Research article

Low-cost capacitive sensor for detecting palm-wood moisture content in real-time

Suratsavadee K. Korkua, Siraporn Sakphrom *

School of Engineering and Technology, Walailak University, Thailand

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ABSTRACTS

In this study, we analyze a non-invasive and low-cost wood moisture meter by means of a capacitive detection circuit. The process of the design and development of an oil-palm-wood moisture meter is described. As part of the study, two electrode structures, i.e., parallel-plate and coplanar electrodes, are tested. The capacitive detection circuit includes a square-wave-generator circuit, low-pass filter circuit, and signal-conditioning circuit. The frequencies of the square-wave excitation signal are in the range of 200 kHz and are analyzed via a microcontroller to interpret the percentage of oil-palm-wood moisture content. The applicability of the capacitive moisture measurement is investigated under various moisture conditions of the oil palm wood i.e., 5%–20%. The experimental results show that the measurement accuracy of the detection circuit is high, with an acceptable measurement error.

1. Introduction

Oil palm is a plant that produces the most oil per unit than other oil plants do. It produces an edible vegetable oil that can be used in food industry products such as snack foods, instant noodles, sweetened condensed milk, cream, and margarine. In addition, oil palm is the main raw material in biodiesel production and helps strengthen energy power. In summary, 10% of one palm tree is utilized in the form of oil, and the other 90% is utilized in the form of biomass. The main oil palm product includes bunches of fresh palm fruit, which are later extracted for crude palm oil. However, the palm-oil-production process also produces waste materials, which are put to different uses. For example, palm kernel shells are utilized as fuel materials; the empty fruit bunches are used in mushroom cultivation; and polluted water from the oil palm industries is used to generate biogas. Surprisingly, the waste materials from palm-oil production are not popular in the agricultural field. Although the leaves containing nutrients and vitamins are used as feed for cows, buffaloes, and goats, the trunks are rarely used. In the case of old palm-tree trunks of 25–30 years, farmers usually use a medical drop that causes them to rot and die. During this time, the planting of palm seedlings is undertaken. With the increasing number of the perennial palms every year, the current trend in the lumber industry involves the transformation of oil-palm lumber into furniture and buildings.

Regarding its properties, oil-palm lumber differs from rubber lumber in terms of its hard fiber cells, low density, low-strength material, and high humidity, and therefore, its usage in the lumber industry has proven to be quite unsuccessful. The existing literature on oil palm has focused on the strength of palm lumber. For example, palm lumber is used as the core of light-weight sandwich panels [1]. In addition, it can be sandwiched with other materials, such as rubber wood and aluminum sheets, for increasing the strengths of those materials. This study aimed at the use of oil palm in the development of lightweight furniture and heat insulation panels, which are in demand in the worldwide market.

The production of oil-palm lumber at the industry level is similar to the production of rubber lumber. The first step involves the sawing of the palm trunks into palm lumbers. Then, the lumbers are compressed using liquid-boron treatment, and then dried out in a drying oven.

For the production of oil-palm lumber at higher industry levels, we must determine the factors affecting the quality of palm lumber; these include temperature, relative humidity inside and outside the drying oven, and air circulation in the drying oven. These factors involve consumption of heat energy and electric power, which are utilized in wood drying, and thereby affect the capital cost of lumber production.

* Corresponding author.
E-mail addresses: s.sakphrom@gmail.com, siraporn.sa@wu.ac.th (S. Sakphrom).
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The drying oven uses steam as the heat energy to dry out the lumber; this process takes 5–7 days. The temperature and moisture content (MC) inside and outside the drying oven, along with the wood moisture, are recorded. The MC of the lumber is usually lower than 8%.

In general, the measurement of wood MC involves opening the drying oven and randomly selecting one wood sample to test the MC using a portable moisture meter. This results in the loss of heat energy and electric power. This is also one of the main reasons resulting in the increase of the baking time, which in turn reduces the amount of the baking wood because of technological limitation of the device used to inspect the factor and the status of many important variables in the oven control process. The MC of wood is an important factor that must be considered when deciding whether to stop wood drying in the drying kilns. Therefore, the development of a device to detect the MCs in wood during its drying process will increase growth potentials and competitive opportunities of the lumber industry. The device should present advantages in terms of saving of energy, increase in the capacity of energy usage in the drying process, and reduction of labor cost involved in recording data. Moreover, such a device can help reduce the amount of defective wood being hammered during the process of moisture-content measurement via the old moisture-measuring meter.

This research introduces a design for a sensor device that can be used for detecting the MC of wood. This sensor detects signals from the capacitors (the basic concept of a capacitive sensor) to detect the MC of wood in the drying process. However, this sensor device does not cause any damage to the palm wood. Moreover, the device can function as an artificial intelligent (AI) device, which can process and predict the moisture value of palm wood through real-time monitoring.

2. Materials and methods

2.1. Methods of measuring MC in wood

MC in wood includes the weight of water in the wood and is calculated as a percentage or unit. For example, if wood has an MC of 10%, this implies that its weight is 10 units per weight of that type of wood per 100 units. Methods to determine the MC of the wood can be classified into direct and indirect techniques [2, 3]. Direct measuring procedures, which are probably the most often used, involve drying out the material by using a drying chamber [4]. Indirect techniques include electrical moisture sensors and systems, which measure the moisture content through electrical detection. Capacitive and resistive measurements are popular indirect methods that are based on the working principle of a capacitor and resistor, respectively. Some other possible measurement methods include microwave, infrared, or conductance methods. The drying-out and electrical-moisture-measuring methods are detailed as follows.

2.1.1. Drying-out methods

This method is typically used in a laboratory and is the most popular method owing to convenient and reasonably accurate measurements [5]. In this method, to measure the moisture of wood, a 1–2-cm-wide cross-section of the wood is removed from no less than a foot from the end of the wood to prevent any incorrect calculations of moisture values. Then, this sample is immediately weighed and recorded as the initial weight. The sample is then baked in an oven at a temperature of approximately 103 °C until the wood is completely dry. Next, the wood sample is weighed again to determine the dry weight. These results are used to calculate the MC of the wood as follows:

$$MC = \frac{\text{Initial mass} - \text{Oven dry mass}}{\text{Oven dry mass}} \times 100(\%) \quad (1)$$

where Moisture content (%) is the amount of moisture in wood, Initial mass represents the weight of wood before drying, and Oven dry mass is the weight of wood after drying.

2.1.2. Electrical moisture-meter method

Electrical moisture meters use the principle of determining the electrical properties of the wood, which vary according to the MC and electrical insulation properties of the wood, i.e., the dielectric constant properties of wood. The dielectric constant properties differ depending on the manufacturer and can be classified into the following two types.

2.1.2.1. Resistive- and capacitive-type moisture meter. The resistive-type meter involves hammering the electrode into the wood, resulting in marks on and roughening of the surface of the wood. The measuring range of this method is limited to 5%–30%. Therefore, in a high-moisture-content wood, the value may be incorrect owing to short-circuit currents in the wood. In addition, the measured value of wood that is compressed using a chemical solution and dissolved in water before the drying process will be 1%–5% higher than the actual value, depending on the type of chemicals, i.e., whether they play the role of an electric insulator or electric conductor.

A popular capacitive-type moisture meter includes a tool that uses alternating currents based on the principle of the dielectric constant of wood [5], which increases with the moisture and specific gravity of the wood. However, the MC of wood with natural defects cannot be measured using this method. In addition, when using a dielectric moisture meter, a factor is needed for adjusting the reading of each type of wood.

Capacitive measuring methods with sensor designs can be classified into two structures: the parallel-plate and coplanar electrodes [6, 7, 8]. The parallel-plate electrode comprises two electrodes, with square unit sizes, and a splicing unit with spacing d, as shown in Figure 1 (a). The coplanar electrode comprises two conductors positioned parallel to each other, as shown in Figure 1 (b). The electrical capacitance value at the end of the electrode cable is on both sides.

2.2. Basics of capacitive functional principle

The capacitive functional principles, an interesting trend especially in capacitive measurement, do not directly use the criteria of the residual moisture of solids but rather the physical characteristics of the solids. The basic concept of capacitive measurement is based on the capacitance theory of two conductive plates, and the simplest characteristic of a capacitor is the parallel-plane capacitor [9, 10]. The capacitance is the ability of the capacitor to accumulate electric charging depending on the voltage. When the voltage is applied between two parallel electrodes with separation distance d and overlapping area A, the capacitance varies directly with respect to the overlapping area but is inversely proportional to the separation distance:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \quad (2)$$

where C is the capacitance, $\varepsilon_0$ is the permittivity in free space ($\varepsilon_0 = 8.854 \times 10^{-12} F/m$), and $\varepsilon_r$ is the relative permittivity of dielectric materials. Generally, $\varepsilon_r$ is a complex quantity, as $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$ where $\varepsilon_r'$ and $\varepsilon_r''$ are the dielectric constant and dielectric loss factor, respectively. The dielectric constant depends on the insulation characteristics of the dielectric medium within an electric field. It indicates how permeable the material is for electrical fields and depends on a specimen and vacuum as the dielectric and medium, respectively [11]. The dielectric loss tangent is given as $\tan \delta = \varepsilon_r''/\varepsilon_r'$, where $\delta$ is the loss angle and conductivity $\sigma = \frac{\varepsilon_r''}{\varepsilon_r}$.

![Figure 1. Structures of the capacitive measuring sensor design: (a) parallel-plate electrode and (b) coplanar electrode.](image-url)
where \( \varepsilon_r \) and \( \varepsilon_0 \) are the relative dielectric constants of the filled material at two frequencies. From (3), \((C_1 - C_2)\) was determined to be a good estimator and indicator of the MC values. The two frequencies had two parameters, i.e., dissipation factor \( D \) and phase angle \( \theta \), which were incorporated into an empirical equation along with \((C_1 - C_2)\), thus resulting in the MC values [12, 13, 14, 15, 16]:

\[
MC = A_0 + A_1(C_1 - C_2) + A_2(C_1 - C_2)^2 \\
+ A_3\left[\frac{(\theta_1 - \theta_2)}{(C_1 - C_2) + 2(D_1 - D_2) - (C_1 - C_2)(D_1 - D_2)}\right]
\]

(4)

As shown in (4), the dissipation factor \( D \) and phase angle \( \theta \) are derived on the basis of the two frequencies. When considering only one frequency value, phase angle \( \theta \) can be ignored. Dissipation factor \( D \) has a small value at a low frequency because the dielectric constant slightly changes in the low-frequency range and the percentage of MC is high. In contrast, the percentage of MC involved in the drying-out process is low; thus, \( D \) can also be ignored. Finally, the equation can be rewritten as

\[
MC = A_0 + A_1C + A_2C^2
\]

(5)

From (5), if the capacitance has a small value in pF units, the square root term can be ignored and the MC equation has a linear form, which can be written as a logarithmic or exponential equation owing to the property of a capacitor.

2.3. Equipment

The instruments used for the measurements had a tendency of changing the signals for capacitive detection. In the laboratory tests, LCR-821 was used as the highly precise capacitor meter and LCR-07 was used as the signal probe, as shown in Figure 2 (a) and (b), respectively. The precision of the LCR-821 is approximately 0.05%. Capacitance \( C \) can be displayed in the range of 0.00001–99999 pF, dissipation factor \( D \) ranged from 0.001 to 9999, and phase angle \( \theta \) was 180.00°.

2.4. Oil-palm-wood samples and procedures

The design and test step of wood moisture-measuring system require the MC of the palm wood to be below 20% to reduce the baking time and energy. Therefore, in the first step of the drying-out method, the woodchips were exposed to the sun, and thus the initial MC value before entering the oven is usually lower than 20%. Then, the woodchips are baked in the oven for 5–7 days until the MC value is lower than 8%. These steps can be used for preparing palm wood at different moisture values. (The sample of palm wood used in our test has a specific gravity of 0.5–0.7.)

First, a large size of the palm lumber is sawed into equal square pieces measuring 8 cm (width) \( \times \) 8 cm (length) \( \times \) 1.5 cm (thickness), as shown in Figure 3. Second, the wood-chip samples are dried-out in the drying oven at 103 ± 2°C for 2 days until the samples reach the MC of 12%. When the specified time is reached, the weights of the samples are recorded again. Then, the samples are cooled for 30–40 min and stored in vacuumed zip-lock bags. Fourth, the weight, capacitance, temperature, and MC of the samples were recorded in the laboratory room, as shown in Figure 4. Finally, the fourth step is repeated, and the data are recorded every 15 min until the weight and the capacitance values are stable.

The electrode plate was designed to be compatible with palm-wood samples to measure their capacitance. This study introduces two design structures for this plate: parallel-plate and coplanar electrodes. A shown in Figure 5 (a), the parallel-plate electrode comprises two electrode plates measuring 8 cm \( \times \) 8 cm and is stacked together at a distance of 3 cm. The coplanar electrodes shown in Figure 5 (b) comprise two electrodes measuring 8 cm \( \times \) 3 cm that are parallel to each at a distance of 2 cm.

The relationships between the MC of the palm-wood sample and its capacitance value after being tested using the parallel-plate and coplanar electrodes at various moisture values are in the forms of logarithmic and exponential functions, as shown in Figures 6 and 7, respectively. At the MC of 1%–20%, the palm-wood sample tested using the parallel-plate electrode showed small capacitance values in the range of 10–200 pF. In contrast, the palm-wood sample tested using the coplanar electrode showed small capacitance values in the range of 1 and 28 pF.

According to (5), when the capacitor has a very small capacitance value, the relationships between the MC and capacitance with respect to the parallel-plate and coplanar electrodes are shown as (6) and (7), respectively:

\[
\omega_0\varepsilon_r\varepsilon_0 = \text{a constant as the signal probe, as shown in Figure 2 (a) and (b), respectively. The precision of the LCR-821 is approximately 0.05%. Capacitance } C \text{ can be displayed in the range of 0.00001–99999 pF, dissipation factor } D \text{ ranged from 0.001 to 9999, and phase angle } \theta \text{ was 180.00°.}
\]

\[
MC = A_0 + A_1C + A_2C^2
\]

(5)
\[ MC = A_0 + A_1 \ln(C) \]  
(6)

and

\[ MC = A_2 e^{A_3 C} \]  
(7)

where \( A_0 = 3.2986, A_1 = 3.322, A_2 = 1.5778, \) and \( A_3 = 0.1032. \)

3. Proposed method of detecting palm-wood MC

Kandala and Nelson [13, 14] found that when the MC is lower than 20\%, the dielectric constant changes by approximately 2.5–8; however, the dielectric constant is approximately equal to 2.5 in the high-frequency period (>11 GHz). This could imply that a very high frequency is required to change the dielectric constant, and this affects the change in the MC. Therefore, this process requires expensive equipment and tools, resulting in higher capital cost. However, in this study, the authors introduce a design of a palm-wood-moisture-measurement device (Figure 8), which is cheaper than the existing alternatives and achieves high accuracy. In addition, the device can display and record the moisture of palm wood in real-time monitoring.

As shown in Figure 8, the structure comprises capacitive-sensing, microcontroller, and data-monitoring circuits. The structural principle states that the MC detection is integrated into the circuits of the signal generator and capacitive sensors.

The circuit functions with the application of a frequency of 200 kHz and a timer 555 circuit to capture the signal with respect to the voltage applied. The level and frequency of the signal can be adjusted to allow for the signal to be sent to the signal processor.

The signal processing and display are responsible for randomly reading the analog voltage signal data. The mathematical functions are programmed using the microcontroller for converting the input signal into palm-wood MC. Then, the processed MC data are displayed via the LCD monitor or saved in the cloud for analyzing and displaying the result on a mobile application. Figure 9 (a) shows the actual test of the palm-wood moisture-measuring circuit (during system development) and Figure 9 (b) illustrates a computer display of the frequency data and the calculation of the moisture value obtained from the overall test system [18]–[21].
4. Results

Two experiments were conducted, one involving capacitive detection and the other involving MC detection. Both were conducted using the parallel-plate- and coplanar–electrode structures.

4.1. Experiments involving capacitive detection

In the experiment using the parallel-plate electrodes, the capacitors were used in the range of 4–219 pF, which corresponds to the palm-wood MC in the range of 2%–14%, as shown in Figure 6. As the capacitance used in the testing had a very small pF value, discrepancies may be observed in the MC; these are caused by the parasitic capacitance that passes through the conductor wire, electrical probe, and circuit board. However, latent capacitors are used to compensate for this error via a compensation program being written for higher accuracy. As such, the discrepancy of the capacitors shows a very small value with an average value of 1.27 pF throughout the test; this is in the range of 2%–14% MC. Furthermore, the results of the capacitance detection were used to calculate moisture values corresponding to those in the database. As shown in Table 1, the results show that the error of the palm-wood MC is very low with an average of 0.13%.

In the experiment using coplanar electrodes, the capacitors are used in the range of 20–100 pF, which corresponds to the palm-wood MC of 0%–16%, as shown in Figure 7. Discrepancies of electronic capacitors after being compensated by the latent capacitance value has the average value of 0.67 pF, indicating a highly accurate detection throughout the test, which is in the range of 0%–16% MC. According to Table 2, the results of the capacitance detection show that the error of the palm-wood MC is very low with an average of 0.03%.

4.2. Experiments on MC detection

Next, we compared and tested the accuracy of the palm-wood MC readings obtained using the two proposed methods using the parallel-plate and coplanar electrodes with respect to the weighing method. In addition, the results were compared using (6) and (7). In the experiment, the dry-out method was performed for all the palm-wood samples, the dehydration of which takes three days. Then, the weights of the samples are recorded, and the samples are chilled for 30 min before storage in zip-lock bags. The condition of the test included temperature and MC of 28.6 ºC and 73%, respectively. Then, the recording time was divided into two periods: (1) the MC was recorded every 1 h and (2) recorded every 30 min. These steps were repeated until the weight changed slightly. The results of the weighing method were obtained using (1) to determine the MC value. The solution was compared with that in the case of the proposed detection of palm-wood MC. Then, the results were calculated using (6) and (7). The values of the constants in (6) are determined as

Figure 8. Overall structure of the proposed palm-wood moisture-content-detection device.

Figure 9. Actual test setup of the palm-wood moisture measurement device: a) circuit test in laboratory, and b) the computer displaying the frequency and data calculation of the moisture value.
A_0 = 3.2986, A_1 = 3.322, and A_2 = 1.5778. In addition, the constant in (7) was determined as A_3 = 0.1032. The results of the parallel-plate and coplanar electrodes are shown in Figure 10 and Figure 11, respectively.

Figure 10 shows the results of parallel-plate electrodes, where the MC of the palm-wood samples ranges from 5% to 15% and covered 5–170-pF capacitance. When compared with the palm-wood samples with 12% MC, the proposed system shows higher accuracy during the detection and displays accurate results throughout the testing period. Moreover, the result also corresponds to the MC value gotten from weighing method. Moreover, for palm-wood samples with a higher MC percentage than 12, the proposed method shows higher discrepancies in the MC value. According to the error testing in each period of the MC measurement, the period of 10–11.9 showed the lowest discrepancy with an average of 0.33 and the period of 12–20 showed higher discrepancy with an average of 0.73, as shown in Table 3.

Figure 11 shows the results obtained using coplanar electrodes; the MC of the palm-wood samples is 3–17%, covering capacitance of 6–17 pF, indicating that the MC covers a narrow range for very small capacitance values; this complicates the detection of signals. However, the MC can still be detected and a value close to that obtained using the weighing method can be displayed. From the error testing in each period of the MC, the period of 5–9.9 showed the lowest discrepancy with an average value of 0.24 and the period of 16–20 showed the highest discrepancy with an average of 2.16, as shown in Table 4.

Figure 12 shows the prototype of the palm-wood MC meter used to detect signals from the capacitor that can actually be used. This prototype was tested in this research project.

### Table 1. Results of the capacitance detection using parallel-plate electrodes.

| Measured Capacitance (pF) | Frequency calculation (kHz) | Frequency testing (kHz) | Capacitance detection (pF) | Parasitic capacitance (pF) | Capacitance compensation (pF) | Error of capacitance (pF) |
|---------------------------|-----------------------------|-------------------------|---------------------------|---------------------------|-----------------------------|--------------------------|
| 4                         | 180.37                      | 201.53                  | 19.47                     | 15.47                     | 3.58                        | 0.42                     |
| 10                        | 72.15                       | 69.30                   | 26.07                     | 16.07                     | 10.41                       | 0.41                     |
| 18                        | 40.08                       | 37.26                   | 36.34                     | 18.34                     | 19.36                       | 1.36                     |
| 32                        | 22.54                       | 20.82                   | 52.53                     | 20.53                     | 34.64                       | 2.64                     |
| 55                        | 13.11                       | 12.87                   | 80.13                     | 25.13                     | 56.03                       | 1.03                     |
| 73                        | 9.88                        | 9.56                    | 94.46                     | 21.46                     | 73.41                       | 2.40                     |
| 96                        | 7.51                        | 7.49                    | 121.55                    | 25.55                     | 96.3                        | 0.30                     |
| 126                       | 5.72                        | 5.56                    | 156.69                    | 30.69                     | 129.63                      | 3.63                     |
| 166                       | 4.34                        | 4.33                    | 205.36                    | 39.36                     | 166.35                      | 0.35                     |
| 219                       | 3.29                        | 3.29                    | 260.42                    | 41.42                     | 218.81                      | 0.19                     |

### Table 2. Results of the capacitance detection using coplanar electrodes.

| Measured Capacitance (pF) | Frequency calculation (kHz) | Frequency testing (kHz) | Capacitance detection (pF) | Parasitic capacitance (pF) | Capacitance compensation (pF) | Error of capacitance (pF) |
|---------------------------|-----------------------------|-------------------------|---------------------------|---------------------------|-----------------------------|--------------------------|
| 10                        | 72.15                       | 6.26                    | 115.26                    | 105.26                    | 9.43                        | 0.57                     |
| 20                        | 36.07                       | 5.45                    | 132.26                    | 112.26                    | 20.88                       | 0.88                     |
| 30                        | 24.05                       | 5.07                    | 142.30                    | 112.30                    | 30.68                       | 0.68                     |
| 40                        | 18.03                       | 4.57                    | 157.87                    | 117.87                    | 40.68                       | 0.68                     |
| 50                        | 14.43                       | 4.25                    | 169.40                    | 119.40                    | 50.28                       | 0.28                     |
| 60                        | 12.02                       | 3.95                    | 182.42                    | 122.42                    | 60.88                       | 0.88                     |
| 70                        | 10.30                       | 3.60                    | 200.13                    | 130.13                    | 70.98                       | 0.98                     |
| 80                        | 9.01                        | 3.38                    | 213.14                    | 133.14                    | 80.45                       | 0.45                     |
| 90                        | 8.01                        | 3.27                    | 220.64                    | 130.64                    | 90.95                       | 0.95                     |
| 100                       | 7.21                        | 3.09                    | 233.49                    | 133.49                    | 100.24                      | 0.24                     |

Figure 10. Comparative results between the prototype and dry-out testing of % MC detection by using parallel electrodes.

Figure 11. Comparative results between the prototype and dry-out testing of % MC detection by using coplanar electrodes.
Table 3. Comparison of the results of the average error of capacitance obtained using parallel-plate electrodes.

| Range of %MC | 4-7.9 | 8-9.9 | 10-11.9 | 12-20 |
|--------------|-------|-------|---------|-------|
| Average error| 0.4   | 0.78  | 0.33    | 0.73  |

Table 4. Comparison of the results of an average error of capacitance obtained using coplanar electrodes.

| Range of %MC | 5-9.9 | 10-13.9 | 14-15.9 | 16-20 |
|--------------|-------|---------|---------|-------|
| Average error| 0.24  | 1.78    | 0.79    | 2.16  |

5. Conclusions

This paper presented methods for measuring the MC of palm-wood. The advantages of the proposed device, which was well designed and developed, are its low price and the fact that it would not damage the palm-wood during measurement. This device can also be used to detect the capacitance value in real time. This research provides a circuit design and a capacitance detecting method via two electrode positioning structures: the parallel-plate and coplanar electrode structures. The researchers tested the moisture readings of palm-wood with different MCs between 5%-20% to verify the accuracy of the method for measuring the MC by detecting capacitance values.

The results of the prototype system show that the MC of the palm wood obtained using the circuit with the parallel-plate electrode structure is accurate and has a close value to the MC obtained from the weight calculation after the drying-out method. The use of this achieves the maximum average error of only 0.78% throughout the MC range of 5%-20%. This error is considered acceptable, as the capacitance values detected from this structure are satisfactorily high.

Moreover, the results of the prototype system show that the palm-wood MC obtained from the circuit using the coplanar electrode structure is less accurate than the circuit using parallel-plate electrodes. It results in a maximum mean error of 2.16% because the capacitance value detected from this structure is very low.

However, the higher MCs of palm-wood tend to cause higher discrepancies, which later result in the reduction of the stability of the conductor for detecting the electrical characteristics of the wood. The other factors include humidity and temperature, which also affect the values in the experiment.

Declarations

Author contribution statement

Suratsavadee K. Korkua: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Sriraporn Sakphrom: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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