Received August 10, 2021, accepted September 8, 2021, date of publication September 15, 2021,
date of current version September 22, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3112708

Implementation of Four Terminal Fruit Battery With Charge Switching

NORHISAM MISRON[1,2,3], (Member, IEEE), NUR AMIRA IBRAHIM[1], NISA SYAKIRAH KAMAL AZHAR[1], LUQMAN MOHD SAINI[1], CHOCKALINGAM ARAVIND VAITHILINGAM[4], (Senior Member, IEEE), KUNIHISA TASHIRO[5], (Member, IEEE), AND HIROKAZU NAGATA[6]

[1]Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia
[2]Institute of Advance Technology (ITMA), Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia
[3]Institute of Plantation Studies, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia
[4]High Impact Research Laboratories, Taylor's University, Subang Jaya, Selangor 47500, Malaysia
[5]Faculty of Engineering, Shinshu University, Nagano 380-8553, Japan
[6]Centre of Global Education and Collaboration, Shinshu University, Nagano 380-8553, Japan

Corresponding authors: Norhisam Misron (norhisam@upm.edu.my) and Nur Amira Ibrahim (nuraamiraibrahim@gmail.com)

This work was supported by the Universiti Putra Malaysia (UPM).

ABSTRACT Palm oil sector is considered one of main economical contributions in countries such a Malaysia where approximately 6.1% of their Gross Domestic Product (GDP) is contributed. Low Oil Extraction Rate (OER) from poor quality fresh fruit bunches have led to a decrease the oil palm production. The traditional method of using human naked eye to inspect the Fresh Fruit Bunches (FFB) during reception process is one of common methods that is still being practiced which eventually would lead to inaccuracy in grading and harvesting. This paper presents a new approach to identify the maturity of oil palm fruit using fruit-based maturity sensor and the electronic circuit. The study utilizes multiple terminals to evaluate the sensitivity of the sensor by analyzing the relation between the load voltage and the moisture content in the oil palm fruit. The sensitivity of the sensor increased by three-fold when four terminal fruit battery was used compared to single terminals with 47.61% for the moisture range of 50-80% value. This proposed approach significantly improved the accuracy in grading the oil palm fruit which is the most common challenge posed during the reception process.

INDEX TERMS Fresh fruit bunches, fruit battery, oil palm maturity sensor, sensor voltage.

I. INTRODUCTION

The palm oil industry is one of the important sectors with 56.7% coming from Indonesia and 27.3% from Malaysia which makes up the total world palm oil production capacity. This translates to 6.1% of GDP contribution to the Malaysian Economy. Malaysia witnessed a commendable increase to 16.05 million tons in 2016 from the 90 500 tons in 1960 [1]. The high increment of exports in 2016 placed Malaysia as the second largest exporter and producer of crude palm oil (CPO) [2].

The production quality depends on the quality of Fresh Fruit Bunches (FFB) as the maturity varies from bunch to bunch and cumulative harvesting often leads to low CPO production. This remains the biggest challenge as in most of the conditions, harvesting is decided and based on the visual inspection of the maturity grading for harvesting by the farmers. This translates to a huge loss of close to USD 0.19 million in the oil production, mainly due to unripe inspection by the settlers [3].

The FFBs that are shipped to the mills need to go through a screening process before going through the further Oil Extraction Rate (OER) measure because some harvesters remove the oil palm FFBs from the tree, but not according to the maturity of the fruit. For instance, the ripe FFBs may be harvested with unripe ones during the low harvest time frame to maintain their income and thus overlook the harvesting of the ripe FFBs during the high harvest time frame, and this in turn tends to become overripe by the next reaping session. Hence, to hold the OER value to be high, it is important to harvest at the point when the maturity level of the FFB is critically high.

Imaging techniques and computer vision are short of well-known methods in determine the grading of oil

The associate editor coordinating the review of this manuscript and approving it for publication was Yassine Maleh.

palm [4]–[8]. Machine visioning through RGB decoding (Red, Green, Black) is also used to differentiate the type of oil palm [9]– [13]. Bensaeed *et al.* [14] has utilized a hyperspectral device and machine learning algorithm to classify the various wavelength from the various types of oil palm fruit to grade the oil palm. Thermal sensor prototype, based on its mean temperature is introduced in [15]. Inductive type was introduced by Harun *et al.* [16] that utilized the frequency variations to measure the maturity of oil palm fruit bunches. The sensitivity of the inductive concept was improved from the above research in [17] and a dual flat-type shape of the air coil sensor was introduced in [18]. Jamil *et al.* [19] and Fadilah *et al.* [20] utilized a neural network and the fuzzy technique to classify the ripe oil palm fruit as further development in this area. Imaging techniques, computer vision, and color vision have limitation in mobility because it requires very sophisticated equipment. Therefore, the oil palm fruits need to be transported to the location where this equipment is installed. As a result, the operation in detecting the ripeness of oil palm will be delayed and the effectiveness of such approach will be diminished.

Instead of using imaging techniques, computer vision, and color vision, Minakata *et al.* [21] introduced fruit battery to detect the ripeness of the oil palm with zinc and copper was used as an electrochemical cell. In this study, load voltage is generated from the fruit battery experiment and moisture content determination is measured to identify how ripe the fruit are. The unripe fruit shows low load voltage while ripe fruit shows higher load voltage. Nevertheless, a fruit battery method generates unstable data measurement on its own [21], [22]. To overcome and address this a charging method has been proposed and applied to the fruit battery experiment to determine the stability and reliability of the data. This approach encompasses a fruit battery with charge switching.

This paper focuses on the improvement of the fruit battery concept with charge switching as the oil palm maturity sensor. The electrodes used in this work are copper and aluminum where copper was previously used in combination with zinc [21]. The voltage sensor is used to detect the voltage flow through the load resistance after which, the voltage is sensed by the controller. This sensor provides good mobility since all the equipment is portable and quite inexpensive. It can also identify the maturity of oil palm immediately in the field because it does not require additional analysis.

II. ELECTROCHEMICAL FRUIT BATTERY SENSOR

The proposed oil palm maturity sensor introduces a system to detect the ripeness of oil palm based on the load voltage readings and the moisture content of oil palm. The main part of the oil palm maturity sensor is fruit battery sensor with charge switching. Fruit battery sensor is an electrochemical cell sensor that generates small currents from the chemical reaction that occurs in the fruit battery. Two electrodes, i.e., Aluminum and Copper is thrust onto the oil palm with the oil palm as electrolyte. Fig. 1 shows the schematic diagram of fruit battery where the electrodes are pricked onto the fruit mesocarp. When the switch S_1 is turned on, the voltage V_h charges the fruit for specific charging time. The fruit battery circuit that is connected as S_2 is turned on with S_1 opening and causing the energy of the fruit battery to then be discharged through the circuit. This charging approach increases the sensitivity of the sensor and helps to differentiate the ripe from the unripe based on their load voltage readings.

The charge switching method used in this study helped to obtain a steady-state operation in the fruit battery and acquired a significant value of the load resistance voltage. The performance of the fruit battery with and without charge switching is shown in Fig. 2. It illustrates the readings of the load voltage once the energy from the fruit from charge turns to a discharge state. The load voltage readings indicated a maximum start value as energy began to be discharged from fruit battery when switch S_2 of the fruit battery was closed. This is because the fruit received high energy from the power supply when switch S_1 was closed. Then, the energy decreased to the consistent value when the energy discharge arrived at a steady state. It has been observed that the sensitivity of the load voltage increases up to 4 times of the load voltage without charge switching.

The charging time, charging voltage, and load resistance are chosen based on the probability error value. Based on the experiments carried out on the various oil palm fruit, the charging time, charging voltage, and load resistance were found to be 10s, 250V and 100Ω where the P value (probability of error value) was 8.811×10^{-8} The P-value obtained was less than 0.05 (5%) which is statistically significant. The data analysis involved the automated simulation to obtain results from the different regression data. The P-value was obtained from the simulated calculation of the average load voltage against moisture content. The lower P-value indicated that there are obvious differences between the data points in the random sample chances. The fruit battery sensor presented a reliable detection between the ripe and unripe fruit. The 10s of charging time, 250V of charging voltage, and 100Ω of load resistance gave the lowest probability error compared to 5s and 15s, 500V and 1000V, and 500 Ω, respectively.

Based on the manual for insulation, continuity tester 3132A, when the 250V of normal output voltage is applied, the maximum resistance is 100 MΩ. Therefore, the estimated current during the charging process according to Ohm's Law is 0.0025 mA. The current passed through the fruit is assumed to be similar for every single sample because of the application of the same charging time as well as the charging voltage. When the fruit is charged, the load voltage value differs between the unripe and ripe fruit due the presence of ions in the form of fruit moisture content. The ripe fruit consists of low moisture content and high levels of lipid compared to the unripe fruit and is experimentally tested and presented in [23].

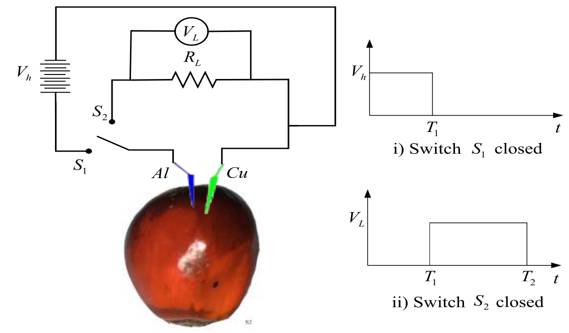

FIGURE 1. Fruit battery sensor with charge switching.

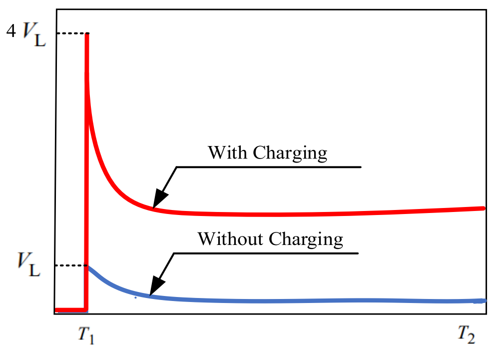

FIGURE 2. Load voltage variations.

III. METHODS

Fig. 3 shows the fruit battery sensor with the external circuit for the fruit battery sensor, dual amplifier, voltage sensor, and Arduino. Due to the chemical reaction that occurs in the fruit battery, the load voltage is generated and will then flow into the dual amplifier. Dual amplifier used in this system is LM358 and it acts as voltage gain amplifier. It is made up of an integrated circuit that consists of two amplifiers, the first stage increases the voltage up to 11 times followed by the second stage, to 3 times. Therefore, the load voltage from the fruit battery increases up to 33 times, which tends to increase the accuracy of the voltage sensor when the voltage is detected and can show a very significant value of the voltage for each grade of oil palm fruit. Then, the amplified voltage flows into the input of the voltage sensor to measure and detect the Direct Current (DC) voltage in the circuit. The calculation of the detect voltage is based on the voltage divider rule. An analog signal from the voltage sensor is directed to the microcontroller. Microcontroller acts as a minicomputer that controls and monitors any peripheral device connected to it. The microcontroller used in this study is 'Arduino Due' due to the high clock speed (16 MHz) that comes with an auto reset feature. It is cost effective, reliable to use, and is fast processing. The category of oil palm, whether unripe, under ripe, or ripe is be displayed on the serial monitor of the Arduino software. The sampling frequency of the sensor is 29.4 Hz as it can detect the load voltage of the resistance for every 34 milliseconds.

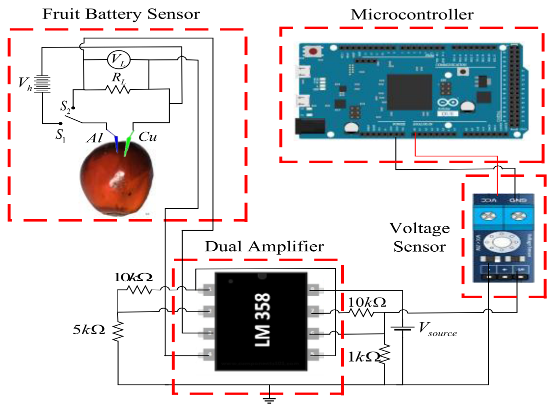

FIGURE 3. Oil palm maturity sensor.

The charging time is set at 10s and after 10s, it is switched S_2 is closed immediately and the chemical reaction in the fruit occurs. The load will drop the voltage across the 100 Ω resistor and is available at the input terminal of the dual amplifier.

As seen in Fig.1, when both the switches are in OFF condition the circuit is open and hence no electric current flow. Therefore, the electrons will not flow from the aluminum to the copper. When S_1 is closed for 10s, the electrical current of the voltage will flow through the circuit and charge the fruit. The electrical energy is then converted to chemical energy inside the fruit. When S_2 is closed, the fruit battery will be connected, and this will cause the energy to be discharged through the circuit due to the flow of electrons from the aluminum to the copper. Thus, oxidation and reduction reactions could not take place before switch S_2 is closed. By this method the chemical reaction occurrence, even before the switch stages is reduced.

Misron *et al.* [22] in their earlier work demonstrated that the difference of the load voltage readings between the unripe and ripe fruits, with charging and without charging was highly significant. Due to the significant difference of the load voltage readings, the fruit battery sensor with charge switching helped to determine the ripe and unripe fruits easily. Amplifiers were used to obtain the data of the load voltage through the voltage sensor, however, the difference of load voltage between the ripe and unripe fruit remain the same as they increased the signal of the load voltage, for better sensitivity of the sensor. It must be noted that only sensitivity of the sensor has been examined and described here. For future work, in order to determine the difference of accuracy between the charging and without charging process, investigations on accuracy of the sensor may be conducted.

Fig. 4 shows the raw data of the voltage detected by the voltage sensor for a single reading V_s of a sample of ripe fruit which is recorded for analysis. The voltage sensor senses the voltage flow through the circuit for every 34ms and will then send the data to the microcontroller. In the Arduino programming software, it defines the early voltage as 'old value' and next voltage as 'new value'. When it detects the next new voltage, the new voltage will be of the 'old value' and the next new voltage recorded will be as 'new value'. The voltage sensor will send data to the microcontroller until it detects the 'new value' which would be less than the 'old value'. For instance, the microcontroller received increasing data trend from point A to D and decreasing trend from point D to G as illustrated in Fig. 4. Point D stands for the old value once the microcontroller receives data for point E and point E would be the new value. Because point E is lower than point D, the microcontroller would display point D as the maximum data that has been received, and that data would then be used to grade the oil palm fruit.

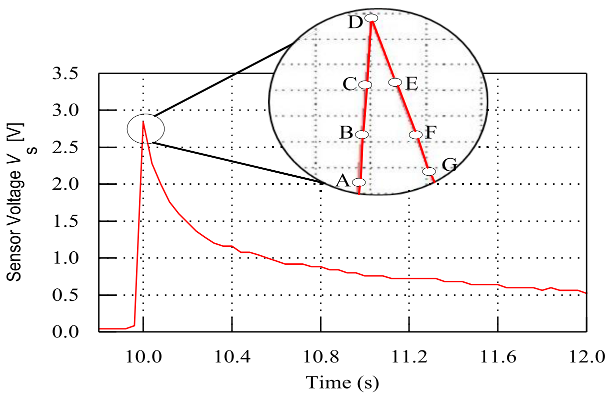

FIGURE 4. The measurement of sensor voltage for single reading.

Once the microcontroller detects the maximum voltage of the oil palm fruit, the received maximum voltage is used to grade the maturity of the oil palm fruit. Table 1 summarizes the various voltage range and fruitlet surface color for each grading of the oil palm fruit for the triple number of terminals. The color of the fruitlet surface is based on the MPOB standard [24]. When the color of oil palm fruit is black to dark purple and the voltage detect from the sensor a range of 1.0 V to 2.3 V, it is classified as unripe fruit, and if the color is dark brown to dark orange and the voltage is quite high, up to 3.3 V, it is classified as an under-ripe fruit.

Also, to note during the development of the sensor detection, the moisture content estimation was added into experiment part is to act as reference. Because of the drying process took an hour to determine the moisture content, several data and testing were recorded to know the range voltage for every type of the oil palm fruit. If this experiment is carried out without a drying process, the ripeness of the oil palm fruit cannot be classified accurately. Even though the fruitlet surface appears to be ripe, the maturity of the fruit cannot be precisely determined. Therefore, determining the moisture content of oil palm fruit after the experiment is important for classifying the maturity of the fruit. For the ripe fruit, the moisture content is below that 50%, under-ripe is in between of 50% to 80% and unripe fruit is more than 80%. Based on the moisture content determination, the range of the voltage is varied for each grading. From the "range voltage" that obtained from different samples, the range voltages are aligned with the moisture content of the fruit. When implementing this sensor for field testing, the sensor will detect and show the value of the sensor voltage. Then, the range of the percentage of moisture content inside the fruitlet may be determined using that voltage value. So, in the range of the percentage of moisture content, the oil palm fruit can be determined whether it ready to harvest or not. Significantly this method is cost effective, it can be an additional or alternative source of oil palm fruit maturity checking in the oil palm mill during inspection as well during harvesting [25]. This sensor is proposed to ensure that the factory would be able to process the high quality of fresh fruit bunches towards better Oil Extraction Rate. In some conditions, the human naked eye cannot differentiate the color of the oil palm fruits, which resulted in harvesters collecting under ripe oil palm fruit and storing it until the color changes before sending it to mills. As the color of underripe fruit transform after storage, the quality of the samples decreases thereby the extraction rate from the fruit bunch [26]. In this approach proposed here, it took approximately 30 seconds compared to the conventional method to detect load voltage and classify the ripeness of the oil palm fruits to determine the effectiveness of the quality of extraction. Therefore, this sensor targeted to be used in the factory before the oil extraction process is carried out, is used for selected fruit only.

TABLE 1. Oil palm fruit maturity grading [23].

Fruit Maturity Grade	Voltage (V)	Fruitlet Surface Color
Unripe	$1.0 \leq V \leq 2.3$	Black to dark purple
Under-ripe	$V \geq 3.3$	Dark brown to dark orange
Ripe	$2.3 < V < 3.3$	Dark red to yellow-orange

The flowchart regarding the software implementation is shown in Fig. 5. Conditional statements in programming are used to determine the grading of oil palm fruit but the grading still depends on the color of the fruitlet. Normally, it is difficult to differentiate the under-ripe from the ripe during the screening process because of the fruitlet surface is almost the same. Therefore, this sensor detects the voltage based on the voltage value, and the ripeness of the oil palm fruit is determined. For instances, the sample is tested using this sensor and the serial monitor displays "under-ripe", it means that the voltage of the samples is high, which is more than 3.3V and the fruit maturity is then graded as under-ripe. The sensor voltage for each grading is verified based on the previous work done by Misron *et al.* [22], [27] as it showed the same characteristics between the moisture content and the sensor voltages of the samples. The moisture content estimation is added into the experiment stage to enable the results to be more reliable. Based on the "range voltage" that has been obtained from different samples, the range voltages are aligned with the moisture content of the fruit. As shown in Table 2 in Section IV, for ripe fruit, the range voltage is

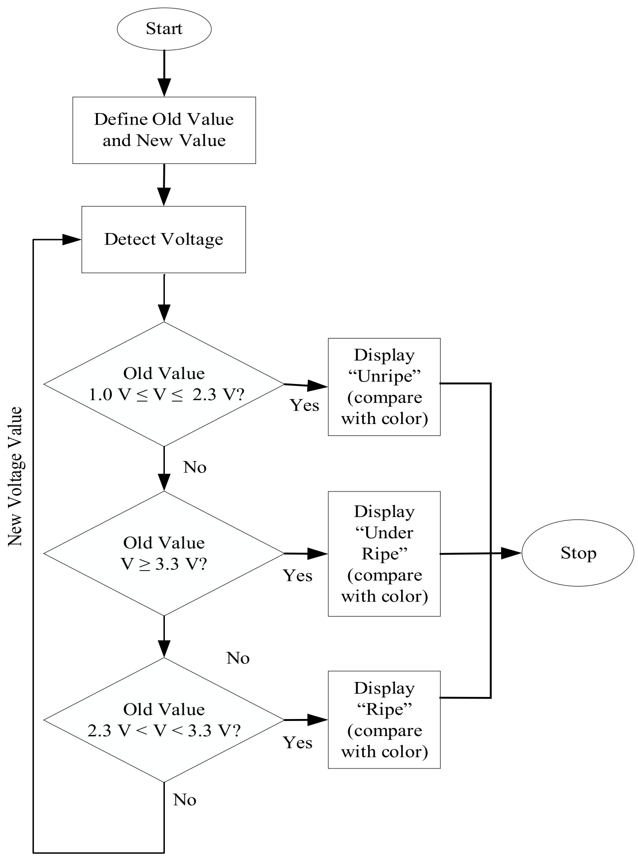

FIGURE 5. Harvest ready condition decision.

2.3 V < Voltage < 3.3 V and the range moisture content for ripe fruit is less than 50%. Therefore, even the surface of fruitlet has changed, the references of the moisture content and range voltage can be referred.

Four different terminals were used to determine the effect of the terminals to the performance of the sensor, i.e., one-terminal, two-terminal, three-terminal, and four-terminal. The maximum number of sets of terminals is kept at four due to the limited space and size of the pin diameter for the minimal available average size of the palm fruit [28]. For a single terminal, it consists of a set of aluminum and copper pricked onto the fruit while dual terminal consists of two sets of aluminum and copper, triple terminal consists of three sets of aluminum and copper, and four terminal consists of four sets of aluminum and copper as illustrated in Fig. 6. The dimensions of all the different number of terminals are the same, the difference is only the number of sets of the aluminum and copper pricked onto the fruit. The sets of aluminum and copper are placed in a circular position. The size of electrodes also is very small, and the pricking is not too deep, to avoid destroying the mesocarp flesh. The connection of the sets of terminals is shown in Fig. 7. Aluminum electrodes are connected in parallel and share one point, while copper electrodes also connected in parallels and share one point. In the fruit battery sensor, the point of Al will be connected to the switch while the point of Cu will connect to the resistance. Since the fruit is placed on an insulator, the cork surface layer at the clamp that tighten the fruit position is set in place to avoid the leakage current.

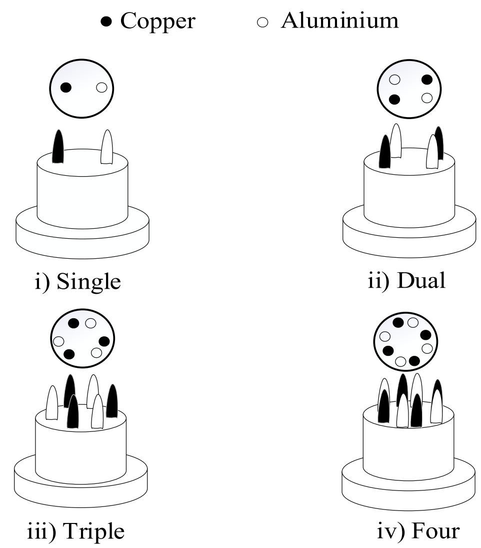

FIGURE 6. Set of terminal's number.

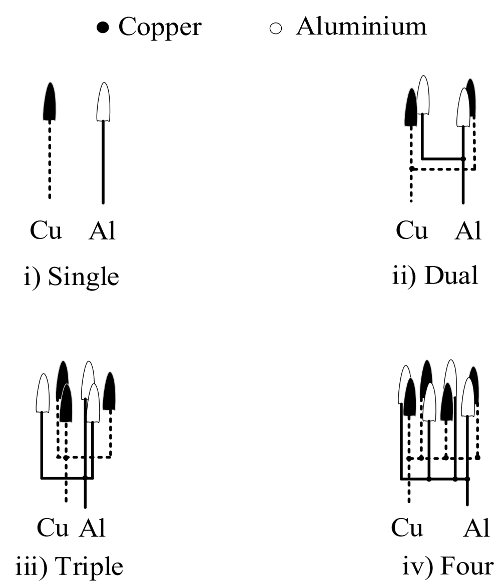

FIGURE 7. Connection of terminals.

The fresh of the oil palm fruits were collected on the same day as the experiments were conducted to avoid degrading of the moisture content in the fruit. The maturity of the oil palm at first is classified based on the percentage of the moisture content. The load voltage is plotted based on the moisture content inside the oil palm fruit to determine the ripeness of the oil palm fruit. The oil content of oil palm fruit increases as it matures, while the moisture content decreases as it is

TABLE 2. Test measurement data.

Sample	Moisture Content			V_L (V)	V_{amp} (V)	V_{sensor} (V)	Oil Palm Type	Fruit Appearance
	w_b	w_a	%					
1	2.22	1.62	31.33	0.070	2.45	2.56	Ripe	
2	3.33	2.415	32.69	0.085	2.77	2.81	Ripe	
3	2.56	1.23	45.29	0.089	2.92	3.15	Ripe	
4	2.56	1.23	51.95	0.092	3.02	3.38	Under Ripe	
5	2.265	1.075	52.54	0.095	3.85	3.99	Under Ripe	
6	1.88	0.26	86.17	0.051	1.69	1.91	Unripe	
7	1.62	0.165	89.81	0.06	1.64	1.85	Unripe	

converted to lipids [21]. The load voltage of unripe fruit tends to be lower than ripe fruit due to higher moisture content inside the fruit. Therefore, it is importance to do the drying process to determine the moisture content which can be used as a point of reference.

To ensure the effectiveness and reliability of the moisture content, the testing is carried out multiple times to ensure that the data is reliable for all ripeness and data range. Thus, after the data obtained is determined to be reliable, the field testing can be carried out without moisture content implementation.

There are around 10 samples of unripe, under-ripe, and ripe oil palm fruits that were tested, respectively. Each sample underwent the drying process after the experiment was carried out for moisture content determination using an infrared moisture determination balance FD-610 by Kett Electric Laboratory. 75% of the sample was cut and weighed before the drying process. The drying process was carried out utilizing a temperature of 115°C for 60 minutes. The dried sample was weighed and recorded as after the drying weight. The moisture content was calculated using equation (1), where w is moisture content, w_b is weight of sample before the drying process, and w_a is weight of sample after the drying process.

$$w(\%) = \frac{w_b - w_a}{w_b} \times 100 \tag{1}$$

IV. RESULT AND DISCUSSION

The summary of the grading of oil palm fruit in terms of moisture content w, voltage value and fruitlet surface color for seven different samples are presented in Table 2. The manual visual inspection on the color of the FFB is compared to give clear indication of the necessity for maximizing the OER of the oil palm fruit. The readings of each sample were repeated at least three times to confirm the repeatability of the measurements. As seen in Table 2, Load Voltage V_L is the average primary voltage drop at the load resistance, Amplified Voltage V_{amp} is the average original voltage that has been amplified by the dual amplifier, and sensor voltage V_{sensor} is the average sensor voltage which is used to acquire a single data before plotting the moisture content and is dependent on the sensitivity of the sensor performance. Both V_L and V_{amp} are obtained through the oscilloscope, and V_{sensor} is the voltage that is obtained from the Arduino. The sensor voltage for every sample is different, even the fruitlet surface color is almost the same. For instance, the color of sample 3 and sample 4 is very close but in terms of sensor voltage, sample 4 gave a higher voltage which is more than 3.3 V compared to sample 3 which is only 3.15 V. It clearly shows that, sample 4 is the under-ripe oil palm fruit while sample 3 is the ripe oil palm fruit.

Besides, the ripeness of the oil palm is classified based on the sensor voltage V_{sensor} and moisture content w. The sensor voltage V_{sensor} of each sample of the oil palm fruit are plotted based on the moisture content w for each grade of oil palm fruit which is illustrated in Fig. 8. The sensor voltage V_{sensor} is at the y-axis and the moisture content of the samples w is at x-axis. The average data is illustrated as a black circle while the red line indicates the polynomial expression following the trend of the graph. The voltage difference of the sensor voltage ΔV_{sensor} is analyzed between the region of the moisture content difference Δw from 50% to 80% to observe the sensitivity of the sensor when changing the set of the terminal's numbers. It has to be noted that only the under-ripe and unripe quality of the voltage difference is examined and described. From the measurement, unripe fruits show the lowest voltage recorded compared to ripe and under-ripe samples and the sensitivity of sensor voltage, ΔV_{sensor} where $50\% < w < 80\%$ is 0.88 V.

As seen in Fig. 8, the red line can reach to the voltage sensor value of 3.2 V for two different moisture content value. For this condition, the grading of oil palm fruit identified by observing the fruitlet surface color. If the color of the oil palm fruit is a darker brown to dark purple, it is classified as under-ripe fruit and if the color is dark red to yellow orange, it is a ripe fruit.

The charging is not changing properties of the fruit because each sample is repeated at least three times to confirm the authenticity of the measured value.

Most value of the readings does not indicate much difference as displayed in table below. For sample 1, the sensor voltage for three repeated readings is almost the same, i.e., 2.58 V, 2.55 V and 2.56 V. This is also proven by the unripe fruit as well as the under-ripe fruit. Also, after the charging experiment, the fruit undergoes the moisture content determination experiment. The moisture values of the fruit remain as its characteristic and will not disrupted by the charging properties. For instance, for the ripe fruit, the moisture content still below 50%, while for unripe fruit, the moisture content will be more than 80%.

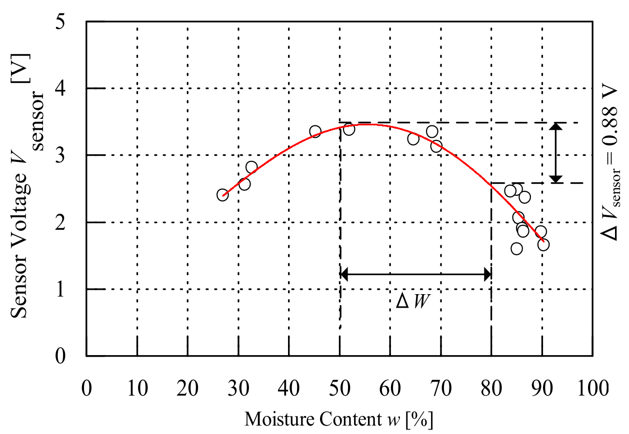

FIGURE 8. Voltage sensor measurement.

The effect of the different terminal is explained in Fig. 9 which the parameter chosen is $R_L = 100\Omega$, $V_C = 250$V and $t_C = 10$s to test all four different terminals. The data is recorded and then summarized in Fig. 9. Fig. 9 shown below represents the graph for sensor voltage, V_{sensor} against moisture content, w for different terminal. The line indicates the polynomial expression following the trend of the graph. The moisture content w is less than 50% and is considered as ripe oil palm fruit. Based on the triangle line, the difference of sensor voltage, ΔV_{sensor} obtained between

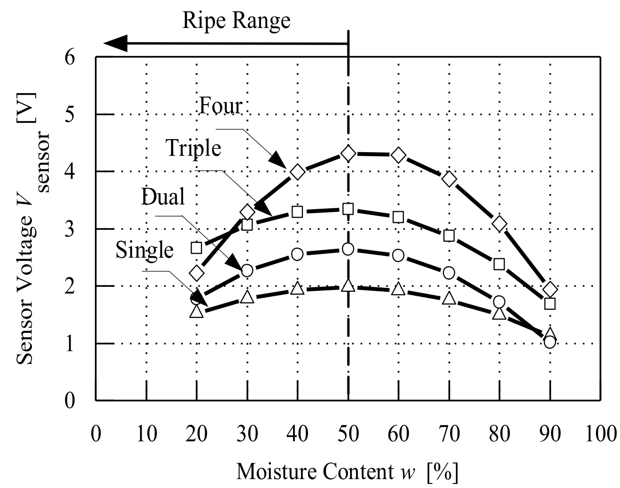

FIGURE 9. Sensor voltage of different terminal's number.

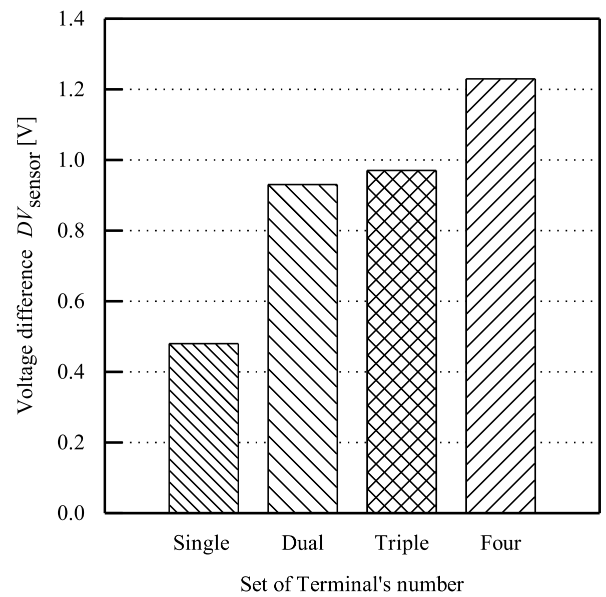

FIGURE 10. Performance comparison between difference terminal's number.

50% and 80% moisture content, is 0.48 V. The single terminal fruit battery shows that it has the lowest sensitivity. The circle line indicates the dual terminal fruit battery sensor contains varieties of fruit battery maturity. The V_{sensor} against w the difference of sensor voltage ΔV_{sensor} where $50\% < w < 80\%$ is 0.93 VCompared to a single terminal sensor, the sensitivity sees a double increase when the set number of electrodes increases and in terms of accuracy, single terminal reached 95.83% while dual terminal reached 87.5%. Besides, the square line shows the three terminal fruit battery sensors of V_{sensor} against w graph. From the measurement, the difference is sensor voltage, ΔV_{sensor} obtained 0.97V between 50% and 80% of moisture content. There is a slight increment and a higher than single terminal sensor. The accuracy of the triple terminal fruit battery sensors is 93.1%. The diamond line shows the polynomial expression for four terminal of fruit battery sensor when tested on a variety of fruit ripeness. The difference of sensor voltage where 50% < w < 80% is 1.23 V and the accuracy is 87.5%. The sensitivity of the sensor increasing at a triple rate compared to the single terminal sensor which has the highest sensitivity on average, the accuracy for all terminals is about 90%.

Fig. 10 shows the bar chart for all four different terminal sensors which is illustrated in voltage difference of sensor voltage ΔV_{sensor} against type of sensor's terminal number. From the results shown, it is concluded that the increase in the sensor's terminal number, the higher the sensitivity of the sensor in detecting the oil palm ripeness due to the increase of equivalent surface area of the electrode.

V. CONCLUSION

The ripeness of oil palm fruit is of importance to obtain quality OER. The FFBs need to go through the screening process which is usually carried out via a manual inspection to determine the grading of oil palm fruit. This paper presents the fruit battery with charging method to facilitate people and to avoid inaccuracy during the screening process. The improvement is achieved on the fruit battery and charging it with charge switching approach. It shows that the ripe and under-ripe oil palm fruit is differentiated based on the voltage value. Moreover, the performance of the sensor increases three times when four terminal fruit battery is tested. The increased sensitivity on the ripeness factor adds value to the oil that is extracted when embedded with other techniques such as the imaging or machine vision techniques. This contributes to increased performance in palm oil harvesting with the accurate prediction for maturity. An advanced functional material can be considered for future works to get a better and accurate result, as well as improve the performance of the sensor.

REFERENCES

[1] N. Fold and L. Whitfield, "Developing a palm oil sector: The experiences of Malaysia and Ghana compared," DIIS, Copenhagen, Denmark, Tech. Rep. 2012:08, 2012.

[2] E. H. Ezechi and K. Muda, "Overview of trends in crude palm oil production and economic impact in Malaysia," *Sriwijaya J. Environ.*, vol. 4, no. 1, pp. 19–26, Mar. 2019.

[3] (Mar. 17, 2017). *FGV Targets 22% Oil Extraction Rate by 2020*. Accessed: Feb. 1, 2020. [Online]. Available: https://www.thestar.com.my/business/business-news/2017/03/17/fgv-targets-22pc-oil-extraction-rate-by-2020/

[4] O. M. B. Saeed, S. Sankaran, A. R. M. Shariff, H. Z. M. Shafri, R. Ehsani, M. S. Alfatni, and M. H. M. Hazir, "Classification of oil palm fresh fruit bunches based on their maturity using portable four-band sensor system," *Comput. Electron. Agricult.*, vol. 82, pp. 55–60, Mar. 2012.

[5] Z. M. Zulkifli, F. H. Hashim, T. Raj, and A. B. Huddin, "A rapid and non-destructive technique in determining the ripeness of oil palm fresh fruit bunch (FFB)," *Jurnal Kejuruteraan*, vol. 30, no. 1, pp. 93–101, Jun. 2018.

[6] M. Makky, P. Soni, and V. M. Salokhe, "Automatic non-destructive quality inspection system for oil palm fruits," *Int. Agrophys.*, vol. 28, no. 3, pp. 319–329, 2014.

[7] M. S. M. Alfatni, A. R. M. Shariff, M. Z. Abdullah, M. H. Marhaban, S. B. Shafie, M. D. Bamiruddin, and O. M. B. Saaed, "Oil palm fresh fruit bunch ripeness classification based on rule-based expert system of ROI image processing technique results," in *Proc. IOP Conf. Earth Environ. Sci.*, vol. 20, 2014, pp. 1–8.

[8] M. S. M. Kassim, W. I. W. Ismail, A. R. Ramli, and S. K. Bejo, "Image clustering technique in oil palm fresh fruit bunch (FFB) growth modeling," *Agricult. Agricult. Sci. Procedia*, vol. 2, pp. 337–344, Jan. 2014.

[9] M. S. M. Alfatni, A. R. M. Sh, H. Z. M. Shafr, O. M. B. Saa, and O. M. Eshanta, "Oil palm fruit bunch grading system using red, green and blue digital number," *J. Appl. Sci.*, vol. 8, no. 8, pp. 1444–1452, Apr. 2008.

[10] M. S. M. Alfatni, A. R. M. Shariff, S. K. Bejo, O. M. B. Saaed, and A. Mustapha, "Real-time oil palm FFB ripeness grading system based on ANN, KNN and SVM classifiers," in *Proc. IOP Conf. Earth Environ. Sci.*, vol. 169, Apr. 2018, Art. no. 012067.

[11] F. S. Mohamad, A. A. Manaf, and S. Chuprat, "Histogram-based fruit ripeness identification using nearest-neighbor distance," in *Proc. 3rd Int. Conf. Comput. Eng. Technol.*, Chongqing, China, May 2019, pp. 483–490.

[12] N. Sabri, Z. Ibrahim, and D. Isa, "Evaluation of color models for palm oil fresh fruit bunch ripeness classification," *Indonesian J. Electr. Eng. Comput. Sci.*, vol. 11, pp. 549–557, Aug. 2018.

[13] Z. May and M. H. Amaran, "Automated ripeness assessment of oil palm fruit using RGB and fuzzy logic technique," in *Mathematical Methods and Techniques in Engineering and Environmental Science*. Athens, Greece: WSEAS Press, 2011, pp. 52–59.

[14] O. M. Bensaeed, A. M. Shariff, A. B. Mahmud, H. Shafri, and M. Alfatni, "Oil palm fruit grading using a hyperspectral device and machine learning algorithm," in *Proc. IOP Conf. Earth Environ. Sci.*, vol. 20, Apr. 2014, Art. no. 012017.

[15] S. Zolfagharnassab, C. N. Vong, A. R. M. Shariff, R. Ehsani, H. Z. E. Jaafar, and I. Aris, "Comparison of mean temperature taken between commercial and prototype thermal sensor in estimating mean temperature of oil palm fresh fruit bunches," *Int. Food Res. J.*, vol. 23, pp. S91–S95, Jan. 2016.

[16] N. H. Harun, N. Misron, R. M. Sidek, I. Aris, D. Ahmad, H. Wakiwaka, and K. Tashiro, "Investigations on a novel inductive concept frequency technique for the grading of oil palm fresh fruit bunches," *Sensors*, vol. 13, no. 2, pp. 2254–2266, 2013.

[17] N. Misron, N. Harun, Y. Lee, R. Sidek, I. Aris, H. Wakiwaka, and K. Tashiro, "Improvement in sensitivity of an inductive oil palm fruit sensor," *Sensors*, vol. 14, no. 2, pp. 2431–2448, Feb. 2014.

[18] N. H. Harun, N. Misron, R. M. Sidek, I. Aris, H. Wakiwaka, and K. Tashiro, "Dual resonant frequencies effects on an induction-based oil palm fruit sensor," *Sensors*, vol. 14, no. 11, pp. 21923–21940, 2014.

[19] N. Jamil, A. Mohamed, and S. Abdullah, "Automated grading of palm oil fresh fruit bunches (FFB) using neuro-fuzzy technique," in *Proc. Int. Conf. Soft Comput. Pattern Recognit.*, 2009, pp. 245–249.

[20] N. Fadilah, J. M. Saleh, H. Ibrahim, and Z. A. Halim, "Oil palm fresh fruit bunch ripeness classification using artificial neural network," in *Proc. 4th Int. Conf. Intell. Adv. Syst. (ICIAS)*, Jun. 2012, pp. 18–21, doi: 10.1109/ICIAS.2012.6306151.

[21] K. Minakata, K. Tashiro, H. Wakiwaka, K. Kobayashi, N. Misrom, N. A. Aliteh, and H. Nagata, "Proposal of fruit battery method for estimating oil palm ripeness," in *Proc. 12th Int. Conf. Sens. Technol. (ICST)*, Limerick, Ireland, Dec. 2018, pp. 399–402.

[22] N. Misron, N. S. K. Azhar, M. N. Hamidon, I. Aris, K. Tashiro, and H. Nagata, "Fruit battery with charging concept for oil palm maturity sensor," *Sensors*, vol. 20, no. 1, p. 226, Dec. 2019.

[23] N. Misron, N. Aliteh, N. Harun, K. Tashiro, T. Sato, and H. Wakiwaka, "Relative estimation of water content for flat-type inductive-based oil palm fruit maturity sensor," *Sensors*, vol. 17, no. 12, p. 52, Dec. 2016.

[24] *Oil Palm Fruit Grading Manual*, 3rd ed., Ministry Plantation Industries Commodities, Kajang, Selangor, Malaysia, 2015, pp. 8–13.

[25] N. A. Aliteh, K. Minakata, K. Tashiro, H. Wakiwaka, K. Kobayashi, H. Nagata, and N. Misron, "Fruit battery method for oil palm fruit ripeness sensor and comparison with computer vision method," *Sensors*, vol. 20, no. 3, p. 637, Jan. 2020, doi: 10.3390/s20030637.

[26] A. Ruswanto, A. H. Ramelan, D. Praseptiangga, and I. B. B. Partha, "Effects of ripening level and processing delay on the characteristics of oil palm fruit bunches," *Int. J. Adv. Sci., Eng., Inf. Technol.*, vol. 10, no. 1, pp. 389–394, 2020, doi: 10.18517/ijaseit.10.1.10987.

[27] N. Misron, N. S. K. Azhar, M. N. Hamidon, I. Aris, K. Tashiro, and H. Nagata, "Effect of charging parameter on fruit battery-based oil palm maturity sensor," *Micromachines*, vol. 11, no. 9, p. 806, Aug. 2020, doi: 10.3390/MI11090806.

[28] M. Basyuni, N. Amri, L. A. P. Putri, I. Syahputra, and D. Arifiyanto, "Characteristics of fresh fruit bunch yield and the physicochemical qualities of palm oil during storage in North Sumatra, Indonesia," *Indonesian J. Chem.*, vol. 17, no. 2, pp. 182–190, Jul. 2017, doi: 10.22146/ijc.24910.

NORHISAM MISRON (Member, IEEE) received the B.Eng., M.Eng., and Dr.Eng. degrees in system engineering from Shinshu University, Nagano, Japan, in 1998, 2000, and 2003, respectively. He joined the Department of Electrical and Electronic Engineering, Universiti Putra Malaysia, as a Lecturer, in 2003, where he became an Associate Professor and a Full Professor, in 2009 and 2016, respectively. He is currently an Associate Researcher with the Institute of Advance Technology (ITMA) and the Institute of Plantation Study (IPS). His research interests include magnetic application, including sensor and electrical machine development. His current research focuses on the design and development of agricultural sensor and actuator devices for the oil palm industry, including magnetic gear, high torque density motor, and fruit battery sensors. He serves on various technical committees for IEEE.

NUR AMIRA IBRAHIM received the Bachelor of Engineering degree in electrical and electronics from Universiti Putra Malaysia, Malaysia, in 2020, where she is currently pursuing the M.Sc. degree with the Faculty of Engineering. Her current research interest includes the development of generator for vertical axis wind turbine.

NISA SYAKIRAH KAMAL AZHAR was born in Perak, Malaysia. She received the Bachelor of Engineering degree in electrical and electronics and the M.Sc. degree in power electrical engineering from Universiti Putra Malaysia, Malaysia, in 2018 and 2021, respectively. Her research interest includes the development of sensor in oil palm maturity detection using fruit battery technique.

LUQMAN MOHD SAINI was born in Johor, Malaysia, in 1996. He received the B.Eng. degree in electrical and electronics engineering from Universiti Putra Malaysia, Selangor, Malaysia, in 2019, where he is currently pursuing M.Sc. degree. His current research interest includes designing magnetic gear as alternative to mechanical gear.

CHOCKALINGAM ARAVIND VAITHILINGAM (Senior Member, IEEE) received the B.Eng. and M.Eng. degrees from Bharathiyar University, India, in 1998 and 2001, respectively, and the Ph.D. degree in electrical power engineering from Universiti Putra Malaysia, in 2013. He is heading the Electrical and Electronic Engineering Program, Faculty of Innovation and Technology, Taylor's University, Malaysia, and the research cluster VERTICALS aligned with SDG goals on sustainable energy and mobility (SDG 7, 11). He is a very frequent speaker at various international and national platforms. He is also a Professional Technologists with the Malaysian Board of Technologists. He is a member of IET, U.K., and the Society of Engineering Education Malaysia. He is a Registered Chartered Engineer registered professional with the Engineering Council, U.K.

KUNIHISA TASHIRO (Member, IEEE) received the B.Eng. and M.Eng. degrees from Kanazawa University, Japan, in 1998 and 2000, respectively, and the Ph.D. degree in engineering from Kyushu University, Japan, in 2006. From 2000 to 2006, he joined as a Research Assistant with Kyushu University. He joined the Faculty of Engineering, Department of Electrical and Computer Engineering, Shinshu University, Japan, as an Assistant Professor, in 2006, where he became an Associate Professor, in 2012. He was the Head of Magnetic Energy Harvesting Project, Shinshu University, from 2012 to 2019. His research interests include innovation research with electromagnetic phenomena, including application of magnetic energy, sensor, actuator, and shield. He is a Senior Member of Institute of Electrical Engineering of Japan (IEEJ), and the Director of Japan Society of Applied Electromagnetics and Mechanics (AEM). He is currently the Head, where he investigating research and development committee on magnetic sensor with machine learning (AMAG1209) in IEEJ. He also serves on various technical committees, such as AMAG1203 (Biomagnetics) and AEMC1049 (IoT and EMC) of IEEJ, and other academic society.

HIROKAZU NAGATA received the master's degree in engineering from Kyushu Institute of Technology. He is currently an Associate Professor with the Center of Global Education and Collaboration, Shinshu University, where he is managing global education programs. His research interests include intercultural co-learning and human resource management.