A Review of Oil Palm Fruit Ripeness Monitoring Using Microwave Techniques in Malaysia

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Abstract. Palm oil products are one of the most important sources of economic and export products in Malaysia. Furthermore, now, the evolution of industry 4.0 has begun to take place globally. The development of sensors has played a role in this evolution. In this paper, various microwave sensors used in oil palm monitoring are reviewed. The advantages and disadvantages of each microwave sensor are discussed in detail. However, conventional and optical monitoring methods are also briefly described.

1. Introduction
This article focuses on the research and measurements of microwave sensors for oil palm fruit ripeness processing applications. Normally, sensory devices that operate in the microwave frequency range (300 MHz to 300 GHz) can be called as microwave sensors. The microwave sensor techniques have been widely used in the food industry and agriculture processing. Due to different configuration of sensors, the operating frequencies and the measurement techniques involved with sensors are different as well. Measurement methods can be grouped into either resonant technique or non-resonant technique according to the structure and sub-principle of the measurements. Free-space and reflection / transmission measurement methods are classified into the category of non-resonant techniques. To be specific, the free space method appeared as a far-field measurement and a horn antenna is mainly used as the sensor or radiator; whereas circular, rectangular or coaxial waveguides are applied in reflection / transmission measurement methods and the sample is contacted directly.

During the time that choosing for appropriate method, there are a few factors which need to be considered albeit different types of measurement methods are available to utilize, for instance cost,
accuracy, operating frequency and shape of sample. Most of those measurement methods are applied in order to analyze the moisture content, \textit{m.c.} in the foods under test and agriculture products. It is because of the polarization of water molecules which comprised in the agri-foods products which are sensitive and showed an evident response when the water molecules are exposed to microwaves. The microwave device can be applied as a measuring method to detect the moisture content, \textit{m.c.} in agri-foods products that contain water due to the inclination of water to absorb microwave energy. Therefore, when there are changes in the amount of moisture among agricultural products, a change in the transmission / reflection coefficient or resonant frequency (from the change in dielectric permittivity) will be measured by the sensor. Here, authors attempt to provide comprehensive guidelines in microwave sensor design, which is particularly for oil palm fruits measurement.

2. Oil Palm in Malaysia

The first commercial planting of the oil palm \textit{(Elaeis guineensis)} (from African) in Malaysia was planted at Rantau Panjang, Kuala Selangor in 1911-1912 by Fauconnier and were ready for harvesting in 1917. Nonetheless, the planted region remained small until 1965, the private sector and statutory bodies, for instance the Federal Land Development Authority (FELDA) had implemented large-scale plantings; this significant increase had also led FELDA becomes the world's second-largest oil palm plantation company. Recently, Malaysia has becomes the world's second-largest producer of palm oil. The primary palm oil importers of Malaysian are Pakistan, India, China, the United States and the European Union.

The Malaysia production of crude palm oil for 2018/19 was reached 20.5 million metric tons. A rich source of vitamin E and \( \alpha \) and \( \beta \)-carotene can be provided by palm oil, which serves a vital role in cancer inhibition, suppression of cholesterol production and blood coagulation; thus, palm oil has gradually becomes popular. Nutrition, likewise the environmental preservation, will figure prominently in consumer’s option of edible oils consumption. Apart from its value of nutrition, it is increasingly popular as raw materials for the bio-fuel for automobiles and industry of oleochemical.

3. Oil Palm Fruit Bunch

The fruit bunch, as shown in Figure 1 is void and might reach 35 cm in breadth and 50 cm in length. The bunch comprises the spikelets, spines, stalks and fruit. The composition of the fruits bunch is shown in Figure 2. The oil palm fruit is a drupe, 2 to 5 cm long and weighs about 4-20 g. It consists of a kernel which is encapsulated by the pericarp, which comprises endocarp (shell), mesocarp (pulp) and exocarp (skin). The mesocarp contains 16 \% of fibers [1], which run in a longitudinal manner through the oil-bearing tissue from the base towards the fruit tip.

A palm or fruit may be explained as being tenera, pisifera, or dura variety according to the thickness of shell. The pisifera is shell-less, thus the pisifera is not vital in terms of commercial value. The variety which carries thick shell is described as dura; meanwhile tenera has a high mesocarp content and thin shell. The kind of fruit which is mostly preferred for commercial purpose is the tenera variety, due to its high mesocarp to oil potential.

![Figure 1. A tenera bunch halved to show (1) the stalk plus (2) spikelets and fruits, comprising (3) the mesocarp, (4) the shell, and (5) the kernel.](image-url)
4. The Ripeness of Oil Palm Fruits

The mesocarp of the oil palm fruits produces the palm oil. Usually, the first fruit bunch is produced by a palm tree in approximately three years. According to Ariffin et al. (1990) [2], during the early stage of fruit establishment, the amount of moisture content, m.c appeared to be higher. When the fruit ripens, the excessive water in the mesocarp is diminished, whereby occurs simultaneously with oil accumulation which approaches around 14 to 15 weeks after anthesis. There is about 80% of water in the fresh mesocarp; at around 20 to 24 weeks after anthesis, the amount will be reduced swiftly to approximately 30-40% in the ripe fruit. The reduction in moisture content, m.c from 15 to 20 weeks after occurs in relation to the increased accumulation of oil in the mesocarp as shown in Figure 2 (a) [3]. The fruit will fall to the ground when the fruit is loose as the oil content approaches maximum level. This optimum time for oil palm harvesting. In addition, Hartley, (1977) [1] proposed that the relationship between oil and moisture content, m.c in a mesocarp may be expressed as:

\[ \text{Oil} = 87.38 - 1.08 \text{Water} \]  \hspace{1cm} (1)

where ‘Oil’ and ‘Water’ are the percentage of oil per mesocarp and percentage of water per mesocarp, respectively. There is a possibility given by the close relationship between oil contents and moisture, whereby the percentage of moisture content, m.c can be used as a parameter in order to determine the mesocarp ripeness. The relationship between the oil content and moisture content, m.c in mesocarp of oil palm fruit is shown in Figure 2 (b).

5. A Measure of Ripeness of Oil Palm Fruits

The visual indications for instance flotation method, number or percentage of detached fruits per bunch and changes in colour of the fruits have helped to develop different methods to determine the ripeness of oil palm fruits. Fruit ripeness is usually characterized by the variation in colour from reddish-orange to black to orange as shown in Figure 3. Unfortunately, the colour change that takes place on ripening is not a consistent feature and differs from individual palm types and geographical regions.

The percentage or number of detached fruits per bunch appeared to be a usual practice that helps to gauge the ripeness of bunch in the oil palm plantation. This is due to the fruit which is about to be separated from the bunch will lead to the maximum oil production. However, ripening probability among a fruit bunch is not uniform. Different grading plans of bunch ripeness have been proposed in order to resolve this issue [1] for instance 2 detached fruits per kilogram of bunch weight, 20 to 40 detached fruits per bunch or 20-25% detached fruits to total fruits.

![Figure 2](image-url)

**Figure 2.** (a) Difference in moisture content, m.c and oil content with weeks after Anthesis. (b) The relationship between the oil content and moisture content, m.c in oil palm mesocarp.
This technique does not correlate with oil quantity and quality, thus it is inaccurate. In addition, it is unable to determine differentiation between fruits that are easily detached by hand and detached fruits that are on the ground. Furthermore, due to the wide range of bunch size within a population of oil palms, it will cause quite large variations in percent-detached bunch / fruits.

The particular gravity of the mesocarp of the ripened fruit, which is much lower than water, is the fundamental concept behind the flotation method [2]. Usually, a particular gravity of 0.89 will be obtained by the segment of mesocarp around the fruit tip. The method is quick and simple to apply, however, the entire oil content in the fruit is unable to determine. The amount of moisture content, $m.c$ of the mesocarp can be a foundation of a feasible parameter, which is useful to gauge the degree of fruit ripeness.

Recently, many advanced indirect methods are proposed, namely using its natural physics parameters such as refractive index, $n$ (Imaging and optical techniques) and relative complex permittivity (Microwave techniques) of the oil palm fruits to correlate with oil and water contents, $m.c$ in the oil palm fruits. To be specific, the optical sensor system comprises primarily of a receiver for receiving light (such as optical spectrum analyzer) and an emitter (such as Mid-infrared source) for emitting light. When the emitted light is reflected or interrupted by the sensing oil palm sample, the amount of light that reaches at the receiver will be changed [3-4]. Additionally, the receiver detects these changes and correlates to desired measured oil or moisture content, $m.c$ of the oil palm fruits. Also, some researchers use imaging methods to distinguish fruit maturity depending on the ripe fruit being reddish-orange, and the unripe fruit is black [5-7] as shown in Figure 2. Besides, the bulk nuclear magnetic resonance (NMR) and magnetic resonance imaging (MIR) methods also are applied for monitoring ripeness of oil palm fruit in accord with the change of spin-spin relaxation times respect to the ripeness stages [8]. Recently, wire coil resonators [9] are used to gauge the ripeness of the oil palm fruit based on the shifting of resonating frequency.

Similar to the optical method, oil and moisture content, $m.c$ using microwave technique can also be referred to the shifting resonance frequency/wavelength or the change in the reflection/transmission coefficient. Different microwave sensors were utilised to gauge the ripeness of oil palm fruits, for example microstrip sensor [10], coplanar sensor [11], rectangular dielectric waveguide [12], monopole [13], rectangular waveguide [14], open-ended coaxial probe [15-18], and microstrip ring resonator [19] as illustrated in Figure 4. The moisture content, $m.c.$ in the oil palm mesocarp under test is monitored using most of those ripeness measurement methods. It is due to the oil palm mesocarp contains polarization of water molecules that is sensitive and demonstrated a crucial response when it is exposed to microwaves. The inclination of water to absorb microwave energy, enabling the microwave device to be utilized as a measuring method to observe the moisture content, $m.c.$ in agri-foods products comprising water.

Microstrip and coplanar sensors (in Figure 4 (a), (b)) the amount of moisture content, $m.c$ in the oil palm fruits has been successfully estimated according to the attenuation measurement. The characteristics and microstrip and coplanar line discontinuities when the line was filled by oil palm mesocarp. The microstrip and coplanar line sensor measure the ripeness of the oil palm mesocarp, in accord with the correlation between the measured attenuation and the $m.c$ inside the mesocarp fruit. For rectangular dielectric waveguide measurements, the oil palm mesocarp is placed in the sample
holder between the two dielectric waveguides, as illustrated in Figure 4 (c). Nevertheless, laborious sample preparation is required by the sensors since the fresh mesocarp of the oil palm fruit has to be detached from the nut and crumbled into a form of semi-solid sample. It is undeniably time-consuming in order to prepare the fruit sample.
Figure 4. (a) Microstrip waveguide (MWG) [11]. (b) Multilayer conductor-backed coplanar waveguide (CBCPW) [12]. (c) Rectangular dielectric waveguide (RDWG) [12]. (d) Rectangular waveguide (RWG) [14]. (e) Monopole [13]. (f) Open-ended coaxial waveguide (OECWG) [16-18]. (g) Microstrip ring resonator [19].

Table 1. Comparison of previous works features for oil palm fruits measurements using microwave sensors

| Type of sensor          | Operating frequency | Set-up speed | Nondestructive test | Sensitivity | Cost of sensor | Precision | One-port measurements | Single fruit measurements |
|-------------------------|---------------------|--------------|---------------------|-------------|----------------|-----------|------------------------|--------------------------|
| MWG [10]                | 10.7 GHz            | Slow         | No                  | Good        | Low            | Good      | No                     | No                       |
| CBCPW [11]              | 2.2 GHz             | Slow         | No                  | Good        | Low            | Good      | No                     | No                       |
| Commercial HP 85070B OECWG [15] | 0.13 – 20 GHz    | Slow         | No                  | Good        | Expensive      | Good      | Yes                    | No                       |
| RDWG [12]               | 8 – 12 GHz          | Slow         | No                  | Good        | Low            | Good      | No                     | No                       |
| Monopole [13]           | 0.5 GHz             | Very fast    | Yes                 | Very good   | Very low       | Poor      | Yes                    | Yes                      |
| RWG [14]                | 8 – 12 GHz          | Fast         | No                  | Good        | Low            | Good      | Yes                    | No                       |
| OECWG [16-18]           | 1 – 5 GHz           | Very fast    | Yes                 | Good        | Very low       | Good      | Yes                    | Yes                      |
| MRR [19]                | 2.2 – 3 GHz         | Fast         | Yes                 | Good        | Low            | Fair      | No                     | Yes                      |

In general, the structure of a monopole (in Figure 4 (e)) is similar to that of the coaxial waveguide (in Figure 4 (f)), except for the protruding center conductor. The monopole measurement is in accord with the concept whereby a reflected signal through the coaxial line, in which the extended center conductor is buried into the oil palm mesocarp. This type of sensor is much more sensitive than many other types of slot sensors. Nevertheless, the measurement precision is less due to its scattering and radiating tendency. Figure 4 (f) type measurements, solid sample and parallel interfaces which carefully machined are required, likewise the whole cross-section of the coaxial line must be perfectly filled. Recently, the microstrip ring sensor (in Figure 4 (g)) for oil palm fruit measurement is proposed by [19]. Although, the microstrip ring resonator is sensitive in monitoring the maturity of the palm fruit, but the precision of measurement is influenced by the size of the fruit is measured. The comparison of previous work features for oil palm fruit measurements using microwave sensors was tabulated in Table 1.

6. Relationship between Dielectric Properties and Moisture Content
The relationship between a microwave with agri-foods materials can be expressed by the relative complex permittivity, $\varepsilon_r$

$$\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$$  \hspace{1cm} (2)
in which the real part, \( \varepsilon_r' \) is the dielectric constant, whereas the imaginary part, \( \varepsilon_r'' \) is the dielectric loss factor. Furthermore, the electric field distribution is influenced by the dielectric constant, \( \varepsilon_r' \) and thus the phase of waves travelling through the material. On the other hand, the attenuation or energy absorption of the material is influenced by the loss factor, \( \varepsilon_r'' \). Since water absorbs most of the electromagnetic energy at microwave frequencies, hence both \( \varepsilon_r' \) and \( \varepsilon_r'' \) are closely related with moisture content [20] and also, the relative permittivity of the material is predominantly influenced by the amount of moisture in the total volume of the material. It is because of the relative permittivity of water \( (\varepsilon_r = 80 \text{ at dc frequencies}) \) which usually being much greater than the other elements in the oil palm fruits (fiber: 2.2, oil: 2.5). Therefore, a change in resonant frequency (from the change in dielectric permittivity) or transmission / reflection coefficient will be measured by the sensor when there are changes of the amount of moisture in the oil palm mesocarp; in other words, it can be directly related to a change in m.c of the mesocarp that was acquired from oven drying technique. The relative complex permittivity, \( \varepsilon_r \) of oil palm mesocarp is well described by using the following model as [18]:

\[
\varepsilon_r = \varepsilon_n + \frac{\varepsilon_r - \varepsilon_i}{1 + (j \omega \tau_1)^{a_1}} + \frac{\varepsilon_i - \varepsilon_o}{1 + (j \omega \tau_2)^{a_4}} = \frac{j \sigma}{2 \pi \varepsilon_o f} 
\]

where \( a_1, a_2, a_3, \) and \( a_4 \) are the empirical constant, which determined by optimizing measured data. The \( \tau_1 \) and \( \tau_2 \) are the relaxation time for low and high-frequency processes, respectively. The \( \varepsilon_n \) is the height of the intermediate plateau from the baseline as well as the intersection between the line and \( \varepsilon_r' \)-axis yields the value of \( \varepsilon_o \). Generally, the optical permittivity, \( \varepsilon_o \) is independent of temperature, \( T \) and frequency, \( f \) [21]. The conductivity term, \( \sigma \) is determined by optimized with the measured loss factor, \( \varepsilon_r'' \) at low frequency (\( \leq 5 \text{ GHz} \)). Moreover, the approximate values of conductivity, \( \sigma \) are tabulated in Table 2.

However, equation (3) is limited for room temperature, \( T \) (25 ± 1 °C). The estimated values of \( \varepsilon_n, \varepsilon_1, \tau_1 \) and \( \tau_2 \) correlate with the different percentages of water content, \( \text{m.c.} \) are displayed in Table 2. The value of the relative complex permittivity of the oil palm mesocarp is mainly contributed by the water content, \( \text{m.c.} \), since the permittivity of water is more significant than other substance in the mixtures (such as oil and fiber) and it is sensitive to the microwave frequencies, particularly at 2.45 GHz and 10 GHz [21]. The displacement of water by the fiber contents and oil has caused the decrease in relative complex permittivity of the oil palm mesocarp.

The oil palm mesocarp has higher relaxation time, \( \tau \) below the frequency of 10 GHz for various water content, \( \text{m.c.} \), while the relaxation of oil palm mesocarp is approximated to 8.377 ps relaxation of free water for frequencies that are above 10 GHz. The high value of relaxation time, \( \tau \) of oil palm mesocarp at low frequencies is caused by the binding of water molecules in the mixtures which has slowed down the orientation polarization of polar molecules, such as the water adsorption by fibers and the capillary water between the fibers. However, the bound molecules are broken down above 10 GHz. As a matter of fact, the overall effect on water structure in oil palm mesocarp is extremely complex.

The correlation between both dielectric constant, \( \varepsilon_r' \) and loss factor, \( \varepsilon_r'' \) of oil palm mesocarp and frequency (2.6 GHz to 5 GHz) for the different percentage of water content, \( \text{m.c.} \) is demonstrated in Figure 6 and Figure 7. The dielectric constant, \( \varepsilon_r' \) were measured using commercial Agilent 85070E dielectric probe. From Figure 6, dielectric properties are quite linear at moisture content below 40 %, suggesting that at low moisture, there is higher oil-water emulsion concentration. When the sensor is pressed firmly to the sample of fruits, water begins to accumulate at the surface between fruit and sensor, hence higher uncertainty measurements occurred when the moisture is above 70 %. Based on Figure 7, the relationship between percentage of moisture content in mesocarp and dielectric constant, \( \varepsilon_r' \) are listed in Table 3. In all measured fruits, during low frequency, the loss factor, \( \varepsilon_r'' \) decreased,
and a broad minimum between 1 and 3 GHz is reached, subsequently increased again as shown in Figure 7. Since dielectric properties in agriculture is considered primarily depended on ionic conductivity of fluids comprised in their cellular structure and water activity, thus ionic conductivity, \( \sigma \) at lower frequencies is the factor which influences this behaviour.

\[ 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 67 \]

\[ 2.6 \text{ GHz} \]

\[ m.c \text{ (%)} \]

\[ \varepsilon_r', \varepsilon_r'', \]

\[ 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 67 \]

\[ 3 \text{ GHz} \]

\[ m.c \text{ (%)} \]

\[ \varepsilon_r', \varepsilon_r'', \]

\[ 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 67 \]

\[ 4 \text{ GHz} \]

\[ m.c \text{ (%)} \]

\[ \varepsilon_r', \varepsilon_r'', \]

\[ 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 67 \]

\[ 5 \text{ GHz} \]

\[ m.c \text{ (%)} \]

\[ \varepsilon_r', \varepsilon_r'', \]

**Figure 5.** Part of the open-ended coaxial waveguide (OECWG) experimental set-up.

**Figure 6.** Variation in dielectric constant, \( \varepsilon_r' \) and loss factor, \( \varepsilon_r'' \) with \( m.c \) of 25 °C [17].
Table 2. The Debye and Cole-Cole parameters of oil palm mesocarp as a function of percentage water content, \( m.c \) (%) at (25 ± 1)°C [18].

| Frequency, \( f \) (GHz) | Dielectric Constant, \( \varepsilon'_r \) | Loss Factor, \( \varepsilon''_r \) |
|--------------------------|-----------------|-----------------|
| 0.13 GHz ≤ \( f \) ≤ 20 GHz | (30 % ≤ \( m.c \) ≤ 80 %; pure water) | (25 ± 1)°C |

\[ \varepsilon'_r = -3.9899 \times 10^4 (m.c)^1 + 8.0046 \times 10^{-2} (m.c)^2 - 3.8988 (m.c) + 67.258 \pm 0.9792 \]

\[ \varepsilon''_r = -1.8394 \times 10^{-5} (m.c)^4 + 3.8076 \times 10^{-1} (m.c) - 0.27371 (m.c)^2 + 8.7394 (m.c) - 98.783 \pm 0.5093 \]

\[ \varepsilon'_r = -v_{water}\varepsilon'_{water} + (0.84 - v_{water})\varepsilon'_{oil} + (0.16)\varepsilon'_{fiber} \]

where \( \varepsilon'_{water} = 4.9 \), \( \varepsilon'_{oil} \approx 2.5 \), \( \varepsilon'_{fiber} \approx 2.2 \)

\[ v_{water} = \frac{0.01m.c(0.16\rho_{fiber} - 0.16\rho_{oil} + \rho_{water})}{\rho_{water} - 0.01\rho_{water} + 0.01\rho_{oil}} \]

\[ \tau_1 = -1.1394 \times 10^{-17} (m.c)^1 + 1.3309 \times 10^{-15} (m.c)^2 - 1.0209 \times 10^{-13} (m.c) + 1.6660 \times 10^{-11} \pm 1.119ps \]

\[ \tau_2 = -5.5307 \times 10^{-17} (m.c)^3 + 8.7071 \times 10^{-15} (m.c)^2 - 4.6620 \times 10^{-13} (m.c) + 1.6004 \times 10^{-11} \pm 0.478ps \]

\[ \sigma = 6.2861 \times 10^4 (m.c)^2 - 3.6521 \times 10^2 (m.c) + 6.3931 \times 10^{-1} \pm 0.02482 \Omega^{-1}m^{-1} \]

Table 3. Relationship between % water content, \( m.c \), dielectric constant, \( \varepsilon'_r \) and conductivity, \( \sigma \) of oil palm mesocarp for 3 GHz at (25 ± 1)°C [18].

| Water Content, \( m.c \) (%) | Dielectric Constant, \( \varepsilon'_r \) | Conductivity, \( \sigma \) (\( \Omega^{-1}m^{-1} \)) |
|-----------------------------|-----------------|-----------------|
| 30 – 40                     | 10 – 20         | 0.11 - 0.17     |
| 40 – 50                     | 20 – 25         | 0.17 - 0.38     |
| 50 – 60                     | 25 – 35         | 0.38 - 0.7      |
| 60 – 70                     | 35 – 55         | 0.7 - 1.1       |
| 70 – 80                     | 55 – 65         | 1.1 - 1.7       |
7. Conclusion
In this paper, various microwave sensors particularly for oil palm moisture measurement have been reviewed. In addition, the permittivity formula for oil palm fruits has also been revisited in which the permittivity values of oil palm fruits is very important to optimize the pretreatment process of mill crude palm oil using microwave and solvent extraction methods. Hopefully the microwave sensor for oil palm fruit measurements will be commercialized in the near future.

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