluctuations. Nevertheless, the sensor system was able to classify the levels of adulteration with an accuracy of 95.83%, demonstrating that non-contact classification using microwave frequencies can be performed effectively.

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