Pre-harvest oil palm FFB nondestructive evaluation technique using thermal-imaging device

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Abstract. Oil Palm is widely cultivated in Indonesia due to its superior economical value. Currently, oil palm plantations have many challenges, particularly the time of harvesting. Many losses occurred during this process and therefore, they need best harvesting practice to obtain good results. While the quality of oil palm fresh fruits bunch (FFB) (i.e. ripeness) can be determined after harvest, a pre-harvest assessment technique is not present at the moment. In this study, we observe FFBs at four different fruit ages, e.g. 120, 140, 160 and 180 days after anthesis (DAA). A non-destructive evaluation was performed by measuring the FFBs surface temperature using a thermal camera. In addition, the influence of ambient temperature and other environment parameters were observed. Afterwards, the FFBs harvested, and its chemical compositions measured. A model developed to correlate the FFB surface temperature with its ripeness. Results showed that, regression model of the ratio of FFB oil content and moisture content with surface temperature has coefficient of determination of 0.6732. Moreover, when FFB surface temperature was correlated with its carotene content using multiple regression, the model R² was obtained at 0.8122. In addition, FFB surface temperature can be used to predicted the FFB age with R2 of 0.8344. This suggests a strong correlation between FFB surface temperature and its age. Furthermore, the ratio of FFB oil content and moisture content with its ripeness, and surface temperature, open the opportunity for a more accurate pre-harvest nondestructive evaluation technique to determine optimum harvest window (OHW) prediction of the bunch. The result delivers a solution of better harvesting practice in oil palm industry.

Keywords: Oil Palm; Optimum Harvest; Ripeness; Quality; Model

1. Introduction

Harvesting is a significant problem in oil palm cultivation. Based on previous studies [1], yield losses in oil palm plantation could reach up to 15% due to improper harvest. Normally, oil palm fresh fruits bunch (FFB) developed for 140-180 days after anthesis (DAA) before fully ripe and ready to harvest [2]. However, climate change and genetic engineering (GMP) can cause shifts in harvest age.

Harvesting FFB based on visual observation is heavily influenced by the harvester's experience and skills, and emotional condition. The fruit's position, the height of the trees, and the sunlight direction make determining the harvest visually more difficult. The method currently used to determine whether the FFB is fully ripe and ready for harvest is by observing the number of detached fruitlets on the ground [3]. This method has high error-rate (up to 20%) and cannot predict the internal quality parameters of the FFB [3].

Currently, the total production of oil palm FFB in Indonesia reach 165 million tonnes per annum [4]. The potential loss due to improper harvest throughout Indonesia reaches more than 4.2 billion USD [4].
Therefore, a better method, for precisely determining whether the FFB is ready to harvest, is essentially desired by the oil palm industry.

Previous studies employed optical devices, equipped with image processing algorithms, to produce better observation results for determining the fruit maturity level [5]. The system works by quantifying the bio-metric features of the observed fruits, then compare it with a decision model to determine whether the fruit is ready to harvest. This solution has limitation, where the variation of sunlight intensity influences the object color significantly. Moreover, the solution did not have the ability to determine the quality of the observed fruits. Therefore, the true value of the fruit cannot be deduced. Hence, the device for predicting harvest, ripeness and the quality of fruit should not be influence by external light factors.

When fruit ripening, changes in chemical composition and enzymatic reactions generally occur, which cause distinct in fruit temperature [6]. Whereas this occur in FFB, the phenomenon can be used as a reference to arbitrate a ripe condition. The concept has previously studied [7], where fruit temperature changes can be exercised to determine maturity. Therefore, it might be possible to observe the ripeness of the FFB from the surface temperature of the fruit.

In addition to maturity, the quality of FFB also plays an important role in determining the harvest [8]. The palm oil produced from FFB processing has standard quality parameters. These parameters include moisture content, oil content, Free Fatty Acids (FFA), Deterioration of Bleachability Index (DOBI), and carotene [9]. These five components have different thermal capacities to affect the FFB temperature when the air temperature changes [10]. Therefore, the quality of FFB can be potentially determine based on its surface infrared radiation.

From the background, this study was performed to explore the correlation between FFB temperature and the level of its maturity and quality. Changes in fruit temperature due to ripening processes and quality changes are minimal [2], and difficult to observe using simple devices such as thermometer. Currently, a thermal imaging device using a metal-oxide microbolometer sensor that can monitor a temperature difference of up to 0.07 °C [6] was available. With its highly sensitive sensor, this study uses the device for predicting the FFB harvest, ripeness and quality. Statistical analyses were used to explained the relationship of FFB age, maturity, and quality with its temperature. The relationships were explained in mathematical equation where FFB temperature was used as independent variable.

Measurement results from a device do not necessarily provide the desired information. Signal processing is needed to translate the changes in measured physical quantities into useful information. In general, signal processing is a programming algorithm that can model changes in physical quantities into this information. For this reason, a signal processing system was developed to operate the device used in this study.

The study produced better harvest method for oil palm FFB. The method can be replicated for harvest and quality determination of other crops and agricultural products. Reduction of incorrect harvest can minimize product and economic losses from oil palm, or other plantations. The result can be used to design a similar system for other plantation commodities. Therefore, this study is instrumental in achieving food security, improve nutrition, promote sustainable agriculture, ensure access to sustainable and modern energy, promote decent work, promote sustainable use of terrestrial ecosystems, reduce land degradation, and revitalize the global partnership for sustainable development.

2. Material and Methods
In this study, oil palm Fruit Fresh Bunches (FFBs) were observed from anthesis until harvest. The plant samples are of the greater age than seven years [11]. The samples located in Sijunjung district (0°41’44.6”S and 100°58’54.7”E). The FFBs were harvested at four groups according to development stages (120, 140, 160, dan 180 days after antheses).

A thermal imaging device was constructed and calibrated with a standard thermometer. The imaging device was used for recording the FFBs samples before harvested. Each sample was recorded from two different lines of sight. The device measured visible surface temperature of the FFB, around its equator [12]. Distance between object and camera was obtained for each measurement. Incident light on imaging device was measured [3]. Daytime temperature during measurement was between 28 and 30°C.
Immediately after the FFB images were obtained, the fruit was harvested and weighed. All FFB then brought to laboratory for chemical analysis.

First, the FFBs were sterilized to deactivate the enzymes. Then, the fruitlets were detached and weighed. The fruits mesocarp then separated and weighed, and immediately dried at 105°C in hot dry air-blasting oven [6]. The oil from mesocarp was extracted by soxhlet method [2]. FFA, DOBI, and carotene content of the oil was measured according to [6]. The oil content for each FFB sample was calculated according to [9]. Mesocarp moisture content was determined according to [2].

The average surface temperature of FFB was calculated by processing the image from thermal camera. Image segmentation was done by removing non FFB fruit parts from the image. The thermal camera imaging produces pseudo-color image which can be translated to temperature, according to a color-temperature-chart presented in the image. After segmentation, the object (FFB) color was subtracted into red (R), green (G), and blue (B) color. The object (FFB) average surface temperature (T) then calculated according to Eq.1 through Eq.5.

\[
\begin{align*}
\text{When } R \leq 10 \text{ and } G &> B, \\
T &= (0.0034 \times B) + 23.076 \\
\text{when } R \leq 10 \text{ and } \frac{R+G+B}{3} &> G, \\
T &= (0.0086 \times G) + 22.967 \\
\text{when } B \leq 10 \text{ and } R \geq 10, \\
T &= (0.002 \times R) + 24.337 \\
\text{when } R \geq 245 \text{ and } B \leq 10, \\
T &= (-0.0024 \times G) + 25.475 \\
\text{else,} \\
T &= (0.0034 \times \frac{R+G+B}{3}) + 25.051
\end{align*}
\]

A coefficient of determination was used to predict the dependent variables (FFB age, ripeness, oil content, moisture content, FFA, DOBI and carotene) that is predictable from the independent variable (T). Nonlinear correlations between each dependent variables and independent variable (T) were performed by multiple regression. Using the method, the FFB quality indices can be predicted according to its the surface temperature.

3. Results and Discussion

To determine variation of FFB ripeness and quality, different samples were used. In this study the sample was limited to four groups according to fruits age (120, 140, 160, and 180 DAA) [13]. Normally, oil in the fruits mesocarp will start to accumulate at around 110-120 DAA [13]. In addition, the fruit kernel will start to form at similar time [8]. The oil also accumulated in fruit kernel, although at lower quantity [8, 14]. This process continues until the fruit became overripe and start to senescence [14]. At this stage, fruits components will start to decompose and oil subsequently degrade, indicated by the acceleration of hydrolysis, and thus free fatty acid will form [6]. The oil degradation will exponentially occur if damage was presented on the fruit [10].

The temperature of an object is influence by its thermal capacity and ambient temperature, as well as the duration of the object exposed by external heat [15]. In general, fresh agricultural product contains certain quantity of moisture. The moisture will significantly influence object thermal capacity. Naturally, when oil was formed in fruit mesocarp it will fill the spaces between cells, replacing any present moisture [7]. However, not all moisture can be substituted by oil due to capillarity effect and interfacial properties between moisture and cell wall. Hence, the thermal capacity may not linearly change along with fruits development [15].
Nonetheless, this phenomenon can be used to predict oil and moisture in the oil palm fruits, to acceptable degree [11]. Furthermore, aside from oil quantity, the chemical composition of the oil can further influence the thermal capacity. For instance, the presence of free fatty acid in the oil due to hydrolysis process was triggered by enzyme activity and moisture [16]. Other biologic activities in the fruit, such as cell multiplication, maturation, respiration, senescence and deterioration, can also influence thermal capacity [7].

From the measurement, while many factors can influence the fruit temperature, the fruit age is the most notable aspect that changes the thermal capacity as seen in figure 1.

![Figure 1. FFB Surface temperature according to age under similar condition](image)

During fruits development, many activities occur due to enzymatic and chemical composition change. For instance, accumulation of oil and pigments will substitute the moisture inside the fruit cells spaces [2]. Some fruits accumulated other substances such as starch, sugar, amino acids, and fat [15]. In the case of oil palm, oil accumulation inside its fruits mesocarp changes the color of the fruit, since the oil contains carotenoid pigments [6]. Moreover, temperature of the fruit can be influenced by external and internal factors.

Humidity, air temperature, and sunny intensity may increase or decrease the temperature of an object [15]. This can be exaggerated by the thermal capacity of the fruits and its surface area. Each component of the fruit has unique heat properties and therefore chemical change in the fruit will automatically alter its thermal capacity [6]. Furthermore, ripening process accelerated biosynthesis process such as respiration [14].

Respiration process can increase the temperature of the fruit when stored organic materials are disassembling into simple products [17]. Normally this process will be followed by energy release and thus a slight temperature increment incurred [18]. When fruit respirates, it consumes oxygen (O2) in order to break it down. Stored organic materials [7]. In turn, the fruit will release energy and carbon dioxide (CO2) as effluent [17].

All living organisms continue to respire to maintain sufficient supply of adenosine triphosphate (ATP) [19]. The process catalyzes by certain enzyme which interconnected through metabolic pathways including glycolysis, the tricarboxylic acid (TCA) and the electron transport system [20]. The energy related production occurs in the cristae of mitochondria [21]. This electron transport systems phenomenon produces ATP from FADH2 and NADH on the chemical environment within the cell and mitochondria [21].

\[
y = -0.0003x^3 + 0.1249x^2 - 18.042x + 881.87
\]

\[R^2 = 0.8344\]
In figure 1 the fruit temperature increase when the FFB age was greater than 140 DAA. This condition indicates specific maturity stage where the rate of respiration increases, and thus ripening process commence. Similar pattern can be observed on climacteric fruits during ripening, therefore the FFB can be considered as the member of this type the fruit. In this case, the rise of FFB temperature is caused by acceleration of respiration [15].

Oil palm fruits also produce ethylene during ripening, and the concentration will increase to a saturation level in senescence stage [7]. Ethylene (C2H4) production is in conjunction with respiration process [17]. The production rate was higher when the fruit is immature and decrease after the onset of ripening [19]. When the fruit was harvested immaturely it respiration rate will accelerated [18]. When the fruit reach its maximum ripening stage the ethylene will play the role to increase the senescence process and perform uniform ripeness through out the fruits part [11]. This biosynthesis action influences the physiological development of fruits [14].

In general, ethylene promotes three major steps of biosynthetic process with the help of 1-aminoacyclopropan-1-carboxylic-acid (ACC) enzyme [21]. The enzyme serves as intermediate and immediate precursor, regulating the production of ethylene [20]. However, the enzyme activity can be affected by ripening and senescence process, and influence the overall quality of the fruit [17]. In the case of oil palm fruits, large amount of ethylene is produced when the fruit is going to ripe [14]. This biosynthesis indicator can be used for indicating physiological ripening process. At same cases the autocatalytic ethylene production may produce strong odor which attract pest and insect [22]. Previous study measures the ethylene production can be as high as 500 ppm/kg [23]. Nonetheless, spike of respiration in climacteric fruit only occur one time [20].

Ethylene is a gaseous substance which produces by various component of a plant [20]. The amount of production is not similar between plants organs. Moreover, the production rate depends on vegetative and generative development stages [19]. External factors can influence the ethylene production such as pest and abiotic stress [15]. These factors can accelerate endogenous ethylene synthesis. When FFB was going to ripe, a unique feature will occur due to ACC synthase and/or ACC oxidase activation [19]. Exogenous ethylene exposure to plant significantly inhibits the production of endogenous ethylene. This will induce by ripening, wounding and/or treatment with auxins [7].

During FFB ripening stage, plants will produce ethylene naturally. It will bind with the ACC receptor. Ethylene action can be controlled artificially [21]. Modification may include disruption of receptors and limiting the ethylene binding process [18].

Previous study found that ethylene production in FFB will change according to a fruit development stage [14]. The production pattern and quantity are correlated with ripening and senescence of the fruit [15]. The senescence triggers the dissolution of cells, which altered nucleic acid and protein synthesis, typically upon the onset of climacteric respiration cycle [14]. The senescence enhanced biochemical reactions in spontanius time [17]. Other studies [20] confirm the degardative and synthetic process of climacteric fruit during ripening where ethylene action was known to work at gene expression level.

According to FFB age (x), the temperature-pattern of FFB (y1) can be modeled with the equation 6, where:

$$y1 = -0.0003x^3 + 0.1249x^2 - 18.042x + 881.87$$

(6)

With the coefficient of determination (R2) of 0.8344, the model explained that the highest temperature was obtained at 28.7 °C, which was achieved at the age of 163 DAA fruit. The highest temperature indicates a maximum respiration. This shows the optimum ripeness point that can be reached by the fruit. After passing that age, there is a decrease in temperature, which is most likely to be a senescence process. The process of the fruit to the optimum ripeness point is called on set, while the process from the optimum ripeness point to the senescence process is called offset. The FFB from 140 to 163 DAA is in onset process, where the ripening process occurs, respiration increases, and the internal temperature of the fruit increases. After FFB passing 163 DAA, an offset will occur, namely the completion of the ripening process and the start of the senescence process. The senescence process that occurs will cause the respiration process to slow down. The slowing down of the respiration process...
results in the absorption of O2 and the release of CO2 and the release of energy decreasing so that the temperature of the fruit decreases until the final day of measuring 180 DAA. In this offset ripeness process, there is a decrease in the palm fruit's quality and chemical components because the broken-down structure molecule complex becomes simpler molecules [7].

Changes in water content in oil palm fruit occur along with the growth process (figure 2a). In the early phase of fruit growth, the water content is relatively high, but as the maturity phase changes, the H2O bonds in the mesocarp will be broken down to produce more superficial groups such as C, O2, and CO2 [24]. During this process, the water content of the fruit will decrease. The decreased water content is also caused by the fruit's surface area where natural evaporation and natural transpiration processes occur. The relationship of moisture content change in FFB during growth (y2) follows the equation of

\[ y = 0.0249x^2 - 8.2699x + 713.33 \]

with coefficient of determination \( R^2 = 0.9647 \) (Min at 166 DAA)

With coefficient of determination \( R^2 \) of 0.9647, the model explained that the lowest point of moisture content is reached at the age of 166 DAA. This value is related to the ripening phase of the oil palm fruit (figure 1). The peak of respiration of FFB was reached at this phase. After passing through this phase, the senescence process occurs, and therefore, the moisture content was increasing. This
suggest chemical composition changes, and decreasing quality of FFB. When the fruit go through senescence, the water content of the fruit will increase. The increase in water content again in the senescence process triggers the oil hydrolysis reaction [24]. The oil hydrolysis process will trigger FFA formation, which results in decrease of oil palm quality. One of the indicators that FFA was forming in the oil is the characteristic of "rancid" odor.

Changes of oil content in FFB exist during the growth, as shown in figure 2b. The FFB oil content increased as the fruit ages. The oil buildup came from many activities that occur due to enzymatic and chemical composition changes. The change of FFB oil content follows the equation of:

\[ y_3 = -0.01x^2 + 3.1322x - 219.55 \]  \hspace{1cm} (8)

The model produced coefficient of determination \( (R^2) \) of 0.8116 (figure 2b.). Based on this model, the maximum oil accumulation was obtained when FFB at 156 DAA. This result was in accordance to the peak of respiration which appeared in FFB at 163 DAA. The result showed that oil accumulation peaked prior to maximum respiration, and immediately followed by the senescence process. However, the oil content limit of 18% can be reached when FFB was 140 DAA. Beyond 156 DAA, the oil in FFB started to decreases, since oil is broken-down into FFA through biosynthetic process. This process was triggered by the lipase enzyme in FFB. At this stage, the reduction of oil quality in FFB begin to take-place.

Changes of moisture and oil content, as well as formation of FFA in FFB are related to other quality parameter, the DOBI. DOBI normally change as the FFB ages. The relationship of DOBI value \( (y_4) \) with FFB age was explained in Eq. 9.

\[ y_4 = -0.0006x^2 + 0.2227x - 16.795 \]  \hspace{1cm} (9)

The model produced coefficient of determination \( (R^2) \) of 0.7116. In this study, the DOBI value steadily increased throughout the FFB development. Therefore, the DOBI reached the maximum value of is reached at the end of the FFB growth phase, namely at the age of 180 DAA. DOBI is an indicator of the oxidative status of palm oil. If oil palms are harvested before they reach a certain maturity level, the mesocarp moisture content is still high. The raw fruit has lower oil content. When this fruit is processed, the oil's high-water content causes the oxidation process to speed up. The more the oil is oxidized, the lower the DOBI value. Besides that, DOBI is also influenced by carotene. However, the relationship between water, oil content, and carotene, and DOBI cannot be specifically explained. However, the limit value of DOBI> 2.3 can be reached if the fruit is harvested at 160 DAA.

Carotene is closely related to the oil content because when the oil content is formed, carotene is also formed. This is because carotene is a byproduct of oil. Along with the growth of FFB, carotene's growth pattern follows the pattern of formation of oil content, although it has a lower coefficient of determination. The pattern of carotene growth \( (y_5) \) equations is

\[ y_5 = -0.1953x^2 + 61.681x - 4424.8 \]  \hspace{1cm} (10)

The model produced coefficient of determination \( (R^2) \) of 0.3162. However, carotene remains positively correlated with the formation of oil content. The maximum carotene value was achieved at 158 DAA.

When palm oil is processed, palm oil companies want a high oil yield and low moisture content. This is because the water content requires an evaporation treatment, which involves much energy. The lower the water content, the better the energy efficiency for oil palm processing. Therefore, the relationship between oil content and moisture content needs to be studied. In this study, the measurement was carried out.

Along with the growth of FFB, the ratio of oil content to water content \( (y_6) \) followed the mathematical equation of:

\[ y_6 = -0.001x^2 + 0.3073x - 22.615 \]  \hspace{1cm} (11)
The model produced coefficient of determination (R²) of 0.8938. The optimum point occurs at the age of 158 DAA; this shows that the fruit’s oil content is the highest with the lowest water content. Therefore, based on the data of water content, oil content, DOBI, carotene, and temperature, oil palm harvesting is carried out based on figure 1. namely the age of 156 - 171 DAA.

From the results of previous measurements, the FFB temperature changed with the phase of fruit growth. based on [14-24], this change is due to the process of biosynthesis, enzymatic, respiration, oil and pigment accumulation, and the senescence process. The relationship between this temperature change and the five FFB quality parameters is presented in figure 3. Changes in fruit temperature during observation with water content in the mesocarp follows a multiple second order model, where moisture content (%) is represented by \( y \), where:

\[
y_7 = -1.8389x^2 + 91.529x - 1084.8
\]

\( R^2 = 0.2039 \)

The \( x \) represents the surface temperature of FFB as measured by a thermal imaging device.

The model produced coefficient of determination (R²) of 0.2039. Although the R-squared value is small it not necessarily translated into undirsite result. The different between the observation and model prediction are small and can be accepted since it fitted to observation space. Models with low R-squared
values can be perfectly good models for several reasons, the result still draw important conclusion about the relationship between observe variable.

Therefore, the correlation between fruit surface temperature and fruits moisture content can be considered as weak. However, the multiple-regression model explains the trend of how the moisture develops, accumulate and disperse inside the fruits mesocarp during its development, ripening and senescence stages. The trend follows a curvature line where reduction of moisture content did not necessarily translated into increment of fruits temperature. Water has the highest specific heat capacity of any liquid [25]. Specific heat is defined as the amount of heat one gram of a substance must absorb or lose to change its temperature by one degree Celsius. For water, this amount is one calorie, or 4.184 Joules [25]. During fruit development other substances such as oil, sugar, amino acids, and salts, accumulate in the mesocarp [24]. This substance solube in the moisture and change its specific capacity. This condition shifts the energy levels of molecule in the moisture in various vibrational, rotational and translational motion.

The correlation between fruit surface temperature and its oil content (y8) explain in figure 3b. The correlation can be explained through a multiple-regression analysis where oil content (%) (y) can be determine according to fruit surface temperature (x) using equation of

\[
y_8 = 0.5092x^2 - 25.392x + 333.91
\]  

(13)

The x represents the surface temperature of FFB as measured by thermal imaging device. The model produces coefficient of determination (R²) of 0.2185. This value indicates less than strong correlation between two variables. The multiple-regression model forms a curvature line, because moisture presents in fruit mesocarp and solubed the oil. Hence, heat capacity of the oil changes and influences the fruit surface temperature [25].

Upon expose by heat energy source such as sunray, palm oil will heat up faster than water because the heat capacity of oil is lower than the heat capacity of water. Water requires more energy per gram of liquid to change its temperature. When oil mixed with water, it will require less energy to increase its temperature. Therefore, when this condition occurs in fruit mesocarp, the FFB surface temperature may change although its oil content is constant.

Radiation from the sun have wide spectrum with wavelengths starting from nanometers to greater than meters size. These wavelengths have high frequencies, and therefore constitute higher energies. Certain radiation from the sun are Microwaves. They are much better at heating polar molecules, like water [26]. A molecule is polar when it has a concentration of charge on one side or the other. On the water molecule, the oxygen atom is negatively charged, while the hydrogen atoms are positively charged. Oils, like palm oil, are long, evenly spaced chains and are very non-polar, so they don’t absorb energy from microwaves as well as polar molecules like water do. Microwaves work by causing the poles of a molecule to spin rapidly, which generates heat [26]. This is known as dipole rotation. The present of water caused the oil to solubed and change the polarity of the substance. Therefore, while the oil content inside of fruit mesocarp is similar between samples, the moisture content will alter the fruit surface temperature when measure under same condition. Variation of moisture content, oil content as well as sunlight intensity and surrounding temperature will dictate surface temperature of the FFB.

DOBI is an indicator of the oxidative status of palm oil. It can be measure by extracting the oil from FFB and compare the absorption level of the oil at two wavelengths (269 and 446 nm) using spectrometer [6]. In this study the correlation between FFB surface temperature and its DOBI was presented in figure 3c. Using the multiple-regression, the correlation between DOBI (y9) and fruit surface temperature can be model as

\[
y_9 = 0.0707x + 0.3054
\]  

(14)

where x represents the surface temperature of FFB as measured by thermal imaging device. The model obtains a weak coefficient determination (R²) of 0.0265. The result suggest that no or minimal correlation between FFB surface temperature and its DOBI content. Different approach need to be explored for predicting FFB DOBI by means of nondestructive evaluation.
The correlation between FFB surface temperature and its carotene content ($y_{10}$) was presented in figure 3d. A complex multiple-regression model was used to explain this correlation, where the carotene content (ppm) represents as:

$$y_{10} = 9.3632x^3 - 1201.7x^4 + 61521x^3 - 2E+06x^2 + 2E+07x - 1E+08$$

(15)

The $x$ represents the surface temperature of FFB as measured by thermal imaging device. The model produces strong coefficient of determination ($R^2$) with value of 0.8122. Therefore, the carotene content of FFB can be accurately predicted based on its surface temperature. Since FFB temperature can be used to explain fruit development stage (figure 1), a combination of this model with model in figure 1 can be used to improve the accuracy for predicting the best time to harvest the FFB.

Oil in FFB mesocarp is edible and rich in carotenoids in terms of retinol (provitamin A) equivalent. Its physical and chemical properties are quite distinct from those of oil obtained from the kernel inside the nut. The carotenoids are undoubtedly among the most widespread and important pigments in living organisms. Carotenoid in oil palm normally present in minute quantity (500-700 ppm), 15 to 300 times larger than what is present in vegetables [27].

During fruit development, many substances produce and accumulated in fruit mesocarp. Two main components are moisture and oil. Both have negative relation in quantity, where moisture was abundant in mesocarp during fruit initial development. On contrary, when the fruit is ripening, the plants produce and stored oil in fruit mesocarp, thus replacing the moisture. Throughout this development the ratio of oil and moisture inside fruit mesocarp was change, and therefore, fruit thermal capacity was alter. The correlation between fruit temperature and ratio of oil and moisture in fruit mesocarp ($y_{11}$) was presented in figure 3e. A linear-regression was used to model this correlation, where ratio of oil and moisture in fruit mesocarp modelled as:

$$y_{11} = 0.2064x - 4.0487$$

(16)

The $x$ represents the surface temperature of FFB as measured by thermal imaging device. The model produces strong coefficient of determination ($R^2$) with value of 0.6732. From the model, in agreement with measurement of fruit temperature according to figure 1, the fruit can be categorized as ripe when the ratio of oil and moisture content is greater than 1.6. Therefore result of this study can be used to evaluated whether the FFB can be categorized as ripe whenever the surface temperature reached 27.4 °C when measure by thermal imaging device.

Based on this study result, similar aproach for evaluating the ripeness or predicting the optimum harvest window for climacteric fruits can be duplicated based on the thermal properties of the object. Thermal based imaging device can be design and constructed for specific fruit for ripeness and harvest determination. The method can also reduce untimely harvest, thus minimizing losses and improved productivities of crops and horticultural product. Therefore, this study is instrumental for promoting Sustainable Development Goals (SDGs) in achieving food security, improve nutrition, promote sustainable agriculture, ensure access to sustainable and modern energy, promote decent work, promote sustainable use of terrestrial ecosystems, reduce land degradation, and revitalize the global partnership for sustainable development.

4. Conclusion

In this study a novel method for evaluating the quality of oil palm FFB can be performed nondestructively prior to harvest. The method employed a thermal imaging device to predict the ripeness of oil palm FFB at pre-harvest stage. Furthermore this method can be used for estimating the time for harvesting the oil palm FFB. Linear regression model was developed which can predict the ratio of oil and moisture content of observed FFB with the coefficient of determination of 0.6732, without the need of neither harvesting nor chemical analyzitation. Moreover, a multiple-regression model was developed and sucessfully estimated the concentration of carotene in FFB mesocarp with coefficient of determination of 0.8122. Both models can be integrated in which the observed FFB can be harvested whenever its temperature is equal or greater than 27.4 °C when observed by a thermal imaging device.
Based on this study result, similar approach for evaluating the ripeness or predicting the optimum harvest window for climacteric fruits can be duplicated based on the thermal properties of the object. Thermal based imaging device can be designed and constructed for specific fruit for ripeness and harvest determination. The method can also reduce untimely harvest, thus minimizing losses and improved productivities of crops and horticultural product. Therefore, this study is instrumental for promoting Sustainable Development Goals (SDGs) in achieving food security, improve nutrition, promote sustainable agriculture, ensure access to sustainable and modern energy, promote decent work, promote sustainable use of terrestrial ecosystems, reduce land degradation, and revitalize the global partnership for sustainable development.

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