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Dielectric properties assessment of honey by using non-destructive dielectric spectroscopy

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ABSTRACT

In this research the dielectric constant of three types of Malaysian honey has been investigated using a non-destructive measurement technique. The objective of this research is to assess the dielectric constant of the three types of honey in Malaysia using a non-destructive measurement technique known as an open-ended coaxial probe in the frequency range from 100 MHz to 10 GHz frequency. Analysis on the effect water concentration in honey on the dielectric constant and the effect of temperature on dielectric constant of honey has been conducted. The three types of honey that have been chosen to be investigated in this project are stingless bee honey, wild honey and commercial (organic) honey and together their water adulterated samples. For this research, the probe had been set up by setting a range of frequency from 100 MHz to 10 GHz and needs to be calibrated with three calibration methods namely open, short and reference water. From the result it was found that the higher the temperature of the honey and the higher percentage of water content in the honey, the dielectric constant is increased. The dielectric constants of all honeys decreased with increasing frequency in the measured frequency range and increased with increase percentage of water content and temperature.

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1. INTRODUCTION

Pure honey is very valuable in the market, because of its benefits to health. So, the honey had been used as daily food product for the benefits. Honey consist many vitamin and mineral that good for the human health [1]. One the benefit of honey is it is a good alternative to sugar. Although honey consist sugar, but it is healthier than the sugar. So, it can be replacing sugar as a food sweetener in daily food. Other than that, some research has shown that raw honey can kill unwanted bacteria and fungus. It is reported that it naturally contains hydrogen peroxide, an antiseptic [2].

The honey composition depends on geographical location of where the honey is found [3]. The emergence of synthetic honey and adulterated honey imposes another threat to honey safety and purity due to its relatively high sugar content [4], [5]. One method of adulteration of honey is by the addition of foreign substance directly to honey i.e. by adding water [6]-[8]. Commonly the quality of the honey is measured by sensory and chemical analysis. This type of measurement can be very expensive with a complicated procedure [9]. Therefore, fast, non-destructive, and precise analytical methods are encouraged to complement the existing technique [10]. The relative permittivity is a dielectric property that will determines the interaction of food with the electromagnetic field. During the measurement, dielectric probe to measure the dielectric constant has been used at a range of frequencies. Researchers in [11]-[15], has concluded that moisture content being the dominant factor in determining the permittivity of food. Thus, in this paper, water concentration in honey is one of the parameters that has been considered in the analysis. Comparison has been made for all the three types of honey, in terms of temperature variation with frequency and the water concentration of honey across the measured frequencies.

In this paper the non-destructive measurement has been chosen due to its advantage that it does not destroy the material under test, and it is rapid, thus suitable for quality assessment of certain food i.e. honey [10]. This method can provide the dielectric constant value of a material when subjected to an electromagnetic fields [16]-[18]. Besides that, it covers a wide range of frequency and does not require sample preparation. The non-destructive method are increasingly used in the application of agriculture and food processing industries [19]-[21]. With the uses of the open-ended coaxial probe, the honey dielectric constant can be measured and the quality of honey can be assessed using a simple probing technique [12], [16], [17]. The research on the dielectric constant of the honey may be benefit other researcher because of more data on the dielectric constant of honey can be made available and can serve for quality control.

2. MATERIAL AND METHOD

2.1. Types of honey

For this research, three types of honey has been chosen in the investigation. The three types were stingless bee honey, wild honey and commercial honey as shown in Figure 1. All the honey is used by Malaysian for the daily food consumption, medication or maybe for some specific purposes. All the three honeys are the most popular honey available in the market.

Figure 1. The three-types of honey used in the research: stingless, wild and organic honey

Stingless bee are also popularly known as lebah kelulut in Malaysia with more than 38 stingless bee species [22], [23]. Stingless bee honey is also widely used as medication and it is claimed that it have a high medicinal beneficial than other bee species [6], [24]. Wild bee in the study is name after tualang honey by local people. The honey is produced by the rock bee (apis dorsata), which builds hives on branches of tall Tualang trees located mainly in the north-western region of Peninsular Malaysia. Finally, the commercial honey in this research is a type of honey that has a flower-like aroma. It has a delicate flavor and can be found on acacia mangium trees flowers.

2.2. Dielectric constant measurement method

During the measurement, dielectric probe namely keysight 1501A has been used that can measure dielectric constant from the frequency of 10 MHz to 50 GHz. Figure 2 shows the coaxial cable probe (N1501A keysight). In this research, a vector network analyzer (E5080B) is connected to high temperature probe with a coaxial cable to measure the dielectric constant of the honey as shown in Figure 3. The high temperature probe has a frequency range of 100 MHz to 20 GHz. The setting had been set from 100 MHz to 10 GHz. Before the measurement of the honey is conducted, the probe need to be calibrated. The probe had been calibrated using the three standards of calibration, open (air), short circuit and using 25 °C of deionized water. After the calibration, the deionize water is used as a reference measurement to verify whether the calibration is successful. To do so, the high temperature probe need to be immersed into the deionized water and need to avoid from air bubbles between water and the probe surfaced. Later, the dielectric constant measurement of honey can be resumed.

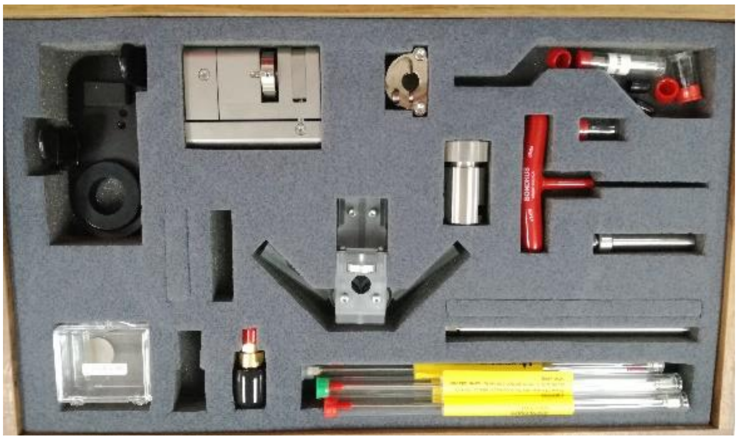

Figure 2. Coaxial cable probe (N1501A keysight)

Figure 3. The vector network analyzer connected with the probe for dielectric constant measurement

2.3. Procedures

The three types of the honey are poured into 20 ml beaker and labeled. The temperature of the honey is measured by using a digital thermometer and the measurement is conducted at room temperature (25 °C). Then, the honey samples, pure honey and honey with different water content of 10%, 20%, and 30% at room temperature had been prepared for testing. Known amount of deionized water was added to the pure honey, with 10% water content, of each type to prepare the adulterated honey samples to get a final water contents (10%, 20%, and 30%) at room temperature.

The calibration consists of measuring three known standards and using the results to characterize the three major sources of measurement error. The default calibration standards are air, a short circuit, and water. After the calibration of the probe, the probe had been adjusted to a suitable height for measurement. Then the probe needs to be completely immersed in the honey sample. In order to get the best result, the air bubble should be eliminated before any measurement to avoid inaccuracy of the results.

After the dielectric constant at 25 °C had been measured, the measurement continues with the honey sample been heated to 30 °C, 35 °C, 40 °C, 45 °C, and 50 °C. The honey samples have been heated up by using a laboratory heating plate and need to be stirred until the honey sample totally heated up until to the suitable temperature. After heated up, the sample been measured with the probe until totally immersed and the measurement are measure from 100 MHz to 10 GHz. After the measurement, all the dielectric constants had been tabulated and analyzed.

2.4. Penetration depth

Penetration depth can be defined as the reducing of electromagnetic power on the surface value [25]. The depth is reducing to 1/e where e=2.7183 that is about 37% of its value. The penetration depth can be calculated as in (1):

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left(1+\left(\frac{\varepsilon'}{\varepsilon''}\right)^2-1\right)}} \tag{1}$$

where:
c=speed of light (3x108 m/s)
f=frequency in Hz
ε'=dielectric constant
ε''=dielectric loss factor

After all the dielectric constants had be measured. The values are fed into the penetration depth equation as stated in (1). The values of frequency, the value of ε' and ε'' had been identified and simulated in MATLAB software to monitor the penetration depth across the frequency with variation of water concentration. The results are discussed in detail in the next section.

3. RESULTS AND DISCUSSION

3.1. Dielectric constant of pure honey

In this research three types of honey that is stingless bee honey, wild honey and commercial honey had been measure the dielectric constant. The honey been measured at frequency from 100 MHz to 10 GHz at room temperature. The measurement was set from 100 Mhz because the interaction of microwaves with biological material at frequencies above 100 MHz depends more or less exclusively on aqueous and ionic content and thus it could give a better accurate result. This is because at lower frequency, the result on the graph will be rippled and the result will be in error. The result of the dielectric constant can be observed in Figure 4.

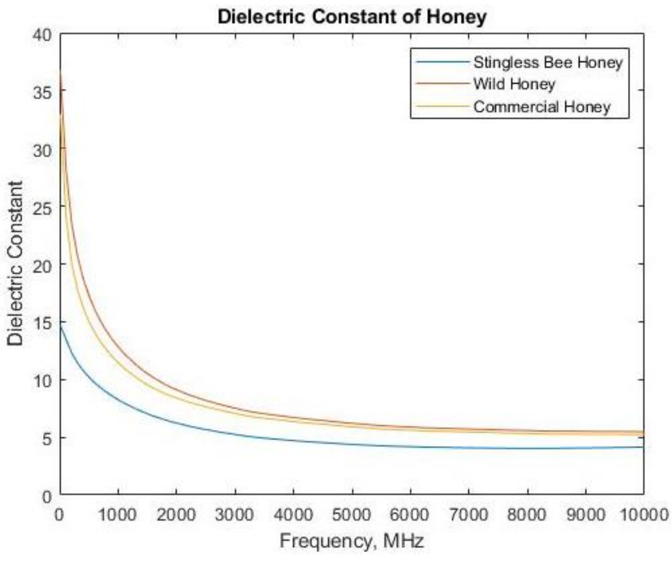

Figure 4. The dielectric constant of the honey

Figure 4 shows the dielectric constant of the three types of honey with the dielectric constant. The figure shows that the graph of the dielectric constant of the honey decreasing with increasing frequency. It is clearly can be observed that the three types of honey had a decreasing value of dielectric constant with increasing frequency. At some level, it seems the dielectric constant been constant at frequency 5000 MHz and higher.

Based on the Table 1, the stingless bee honey has the lowest dielectric constant at 13.46 when frequency is 100 MHz at 25 °C and decreasing to 8.21, 4.37, and 4.14 at frequency of 1 GHz, 5 GHz, and 10 GHz respectively. The highest dielectric constant from the three types is from wild honey which was 28.11 at 100 MHz at 25 °C decreasing to 12.76, 6.20, and 5.47 at frequency 1 GHz, 5 GHz, and 10 GHz respectively. For the commercial honey, although the dielectric constant had a slightly lower than the wild honey, that 24.00 dielectric constant at frequency 100 MHz, but it still higher when compared to the stingless honey at 25 °C. Furthermore, the dielectric constant of the commercial honey had decreased with the increasing of the frequency. The dielectric constant of the wild honey is decreased from 24.00 at frequency 100 MHz to 11.40, 5.89, and 5.22 at frequency 1000 MHz, 5000 MHz, and 10000 MHz respectively. Although all the pure honey might contain water, but the water is in a bound form. The dielectric relaxation is likely resulted from bound water according to the frequency where critical frequency appeared in honey. Although honeys have similar content of total soluble solids, other compositions can also have a major impact on their dielectric properties.

Table 1. The dielectric constant of honey at room temperature (25ºC)

Honey	Permittivity	Frequency (MHz)			
		100	1000	5000	10000
Stingless Bee Honey	ε’	13.46735	8.21695	4.377429	4.146544
Wild Honey	ε’	28.11291	12.7654	6.201249	5.471811
Commercial Honey	ε’	24.00476	11.40298	5.899014	5.220061

Based on the figure, it is found that stingless bee honey has the lowest dielectric constant throughout the measured frequencies. This low dielectric constant of the stingless bee honey may because the stingless bee honey may have lower water content than wild honey and the commercial honey. With low water content in the honey, the dielectric constant value may be low. This is because the content of water can affect the dielectric constant value. The other honey which is wild honey and commercial honey may have a higher bound form of water content than the stingless bee honey.

3.2. The influence of water content to dielectric constant

The increasing of water content can influence the value of the dielectric constant. The higher the percentage of the water content that is mixed to the honey, the higher the dielectric constant. Regardless of how much water content was added in stingless bee honey, wild honey and commercial honey, the dielectric constant decreased with increasing frequencies. This result is justified with the result found by Puranik *et al.* [12]. It was found that the decrease in the relaxation time is caused by the addition of water and thus the dielectric constant is decreased [11]. For this research the water content had been added to 20 ml of honey. The water content will be added as 10%, 20%, and 30% from the honey volume respectively to mimic adulterated honey. For the pure honey, it has the lowest dielectric constant and it increase slowly water content is added.

The Figure 5, Figure 6, and Figure 7 shows the dielectric constant of the three honeys with different water content concentration from 10%, 20%, and 30% at 25 °C respectively. All the three types of honey have an increased in dielectric constant when water concentration is increased. The dielectric constant of the honey increases slowly with the increasing of water content. For the pure stingless bee honey (no water is added) ,as shown in Figure 5, the dielectric constant is low at 18.88 at frequency 100 MHz and the dielectric constant is decreased to 10.64, 6.39, and 5.11 at 1000 MHz, 5000 MHz, and 10000 MHz respectively. But the dielectric constant increases with the increasing of water content across the frequency. At 10%, 20%, and 30% of water content, the dielectric constant of the stingless bee honey is at 50.12, 55.77, and 57.35 respectively. For the pure wild honey as shown in Figure 6, the dielectric constant is 29.86, 13.84, 7.60, and 5.40 with frequency 100 MHz, 1000 MHz, 5000 MHz, and 10000 MHz respectively. The increasing of water content made the dielectric constant of wild honey increase to 44.18, 54.26, and 57.70 at 10%, 20%, and 30% of water content respectively at 100 MHz frequency.

The result is similar for pure commercial honey whereby the dielectric constant increase with increasing water content across the frequency. It can be seen form Figure 7, the dielectric constant also increasing with increasing water content. The dielectric constant of organic honey at water content concentration of 0%, 10%, 20% and 30% is 26.09, 41.59, 55.44, and 59.20 respectively at frequency of 100 MHz. By using this result, the purity of honey can be observed and identified with the volume of water content. The lowest dielectric constant shows that the honey is pure honey, while the higher dielectric constant is because higher content of water presence in the adulterated honey. With this, the purity of honey can be compared using the measured result as a database.

All the changes in the dielectric constant is caused by the ionic behavior. Adding water in honey reduces its viscosity and binding forces to ionic movement, so the ionic conduction plays a growing role in the loss process as the water content increases slowly. It has been identified and shown that ionic conduction is the dominant mechanism of loss in honey [25].

Table 2 shows the table of dielectric constant for different water concentration at four frequencies when measured at 25 °C. The table shows a consistent pattern of the dielectric constant of the three types of honey across the measured frequency, the dielectric constant of all three types of honey decreased with the increase in the frequency. It also can be summarized that the dielectric constant of all types of honey increase with increasing water content across the frequency.

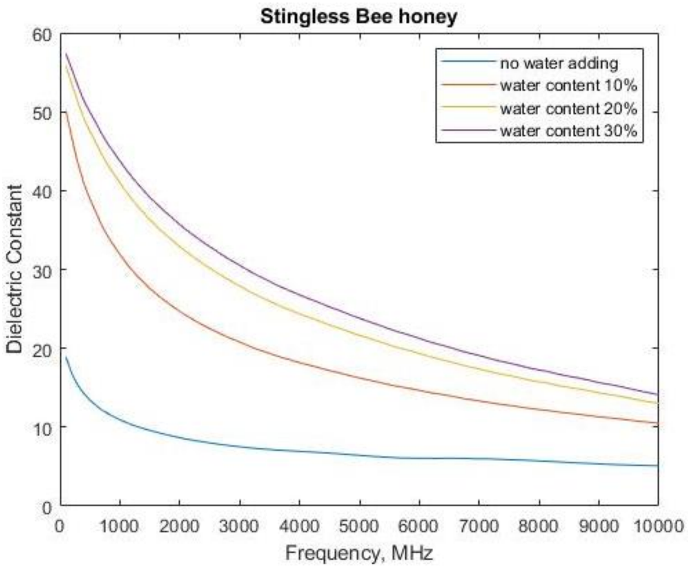

Figure 5. Stingless honey vs the water content

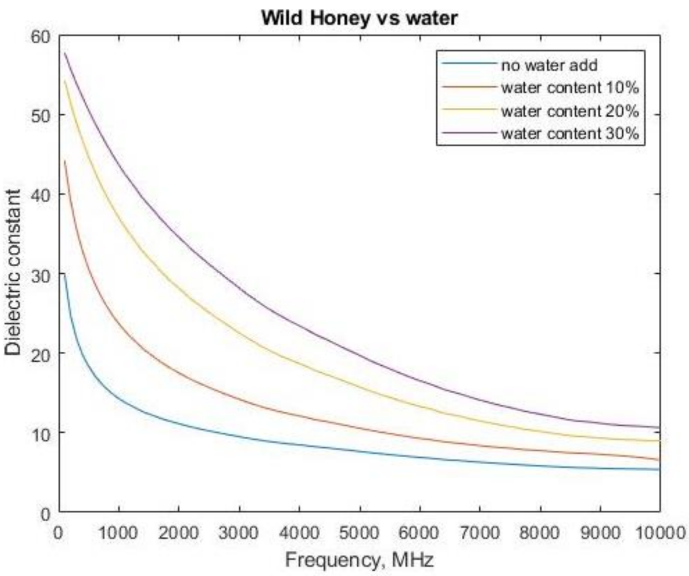

Figure 6. Wild honey vs the water content

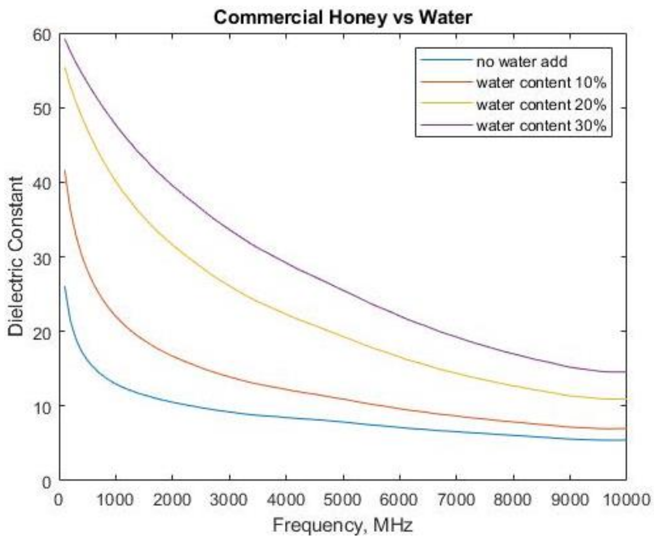

Figure 7. Commercial honey vs the water content

Table 2. The dielectric constant of the honey with difference water content at four frequencies (room temperature 25 °C)

Honey	Water Content (%)	Permittivity	Frequency (MHz)			
			100	1000	5000	10000
Stingless Bee	0	ε’	1888249	10.64884	6393059	5.113504
		ε’’	4398542	5.024878	3.553934	3.120000
	10	ε’	50.12850	30.96371	16.15575	10.49813
		ε’’	9.540305	14.50191	11.86250	8.704843
	20	ε’	55.71556	40.00974	21.52726	12.97834
		ε’’	9.549713	15.70854	15.86650	12.29473
	30	ε’	57.35174	4280638	23.67162	14.10279
		ε’’	9.903941	15.64894	17.12910	13.61364
Wild Honey	0	ε’	29.86604	13.84707	7.604478	5.408130
		ε’’	10.37976	7.815738	5.014079	2.699919
	10	ε’	44.18429	22.85680	10.49061	6.593671
		ε’’	9.499322	13.18460	9.115590	5.845393
	20	ε’	54.26613	35.91661	15.58577	8.976289
		ε’’	6.335697	16.52867	15.22887	8.560610
	30	ε’	57.70876	42.59458	19.50882	10.66041
		ε’’	5.255380	16.65569	18.58330	10.93768
Commercial	0	ε’	26.09218	12.6253	7.826013	5.436938
		ε’’	9.582274	6.31586	4.205070	2.183057
	10	ε’	41.59280	21.29549	10.86041	6.968466
		ε’’	9.825606	11.69846	8.136194	4.479214
	20	ε’	55.44620	39.10415	19.17738	10.93942
		ε’’	5.613902	15.88364	16.18908	9.866185
	30	ε’	59.20388	46.79525	25.34078	14.55121
		ε’’	4.483451	15.09244	19.24625	12.60106

3.3. The effect of temperature

In this research, the effect of temperature variation on the dielectric constant had been observed. All the three types of honey had been heated up using heated plate until it reached the target temperature. The temperature for this research is set from 25 °C, 30 °C, 35 °C, 40 °C, 45°C, and 50 °C. After the honey is heated up and the temperature is stabled, the honey will be probed for the dielectric constant measurement across the frequency. Figure 8, Figure 9, and Figure 10 show the dielectric constant of the stingless bee honey,wild honey and organic honey vs temperature respectively.

Figure 8 shows the dielectric constant of stingless bee honey at various temperature. Although the dielectric constant of the stingless bee honey decreases with the increase in frequency, it seems that the temperature had given an effect. The dielectric constant of the stingless bee honey increases dramatic when had been heated up. When the honey at 25 °C the dielectric constant is 13.80 at frequency 100 MHz but the dielectric constant is increased to 38.04 when temperature is at 30 °C. The highest dielectric constant at frequency of 100 MHz is at 41.72 when measured at temperature 45 °C. There is rapid increment of the dielectric constant at temperature 25 °C to 30 °C. Perhaps because of the hydrogen bonds between water molecules and saccharide molecules are weakening as temperature rises, and the reorientation motions of water molecules would be easier [9]. With that, the dielectric constant will increase with increasing temperature. During and before the measurement the probe is regularly cleaned and wiped and the present of air gap at the surface of the probe is avoided when measurement is done. Table 3 gives the tabulated data of the stingless bee honey with temperature. The table shows the result of the dielectric constant of stingless bee honey at frequency 100 MHz, 1000 MHz, 5000 MHz and 10000 MHz and with temperature at 25 °C, 30 °C, 35 °C, 40 °C, 45 °C, and 50 °C respectively.

The graph in Figure 9 shows for dielectric constant of wild honey with temperature ranges from 25 °C, 30 °C, 35 °C, 40 °C, 45 °C, and 50 °C. For the wild honey, the dielectric constant also increases with increasing temperature. The dielectric constant of the wild honey at frequency 100 MHz increases from 22.26 at temperature 25 °C to 28.18 at temperature 30 °C in frequency. The lowest dielectric constant of wild honey at frequency of 100 MHz is 22.26 when the honey is at 25 °C and the highest dielectric constant is 36.53 when the temperature of honey is increased to 50 °C. It is shown that the dielectric constant is increased with the increasing temperature from 25 °C to 45 °C but when the temperature is at 50 °C the dielectric constant is decrease to a lower value. Table 4 shows the tabulated data of the dielectric constant of wild honey with temperature. The table shows the result of wild honey with frequency at 100 MHz, 1000 MHz, 5000 MHz and 10000 MHz with temperature at 25 °C, 30 °C, 35 °C, 40 °C, 45 °C and 50 °C.

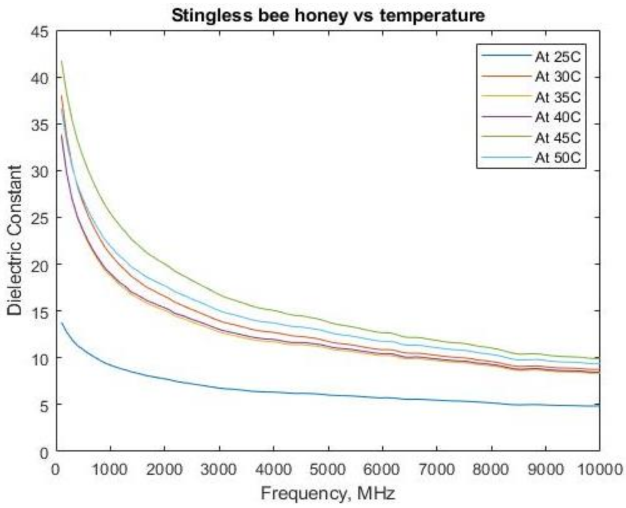

Figure 8. Stingless bee honey vs temperature

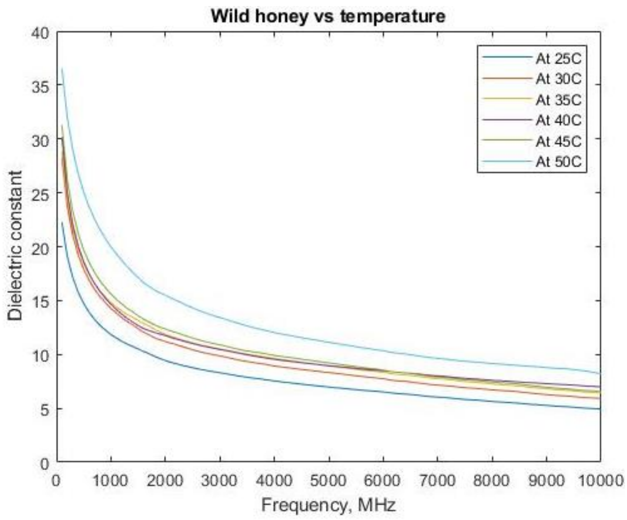

Figure 9. Wild honey vs temperature

Figure 10 shows the dielectric constant of commercial honey with temperature of 25 °C, 30 °C, 35 °C, 40 °C, 45 °C, and 50 °C. The dielectric constant of commercial honey is decreasing with increasing temperature because of the hydrogen bonds between water molecules and saccharide molecules are weakening as temperature rises, and the reorientation motions of water molecules [25]. The lowest dielectric constant of the commercial honey is 22.94 at temperature 45 °C and the highest is 28.62 at 50 °C. The decrement can be seen at temperature 25 °C, 30 °C, and 35 °C where the dielectric constant of honey is 26.37, 23.67667, and 24.68 respectively. Irregular pattern is seen when the temperature increases to 45 °C the dielectric constant is increased but when the temperature increases to 50 °C the dielectric constant is increase for all the selected frequency.

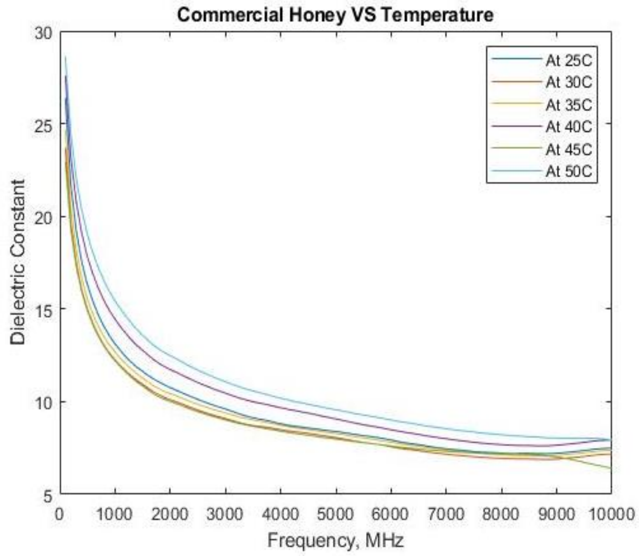

Figure 10. Commercial honey vs temperature

Table 3. The dielectric constant of stingless bee honey with temperature

Frequency (MHz)	Temperature (°C)					
	25	30	35	40	45	50
100	13.80318	38.0404	33.97573	33.71611	41.72636	36.61956
1000	9.036913	20.42367	18.20558	18.46945	24.71557	21.3366
5000	6.009943	11.67778	10.9311	11.14716	13.72811	12.65524
10000	4.874236	8.787185	8.384206	8.512798	9.951243	9.39901

Table 4. The dielectric constant of wild honey with temperature

Frequency (MHz)	Temperature (°C)					
	25	30	35	40	45	50
100	22.26243	28.18403	28.82208	30.14319	31.29385	36.53337
1000	11.5351	13.86211	14.42909	14.19624	15.15291	19.38178
5000	6.946636	8.285865	8.891872	8.891872	9.175980	11.08344
10000	4.925227	5.904124	6.416336	6.98545	6.560615	8.172779

3.4. The penetration depth of honey

The Table 5 shows the tabulated data of penetration depth after all the measured dielectric constant has been obtained. All the measured value will be inserted into penetration depth equation and run using a MATLAB software. This research shows that the higher the frequency, the lower the value of the penetration depth. It is shown that the frequency had been the main factor in getting the value of the penetration depth.

Figure 11 shows the penetration depth of stingless bee honey by using the equation of penetration depth. The data shows that the higher the frequency, the lower the penetration depth. This is because when the frequency increased, the dielectric constant will decrease. It might lead to decreasing of the penetration depth. Furthermore, the water content also effecting the penetration depth. The higher the concentration of water content in honey, the higher the penetration depth with decreasing in frequency.

Table 5. Penetration depth of stingless honey at 10%, 20%, and 30% at 25 °C in m

Honey	Frequency (MHz)	Water Content (%)		
		10	20	30
Stingless Honey	100	0.3559	0.3748	0.3664
	1000	0.0188	0.0916	0.0203
	5000	0.0034	0.0030	0.0029
	10000	0.0019	0.0000	0.0014

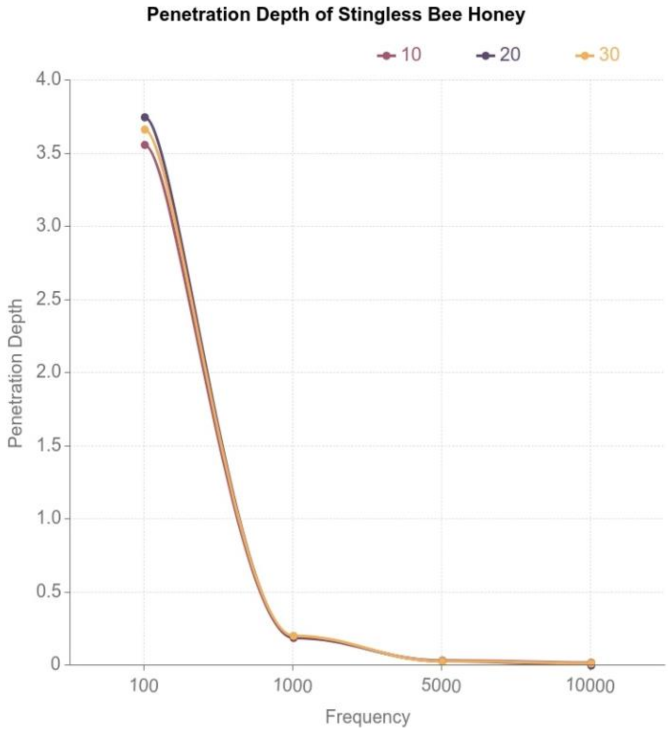

Figure 11. Penetration depth of stingless bee honey at 10%, 20%, 30% of water content

4. CONCLUSION

From the measured data, it is found that frequency, concentration of water and temperature has effect on the dielectric constant of honey. The dielectric constants of pure honeys and honey solutions decreased with increasing frequency in the studied frequency range,and increased with water content. Adding water in honey reduces its viscosity and binding forces to ionic movement, so the ionic conduction plays a growing role in the loss process as the water content increases slowly and leads to increase in the dielectric constant. Of all the honey sample, the stingless bee honey had the lowest dielectric constant compared to wild honey and the commercial honey. The result may be because the stingless bee honey had the lowest concentration of water and lead to lower dielectric constant than other type of honey. When the temperature of the honey sample is increasing up to 30 °C, 35 °C, 40 °C, 45°C, and 50 °C, the dielectric constant of the honey will be increased too. This is because of the hydrogen bonds between water molecules and saccharide molecules are weakening as temperature rises and lead to higher dielectric constant to the honey.The penetration depth of electromagnetic energy in all types of honey decreased with increased frequency. The data been compared with the difference frequency, water content and with a variation of temperature. If an unknown honey is measured or probed and the result was found to be much higher than the measured dielectric constant of pure honey, or lies in between the adulterated range, the purity of honey can be determined. So, the measured data can be helpful in determining the purity of the mentioned types of honey by referring to the measured dielectric constant produced as a reference.

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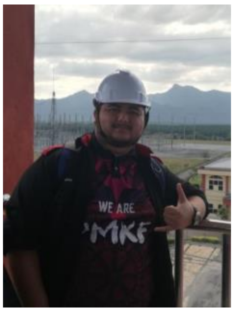

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