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Evaluation of water content in honey using microwave transmission line technique

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A B S T R A C T

The microwave transmission line technique is presented as an effective method for the evaluation of honey for the first time. The electrical permittivity is an intrinsic parameter of a material that can be used as an index of added water content. For the permittivity calculation, it is found that the combination of the characteristic matrix method and Tischer's model can offer the highest accuracy. A genetic algorithm is introduced to provide an initial approximate permittivity value and acquire the Cole-Cole parameters of the honeys examined. The accuracy provided by the methodology used in this study is superior to that offered by a commercially available probe. Operating at room temperature and a frequency range of 6–8 GHz, the measurements demonstrate that the permittivity of honey increases with increased added water. A relationship between the added water content and the permittivity of honey-water mixture is established, which could be a powerful tool for detecting honey adulteration.

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1. Introduction

The average composition of honey is about 80% carbohydrates (e.g., fructose and glucose), 18% water and 2% amino acids, minerals, vitamins and proteins. It has been used as a high nutritional food or as a remedy for many diseases. For these benefits to materialise, honey should be free from water and other sweeteners (National Honey Board, 2003). However, for economic gain, honey has become a target of excessive adulteration worldwide. For example, water is one of the common ingredients for honey adulteration. The adulteration is both fraudulent and unfair to consumers, and it could cause health concerns to those who rely on nutrients from honey products. Therefore, determination of the purity of honey is important for manufacturers, retailers, consumers and regulatory authorities (Chen et al., 2011).

Two types of methods are commonly used for honey quality assessment: sensory and chemical analyses (e.g., liquid chromatography, infrared spectroscopy and mass spectrometry). The sensory analysis mainly detects honey colour, viscosity, smell, flavour and crystallisation. However, the accuracy of the sensory analysis is limited and usually depends on the experience of the sensory panellists. Chemical analysis also has some disadvantages, such as need for highly skilled labour, ultrapure preparation, expensive instruments and large instrumental analysis (Bázár et al., 2016). Thus, the development of a relatively fast, easy-to-use and low-cost measurement method becomes attractive.

A microwave-based technique can be an alternative method for quality assessment on the basis of the electrical permittivity, which is an intrinsic parameter of a material that represents the interaction with the electromagnetic field. Establishing explicit relationships between the permittivity and the agri-food constituents can provide a means of rapid inspection of properties (e.g., moisture, fat and salt content) (Chua et al., 2007; Gibson et al., 2008). Microwave detection methods have various attributes, such as fast (few minutes rather than hours), non-hazardous, capable of measuring bulk properties and less sensitive to environmental conditions (Kharkovsky and Zoughi, 2007; Li et al., 2017). A number of microwave techniques have been reported in the literature and used in practice for liquids: open-ended rectangular waveguide (Karpisz et al., 2016)/coaxial probe (Guo et al., 2010) techniques, time domain spectroscopy/reflectometry (TDR) method (Puranik et al., 1991), resonance methods (e.g., resonant cavity (Liao et al., 2001)

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and coupled split-ring resonator (Watts et al., 2016)) and free space methods (Jose et al., 2001). Each method has its own particular advantages, disadvantages and applications. Specifically, the open-ended methods are prone to errors introduced by improper contact between the probe and the material surface (e.g., air gaps or air bubbles). The TDR measuring instruments are expensive (Venkatesh and Raghavan, 2005). The resonance approach is inherently narrowband and requires careful sample preparation and calibration (Kraszewski and Nelson, 1992). For the free space technique, special attention must be paid to the choice of horn antennae, design of the sample holder and the sample geometry and location. On the other hand, the transmission line technique is robust, broadband and suited to materials with a wide range of dielectric loss. For the liquid measurement, two waveguide cells with window can be made to hold the sample on each side. However, few studies have been made on the measurement of honey using this technique.

In this work, the transmission line technique is adopted for the study of honeys and honey adulteration for the first time. First, the Cole-Cole equation for the description of dielectric properties of liquids is introduced. Then the liquid permittivity measurement and the available methods for the permittivity calculation are addressed. From the measurement of distilled water at room temperature over two frequency bands (i.e., 6–8 GHz and 8–12 GHz), the efficiency and accuracy of each permittivity calculation method and frequency band are evaluated by comparison with the empirical data provided by the Cole-Cole equation. Afterwards, the measurements of two types of honeys are conducted over 6–8 GHz. A genetic algorithm, an optimisation method, is employed to quickly search the possible permittivity of the honey samples, which will be a starting point for further accurate calculation. It is also used to obtain the Cole-Cole dielectric parameters for clear and set honeys. The effect of the calibration errors on the accuracy of the permittivity measurement is studied. In addition, its accuracy is compared with that by a commercially available dielectric probe. Finally, the effect of the added water on the permittivity of honey-water mixture is investigated in detail and a purity index is identified.

2. Dielectric properties of liquids

2.1. Definition of permittivity

When microwave energy is directed towards a material, part of the energy is reflected, part is transmitted and part is absorbed by the sample. The portion of energy that falls into these three categories have been defined in terms of the scattering parameters and these can be related to the dielectric properties of the sample (Gibson et al., 2008). The fundamental electrical property through which the interactions between the electromagnetic wave and the material are described is the complex permittivity ε. It is mathematically expressed as:

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left(\varepsilon_r' - j\varepsilon_r'' \right) \quad (1)$$

where $\varepsilon_0 = 8.8542 \times 10^{-12}$ F/m is the permittivity of free space, and ε_r is the relative permittivity. The real part ε'_r of ε_r, or dielectric constant, characterises the ability of a material or a substance to store the electric field energy. ε''_r (positive), or dielectric loss factor, reflects the ability of a material to dissipate the electric energy in the form of heat.

2.2. Cole-Cole equation for description of liquids

The Cole–Cole equation is a relaxation model that is often used to describe the relative permittivity of liquids. It is given by the equation:

$$\varepsilon_r = \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} + \varepsilon_\infty \quad (2)$$

where ε_s and ε_∞ are the 'static' and 'infinite frequency' permittivity. ω is the angular frequency and τ is a time constant. The exponent parameter α is a value between 0 and 1.

For water, the static frequency constant ε_s is described by (Hasted, 1973)

$$\varepsilon_s = 87.740 - 0.40008\mathrm{T} + 9.398 \times 10^{-4}\mathrm{T}^2 - 1.410 \times 10^{-6}\mathrm{T}^3 \quad (3)$$

where T is the temperature in °C.

And the other relaxation parameters ε_∞, τ and α for water are listed in Table 1.

The variation of the relative permittivity of water with respect to frequency and temperature over 1–20 GHz is plotted in Fig. 1. In this frequency range, ε'_r and ε''_r are of the same order of magnitude, which demonstrates the high-loss characteristic of water.

2.3. Penetration depth of microwaves into dielectrics

Considering the effect of the lossy medium, the power of the microwaves decays exponentially through the thickness. The penetration depth d_p is a practical parameter used for the evaluation of signal propagation. It is defined as the depth where the amplitude of the signal is reduced to $1/e$ (about 37%) below the surface. For a dielectric material, d_p can be calculated by (Pozar, 2011):

$$d_p = \frac{c_0}{\sqrt{2}\pi f \left\{ \varepsilon_r' \left[\sqrt{1 + \left(\varepsilon_r''/\varepsilon_r' \right)^2 - 1} \right] \right\}^{1/2}} \quad (4)$$

where f is the operating frequency, and c_0 is the speed of light in free space. It is seen that the penetration depth is inversely proportional to the frequency.

3. Three-layer problem of the liquid permittivity measurement

The microwave transmission line technique is used with a three-layer arrangement. The schematic diagram of the in-waveguide measurement is illustrated in Fig. 2, where two waveguide flanges with window (i.e., Layer 1 and Layer 3) provide a liquid-

Table 1
Water relaxation parameters derived from the Cole-Cole equation (Hasted, 1973).

T (°C)	0	10	20	30	40	50	60
ε_∞	4.46 ± 0.17	4.10 ± 0.15	4.23 ± 0.16	4.20 ± 0.16	4.16 ± 0.15	4.13 ± 0.15	4.21 ± 0.16
τ (10^{-11} s)	1.79	1.26	0.93	0.72	0.58	0.48	0.39
α	0.014	0.014	0.013	0.012	0.009	0.013	0.011

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