Thermal and Optical Properties of Oil Palm FFB for Optimum Harvest Window Prediction

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Abstract. Best practices in oil palm cultivation to improve efficiency are challenging. Enormous capital has been invested in superior seeds, water and fire management, as well as fertilization. However, heavy loses occurred at the time of harvesting. Oil palm fruits grow in dense bunches, called fresh fruits bunch (FFB), containing mass number of fruits. The fruits ripen non-uniformly and formidable to observe visually. Therefore, untimely harvest is unexceptional. Previous studies suggest that camera-aided observation produce more accurate results for determination of FFB ripeness than visual inspection. However, these techniques prone to environment change such as sunlight. In this study we propose the use of hybrid-camera which can observe the FFB in multispectral-regime. The prototype was able to better identify changes in FFB physical and thermal characteristics upon maturation and ripening. The new approach enables better optimum harvest window prediction for FFB with R² of 0.8344, while previous study can only obtain R² of 0.7818. The result provides better harvest practice in oil palm industry to improve the overall efficiency of cultivation.

Keywords: Hybrid Camera; Ripeness; Multispectral; FFB Characteristics; Loses

1. Introduction
Best practices in oil palm cultivation to improve efficiency are challenging. Oil palm sector is confronted by many important challenges such as yield gap, low productivity, and climate change [1]. Several targets aimed by the oil palm industry among others a higher oil yield in fruits and higher oleic acid composition in fruit mesocarp [2]. The more focus use of new technologies can help achive this target.

Enormous capital has been invested in superior seeds, water and fire management, as well as fertilization [3]. However, problems arise when yield and harvesting efficiency need to be improved [4]. Increasing palm oil output requires a strategy to minimize adverse environmental consequences. None the less, the upstream sector provides significant challenge, and hence, the main researches and development focus in this area.

Oil palm plantation frequently lost the yield, due to improper harvest [5]. The main causes of loses are the activities of picking the oil palm FFB before the fruit fully ripe. More than often harvester failed to identify the ripe FFB, and the fruit missed the optimum harvest window. When this occurred, the fruit will start to senescence in the oil in its mesocarp will start to degradated.

Oil palm fruits grow in dense bunches, called fresh fruits bunch (FFB), containing mass number of fruits. The fruit consist of pulpy flesh (mesocarp), where moisture and oil stored during various development stages. The amount of oil and moisture substance are suplementary, and limited to the cells spaces of the mesocarp. From previous study, the moisture tends to decline along the fruit development, in contras to oil accumulation in mesocarp. At initial stage, the moisture content in fruit mesocarp is
high. By the time the fruits are ripe and ready to harvest, the oil replace the moisture in mesocarp, and changes the fruit color and appearance.

The fruits are ripe non-uniformly, and formidable to observe visually. The body structure of oil palm trees dictate the space of FFB to grow. The fruit located between the trunk and frond, partially hidden, and difficult to observe even by experienced labor. In practice, the number of detached fruitlets is used as the main indicator by all harvesters to crop the FFB.

Therefore, untimely harvest is unexceptional. Unripe FFB has significantly less oil than the ripen one. The yield gap can be as high as 30% or more. Many studies have proposed various methods to reduce this harvest mistake. Most of them suggest the use of optical devices to help the labor correctly observed the FFB. Moreover, previous studies suggest that camera-aided observation produce a more accurate result for determination of FFB ripeness than visual inspection. However, these techniques were prone to environment change such as sunlight.

Other approaches were using non visible spectrum to counter the external factors (i.e. light, humidity, color). Some study employ thermal imaging for predicting the ripeness and harvest window of FFB. Other was using near infrared spectroscopy with promising result. However, the cost, speed, and accuracy hindered the use of these solutions in practical use. Therefore, a robust, low cost, and simple device is required to fulfill the task and reduce loses due to improper harvest of FFB.

In this study we propose the use of hybrid-camera which can observe the FFB in multispectral-regime. The device was used to observe the FFB from two directions, where parts of FFB can be seen by the camera. Models were develop to explain the relationship of fruit appearance and heat capacity with various parameters such as ripeness, moisture and oil content, DOBI, carotene, and ratio of oil and moisture. Linear and multiple-regression were used to develop the model.

The prototype was able to better identify changes in FFB physical and thermal characteristics upon maturation and ripening. Harvest errors can be reduced by using this tool to minimize the potential economic losses from oil palm plantations. The output of this study 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. Materials and Methods

In this study, 120 samples of oil palm Fresh Fruit Bunches (FFB) were observed from the anthesis to harvesting stage by thermal imaging camera and digital camera. The sensor of thermal camera (FLIR, Multi-Spectral Dynamic Imaging (MSX), California) has infrared (IR) resolution of 307200 (640x480) pixels. The camera can measure temperature between 0 and 150°C using focal plane array (FPA), uncooled microbolometer. The camera field of view (FOV) is 15°x11° with focal length of 41 mm. The thermal sensitivity is less than 30 mK when camera operated at 30°C.

The digital camera was using Complementary Metal-Oxide-Semiconductor (CMOS), measuring 22.4x15 mm (APS-C size), with maximum resolution of 20.2 megapixels (5472x3648). The camera was using telephoto lens with optical magnification of 18 times.

The samples were obtained from oil palm plantation located in Sijunjung district (0 ° 41’44.6 "S 100 ° 58’54.7" E). FFB was harvested at five maturity stages, 120, 140, 160, 180, and 200 days after anthesis (DAA). All samples evenly distributed between groups, each maturity stage comprise of 24 FFB samples. Prior to harvest, each sample was recorded with both camera from same position and distance where the FFB can be seen without being obstruct by plant parts. Due to its unique position in plant, the FFB can be observed from two directions.

Normally, FFB growth between the plant trunk and leaf frond, where the anterior and posterior of FFB were enclosed. Only the medial side of FFB is normally observable either the left or right lateral part. The thermal camera and digital camera were used to record these observable parts. All images were recorded with three replications.
The FFB images were recorded with minimum sunlight of 300 lux and maximum light intensity of 1500 lux [6]. Minimum observation distance between camera and FFB was 3 meters. The telephoto lens enables the recording of FFB image as far as 15 meters. Optical magnification was used to enlarge the object (FFB), to maximize its size in the image frame. The tripod was used to stabilize the camera when recording the FFB image. The observation distance was recorded using laser ranging device. The camera will be repositioned if sunlight directly falls onto the lens.

After recorded, the FFBs were harvested and immediately analyze in the laboratory. The fruits were weighed then sterilized to deactivate the lipase enzyme and softening the fruits mesocarp. The dried mesocarp then weighed, and the oil was extracted using soxhlet method. The FFB quality indices were obtained by measuring the moisture content (MC), oil content (OC), Deterioration of bleachability index (DOBI), and carotene. The measurements were performed according to [ ].

The average surface temperature of FFB was calculated by segmenting the image from thermal camera. Segmentation was done by removing non FFB parts from the image. The thermal camera imaging produce a 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.

Condition 1, where $R \leq 10$ and $G>B$:
\[
T = (0.0034* R) + 23.076
\]  
Condition 2, where $R \leq 10$ and $\frac{R+G+B}{3} > G$:
\[
T = (0.0086* G) + 22.967
\]  
Condition 3, where $B \leq 10$ and $R \geq 10$:
\[
T = (0.0024* R) + 24.337
\]  
Condition 4, where $R \geq 245$ and $B \leq 10$:
\[
T = (-0.0024* G) + 25.475
\]  
Condition 5, where condition 1 until 4 is not fulfilled:
\[
T = (0.0034* R) + 25.051
\]

The color feature of FFB was determined by segmenting the image from digital camera, to distinguish between object (FFB) and the background (other plant parts). The image from each FFB was process through color segmentation to obtain the information regarding the value of additive color spectrum, namely Red (R), Green (G), and Blue (B).

The relationships between FFB color feature (RGB) and FFB quality indices (MC, OC, DOBI and carotene) were explained by nonlinear models. Similarly, the relationship between FFB surface temperature (T) and FFB quality indices were explained by multiple nonlinear regression analysis.

The model accuracy was assessed from the coefficient of determination ($R^2$) (Eq. 6), and standard error of validation set (SEP) (Eq. 7).

\[
R^2 = \frac{st - sr}{st} = \sum \frac{(Y_i - \bar{Y}_m)^2}{(Y_i - \bar{Y}^2)}
\]

\[
SEP(\%) = \sqrt{\frac{1}{n-1} \sum (\hat{Y}_i - Y_i - bias)^2}
\]

Where n is the number of the data sample, $\hat{Y}_i$ is the prediction value, $Y_i$ is the measured value, $\bar{Y}_m$ is the mean value. The average differences between predicted and actual values were considered as bias (Eq. 8).

\[
Bias(\%) = \frac{1}{n} \sum (\hat{Y}_i - Y_i)
\]

The performance of model was highly related to the SEP results. The model was considered appropriately accurate when $R^2$ value was acceptable, and SEP and bias were low.
3. Results and Discussion
The process of ripening encompasses catabolic and anabolic transformations in FFB. FFB stored photosynthesis products mainly in the form of oil. Unripe FFB indicated by astringent-tasting phenolic compounds, where the cell walls are ridged, and adjacent cells are held firmly together by pectic substances in the middle lamella between cells. Immature FFB are not soft, therefore it is unwanted to potential herbivores [7]. When the FFB begin to ripe, the component inside the fruit was change, the phenolic compounds were metabolized and the cell wall and middle lamella are altered by specific enzymes. The process was resulting in the softer fruit and accumulation of edible oil in mesocarp.

Beside catabolic, anabolic reactions also occur and transform the composition of ripe FFB. Catabolic and anabolic transformation in FFB produced change appearance, in particular the fruit color. Accumulation of oil in mesocarp was accompanied by buildup of carotenes pigmen. The process was followed by reduction of chlorophyll in fruit exocarp. The yellowish color of FFB was caused by synthesis of carotene pigmen. By the time the fruit mature, the masking chlorophyll is degraded, and FFB color become dark red, due to high concentration of carotenoids. Furthermore, at the final stages of ripening, the FFB produce unique aroma, pleasant to insects and herbivores. Temperature, humidity and damage can influence the catabolic and anabolic reactions, resulting poor-quality FFB [7].

The FFB should be harvested as close as possible to its maximum quality to ensure best attribute parameters of the processed product, the edible palm oil. Beside color, other physical properties such as hardness can be a major exhibit for defining ripeness. The FFB should be harvested at a sufficient level of maturity to survive the rigors of harvesting and handling before being processed in the palm mill. Therefore, FFB must be harvested at sufficient firmness to prevent damage. Consequently, the the decision to harvest FFB was a compromise between potential best quality and minimal risk of damage.

The FFB can be grouped into climacteric fruit. It is characterize by a substantial increase in ethylene production and respiration coincident with the onset of ripening. As FFB shift from immature to mature, it acquire the ability to stimulate the rate of its own synthesis through ethylene positive feedback mechanism. The process was known as auto-catalytic. However, when the FFB was immature, the negative feedback of ethylene on ethylene synthesis causes the low concentration of ethylene.

The upsurge in ethylene production at the start of the climacteric process produces a rise in the internal concentration of ethylene in the fruit tissue. This rise, coupled with increased sensitivity to ethylene, is thought to produce the observed climacteric rise in respiration. The FFB can be harvested at mature but unripe stages. However, it will required exogenous ethylene treatment in a special chamber. Furthermore, the room should be equipped with refrigeration and air circulation to maintain the optimal temperature and humidity to produce best quality of FFB.

The unripe FFB was firmer, and more resistant to mechanical injury and pathogens. At this stage, distant transportation of FFB can be done. Unripe FFB may also be more resistant to water stress. Nonetheless, the fruit only has a fraction of oil when compared to fully ripe FFB. As a result, unripe FFB considered as substandard, and not desire by the palm mills. Exposure of phyto-active levels of ethylene to FFB will stimulate respiration and the onset of senescence, resulting in excessive softening of fruits mesocarp.

Senescence is usually just a continuation of the changes associated with ripening. The difference between a ripe and a senescent FFB can be distinguished through aroma, number of detached fruitlets, and the firmness of the fruit. Other changes characteristic of senescent tissue are reduced respiration, loss of cellular integrity, loss of turgor and increased disease susceptibility. Wounding, water loss, abusive temperatures and diseases all promote premature senescence of FFB. From 120 FFB samples, the color features, surface temperature, MC, OC, DOBI, and Carotene, as well as ratio between OC and MC were obtained. The results were presented in figure 1a until figure 1g. The relation of FFB development with the change of color features were explained by multiple-regression as seen in figure 1a. The change of FFB appearance (color) was observed within three colors spectrum (RGB). The change of red color spectrum (R) of FFB along development stages was following the curvatic line as explained in Eq. 9.

\[ R = -0.0028x^3 + 1.2404x^2 - 176.8x + 8363.7 \quad (9) \]
The x represent the age of FFB, between 120 and 180 DAA. This model produces the coefficient of determination (R²) of 0.4671. The value of R is at maximum when the FFB reach 165 DAA.

The change in green (G) and blue (B) color spectrum of the FFB during its growth was similar and the relationship can be explained by Eq. 10 and Eq. 11.

\[ G = -0.0025x^3 + 1.075x^2 - 151.44x + 7094.7 \]  \hspace{1cm} (10)

\[ B = -0.0022x^3 + 0.9237x^2 - 128.38x + 5938.5 \] \hspace{1cm} (11)

The x represent the age of FFB, between 120 and 180 DAA. The G and B color spectrum model produced the coefficient of determination (R²) of 0.5155 and 0.4549 respectively. The value of G and B is at maximum when the FFB reach 165 DAA, similar to R model.

The relation of FFB development with the change of its surface temperature was explained by non-linear correlation as seen in figure 1b. The change of FFB temperature was following curvatic line where significant change observed when the FFB reach 140 DAA. The fruit temperature rise to maximum when FFB samples were 163 DAA, and decline afterward. The change of FFB temperature (T) along fruits development stages was explained in Eq. 12.

\[ T = -0.0003x^3 + 0.1249x^2 - 18.042x + 881.87 \] \hspace{1cm} (12)

The x represent the age of FFB, between 120 and 180 DAA. The model produced coefficient of determination (R²) of 0.8344. The model performed better than previous study [8] as presented in Eq. 13. The temperature of FFB peaked when the FFB reach 163 DAA, non-significantly different with R, G, B models. This suggests that change of FFB color due to biosynthesis and enzymatic process inside the fruits influence the thermal capacity of FFB.

Understanding thermal capacity and temperature of FFB is ubiquitous, because it is not only explain the fruit physical and chemical development, but also provide crucial data for processing the FFB and preserving the oil obtained [9]. The nature of FFB thermal properties should be understood for designing palm mill machinery and process. It is essential for energy balance estimation, and how much heating and cooling will be required. Furthermore, thermal properties of FFB dictated the heat conductivity, heat specific, enthalpy, thermal diffusivity, latent heat of phase transition, and emissivity of the fruit. Thermal conductivity is defined as the ability of a material to conduct heat [9]. Thermal capacity of FFB depends on composition and porosity of fruits component, and influenced by surrounding temperature, as well as sunlight exposure. Specific heat shows the amount of heat required to increase the temperature of unit mass of the substance by unit degree. Thermal diffusivity measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy [9].

As the FFB grows, the moisture inside the fruit was change. The relationship between FFB age and its moisture content (MC) can be regressed with a non-linear regression as presented in Eq. 13.

\[ MC = 0.0249x^2 - 8.2699x + 713.33 \] \hspace{1cm} (13)

The x represent the age of FFB, between 120 and 180 DAA. The MC model produced the coefficient of determination (R²) of 0.9647. The value of MC is at minimum when the FFB reach 166 DAA.

The ripe FFB can be determined among other through the increase of oil content and a decrease in moisture content. In the early stages of fruit growth, the moisture content is relatively high, but as the maturity phase changes, the H2O bonds in the mesocarp will break down to produce more superficial groups such as C, O2, and CO2. During this process, the moisture content in the fruit will decrease. The decreased water content is also caused by the fruit's surface area, which occurs naturally by evaporation and natural transpiration processes. After the onset of ripeness, the respiratory rate is decreased, which results in the reversal process. The fruit's components start to decay, and the oxygen absorbed by the fruit pores will react with the enzyme and bind with hydrogen atoms, which cause the formation of H2O. Therefore, the senescence of FFB was indicated by reformation of moisture inside the fruit. The result suggested that the senescence of FFB began from 167 DAA onward.
The oil inside the fruit was change accompanying the fruit development stages. The relationship between FFB age and its oil content (OC) can be regressed with a multiple-regression as presented in Eq. 14.

\[ OC = -0.01x^2 + 3.1322x - 219.55 \]  \hspace{1cm} (14)

The x represent the age of FFB, between 120 and 180 DAA. The OC model produced the coefficient of determination (R²) of 0.8116. The value of OC is at maximum when the FFB reach 156 DAA.

The physical appearance of FFB was changed when the fruit develop and ripen. In early development stage the FFB has high moisture content. Oil palm fruit has fleshly part, namely mesocarp. Oil palm fruit begins to form after pollination and fertilization. The young part of the fruit consists of the mesocarp and the empty kernel. In this phase, the fruit content is dominated by high moisture content, increasing the thermal capacity of the fruit. When the FFB became ripe, the moisture content decreased due to the translocation of oil formation to the fruit [10]. The accumulation of oil during this period of fruit development causes water to be spurred out of the oil palm fruit [11].

The formation of oil in FFB began at 110-120 DAA [12]. Gonzales et. al [13] stated that the oil content in the fruit will change during the ripening process. This is due to the physiological and biochemical processes that continuously take place from anthesis to ripening [14]. Oil and moisture have different thermal capacity. When the fruit begin to ripe, biosynthesis process activate the production of oil by the plants. The oil stored in the fruit mesocarp and kernel. The increased of oil accumulation will reduce the thermal capacity, resulting the fruit more susceptible to surrounding temperature. Therefore, fruit temperature was higher at the onset of ripening.

After FFB fully ripe, the senescence will start and the oil in mesocarp will begins to degrade. This will influence the thermal capacity of the fruit. The oil degrades because part of the cell walls in mesocarp has begun to break, discharging the moisture in the cells, and contaminating the oil. This will cause the oil and moisture ratio in fruit to change [15].

The Deterioration of Bleachability Index (DOBI) is a diagnostic method used for the class segregation of palm oil. It provides the information of oxidation level of oil and how much effort required for refining the product. A greater DOBI number suggest FFB is fresh, ripe and free of contaminates when processed. The DOBI determined through spectroscopy analytic by comparing the ratio absorbance of oil when illuminated by two narrow-band-spectrum light (446 and 269 nm). Measurements are made by dissolving the palm oil in hexane and then determining the absorbance in a spectrophotometer. A ratio value of less than 1.68 implies unacceptable oil quality. When the DOBI value was between 1.78 and 2.30, the oil quality considered as poor. A standard oil palm normally obtained a fair DOBI value, between 2.36 and 2.92. A better oil palm quality often has DOBI values of 2.99-3.24. Moreover, when the oil has greater DOBI grade (> 3.24), it is considered as prime quality oil.

In world market, crude palm oil is traded with certain paramaters value, such FFA, MC, and impurities. In addition the palm oil trader should provide product with good merchantable quality (GMQ) where DOBI frequently complement the criteria. In general, the palm oil is traded and refine into refined, bleached and deodorised (RBD) products. Moreover, high DOBI value indicated that the oil has good bleachability. Therefore, most trader use DOBI as an indicator of fitness for processing the oil. Hence, the DOBI oftenly describe as a part to GMQ quality parameter.

Accordingly, the market value the oil palm based on the analysis of FFA, MC, impurity, and DOBI. All this four parameters are considered sufficient for measuring the oil palm market value. In addition, incorporated the DOBI in oil palm quality analysis will completely visualize the oxidation rate, and how much input will be needed to process the oil.

The DOBI value strongly influence by the percentage of ripe FFB, time from harvest to process, and contamination (i.e. sterilizer condensate, oxidised sludge oil) and Prolonged sterilization of FFB at high temperature. The unripe FFB contained oil with the lowest DOBI value. When this FFB was processed, the oil often has DOBI < 1.5. In contrast, optimal ripe FFB can yield oil with DOBI greater than 3.5. In
major plantation, managing the harvest properly can result of achieving FFBs with DOBI greater than three. This will required small effort for planning the harvest.

During the rainy season such as December to January, the torrantle down pour will limit the access in many plantations and reduce the road capacity. Delay in harvesting and processing the FFB will frequently occur. This will result in reduction of DOBI value when oil was extracted from FFB. Certain sterilization method can prevent the reduction of DOBI value, although the breakthrough is still in experimental stage. Overall, high DOBI value is desirable since it will reduce the cost of processing the oil. In addition, high DOBI oil enable milder processing, minimizing the formation of carcinogenic contaminant (i.e. MCPDs, GEs, and Trans fatty acids). The MCPD (monochloropropanediol), such as 2-MCPD and 3-MCPD esters are chemical food contaminannts that are suspected to be carcinogenic. The European and the US food agencies have defined limit values for consumers with maximum daily intake dose of 2 µg/kg body weight. Furthermore, mild processing of high DOBI oil palm enables the preservation of the natural antioxidants (tocopherols and tocotrienols) in the final refined oil.

The DOBI value in FFB was increasing according to fruit age. The relationship between FFB age and its DOBI, can be regressed with multiple-regression, presented in Eq. 15.

\[
\text{DOBI} = -0.0006x^2 + 0.2227x - 16.795 \quad (15)
\]

The x represent the age of FFB, between 120 and 180 DAA. The DOBI model produced the coefficient of determination (R²) of 0.7116. The value of DOBI is at maximum when the FFB reach 180 DAA. The model obtains strong relationship, and can be used to predict the DOBI value of a FFB.

The Carotene content is expressed as ppm of beta-carotene and it is calculated with an appropriate mathematical correlation with absorbance at 446 nm. The quality of palm oil is determined by several factors. One important parameter is its carotene content, which is dependent on the quality of the fruit, as well as its ripeness. The Carotene content is another key quality parameter, with greater values representing better quality.

The carotene in oil palm mainly consists of beta carotene. Beta carotene is a precursor of Vitamin A. Human body needs the substance, in the form of Vitamin A after being converted by the metabolism process. Beta carotene is an antioxidant and reduces the risk of cognitive decline. In addition, consuming beta carotene will improve the health of skin and mucus membrane, promote the immune systems and produce good eye health and vision. Other studies suggest beta carotene can protect the human body from free radicals, and lower the risk of developing cancer and heart disease.

The Carotene value in FFB was increasing according to fruit age. The relationship between FFB age and its Carotene, can be regressed with multiple-regression, presented in Eq. 16.

\[
\text{Carotene} = -0.1953x^2 + 61.681x - 4424.8 \quad (16)
\]

The x represent the age of FFB, between 120 and 180 DAA. The Carotene model produced the coefficient of determination (R²) of 0.3162. The value of Carotene is at maximum when the FFB reach 158 DAA.

The quality of palm oil is closely related to the moisture content (MC) in the fruits. When the oil palm fruit is ripening, the oil content reaches the maximum, but the MC reaches the minimum (approx 30%) in the fruit [16], [17]. Therefore, the close relationship between the moisture and oil contents in the mesocarp [18] gives a possibility of using the ratio of both component as a parameter to gauge the FFB ripeness [19] and the harvesting time [20].

The ratio of the oil content and moisture content in the fruit mesocarp according to FFB age was presented in figure 1g. The relationship can be explained by multiple-regression, as presented in Eq. 17.

\[
\frac{OC}{MC} = -0.001x^2 + 0.3073x - 22.615 \quad (17)
\]

The x represent the age of FFB, between 120 and 180 DAA. The ratio of oil content and moisture content model produced the coefficient of determination (R²) of 0.8938. The value of ratio of oil content and moisture content is at maximum when the FFB reach 158 DAA.
Figure 1. Correlation Value of Temperature to Quality Parameters (a) color features (b) surface temperature (c) Oil content (d) Moisture Content (e) DOBI (f) Carotene (g) Oil and Moisture Ratio

To understand the relationship between FFB thermal and optical features with the fruit’s quality parameters, multiple-regression models were developed [21], as presented in Figure 2. First, the moisture content (MC) of FFB samples was regressed to FFB surface temperature (T) (figure 2a), and FFB optical spectrum (figure 2b). The relationship between T and MC was explained by a model where MC = -0.0028x^3 + 1.2404x^2 - 176.8x + 8363.7

\[ R^2 = 0.4671 \]

G max at 165 DAA

\[ y = -0.0025x^3 + 1.075x^2 - 151.44x + 7094.7 \]

\[ R^2 = 0.5155 \]

G max at 165 DAA

\[ y = -0.0022x^3 + 0.9237x^2 - 128.38x + 5938.5 \]

\[ R^2 = 0.4549 \]

B max at 165 DAA

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

\[ R^2 = 0.8344 \]

22 23 24 25 26 27

120 130 140 150 160 170 180

FFB Age (Day After Anthesis)

\[ y = 0.0249x^2 - 8.2699x + 713.31 \]

\[ R^2 = 0.9647 \]

Min at 166 DAA

\[ y = -0.01x^2 + 3.1322x - 219.55 \]

\[ R^2 = 0.8116 \]

Max at 156 DAA

\[ y = -0.0006x^2 + 0.2227x - 16.795 \]

\[ R^2 = 0.7116 \]

Max at 180 DAA

\[ y = -0.001x^2 + 0.3073x - 22.615 \]

\[ R^2 = 0.8938 \]

Optimum at 158 DAA

\[ y = 0.1953x^2 + 61.681x - 4424.8 \]

\[ R^2 = 0.3162 \]

Max at 158 DAA

\[ y = -0.001x^2 + 0.3073x - 22.615 \]

\[ R^2 = 0.8938 \]

Optimum at 158 DAA

\[ y = 0.0249x^2 - 8.2699x + 713.31 \]

\[ R^2 = 0.9647 \]

Min at 166 DAA

\[ y = -0.01x^2 + 3.1322x - 219.55 \]

\[ R^2 = 0.8116 \]

Max at 156 DAA

\[ y = -0.0006x^2 + 0.2227x - 16.795 \]

\[ R^2 = 0.7116 \]

Max at 180 DAA

\[ y = -0.001x^2 + 0.3073x - 22.615 \]

\[ R^2 = 0.8938 \]

Optimum at 158 DAA

\[ y = 0.1953x^2 + 61.681x - 4424.8 \]

\[ R^2 = 0.3162 \]

Max at 158 DAA

\[ y = -0.001x^2 + 0.3073x - 22.615 \]

\[ R^2 = 0.8938 \]

Optimum at 158 DAA
1.8389T^2 + 91.529T - 1084.8. The model produced coefficient of determination \( R^2 \) of 0.2039. The model correlation was less than 0.5. Hence in the statistical term, the goodness of fit of this model cannot fully produce prediction approximate the real MC data. In comparison, the relationship between FFB spectrum (R, G, and B) and MC can be model by a linear regression. From three FFB spectrum (R, G, and B), only redness (R) was producing higher coefficient of determination \( R^2 \) of 0.2898. The MC can be determined by this model according to Eq. 18.

\[
MC = -0.279(R) + 80
\]

Both model fail to delivered desireable result. However, the study proofs that FFB moisture content can be predicted by observing the temperature or the color of mesocarp, although with limited accuracy.

Next, the oil content (OC) of FFB samples was regressed to FFB surface temperature (T) (figure 2c), and FFB spectrum (figure 2d). The relationship between T and OC was explained by a model where OC = 0.5092T^2 - 25.392T + 333.91. The model produced coefficient of determination \( R^2 \) of 0.2185. The model correlation was less than 0.5. Hence in the statistical term, the goodness of fit of this model cannot fully produce prediction approximate the real OC data. In comparison, the relationship between FFB spectrum (R, G, and B) and OC can be model by a linear regression. From three FFB spectrum (R, G, and B), only bluish (B) was producing higher coefficient of determination \( R^2 \) of 0.1363. The OC can be determined by this model according to Eq. 19.

\[
OC = 0.0501(B) + 12.845
\]

Both model fail to delivered desireable result. However, the study proofs that FFB oil content can be predicted by observing the temperature or the color of mesocarp, although with some degree of accuracy.

Moreover, The DOBI value of FFB samples was regressed to FFB surface temperature (T) (figure 2e), and FFB spectrum (figure 2f). The relationship between T and DOBI was explained by a model where DOBI = 0.0663T^2 - 3.3421T + 43.889. The model produced coefficient of determination \( R^2 \) of 0.093. The model correlation was less than 0.5. Hence in the statistical term, the goodness of fit of this model cannot fully produce prediction approximate the real DOBI data. In comparison, the relationship between FFB spectrum (R, G, and B) and DOBI can be model by a multiple-regression. From three FFB spectrum (R, G, and B), only bluish (B) was producing higher coefficient of determination \( R^2 \) of 0.3735. The DOBI can be determined by this model according to Eq. 20.

\[
DOBI = -0.0003(B)^2 + 0.0796(B) - 3.1647
\]

Again, both model fail to delivered desireable result. However, the study proofs that FFB DOBI can be predicted by observing the temperature or the color of mesocarp, although with some degree of accuracy.

In contrast, when the Carotene content of FFB samples was regressed to FFB surface temperature (T) (figure 2g), and FFB spectrum (figure 2h) the models produce a mix result. The relationship between T and Carotene was explained by a model where:

\[
Carotene = 9.3632T^5 - 1201.7T^4 + 61521T^3 - 2E+06T^2 + 2E+07T - 1E+08
\]

The model produced a high coefficient of determination \( R^2 \) of 0.8122. The model correlation was strong, and in the statistical term, the goodness of fit of this model can be considered to fully produce prediction approximate of the real Carotene data. However, when the relationship between FFB spectrum (R, G, and B) and Carotene was modeled by a multiple-regression, the result was less performing. Of three FFB spectrum (R, G, and B), only greenish (G) was producing highest coefficient of determination \( R^2 \) of 0.1793. The Carotene can be determined by this model according to Eq. 22.

\[
Carotene = 0.0015(G)^3 - 0.6139(G)^2 + 78.573(G) - 2743.7
\]

Based on the performance of both model (Eq. 21 and Eq. 22), FFB surface temperature can be used to properly predict the carotene content of the samples. Whereas, FFB color is not fully suitable to be use as independent variable for estimating the FFB carotene content.
(a) $y = -1.8389x^2 + 91.529x - 1084.8$
$R^2 = 0.2039$

(b) $y = -0.279x + 80$
$R^2 = 0.2898$

(c) $y = 0.5092x^2 - 25.392x + 333.91$
$R^2 = 0.2185$

(d) $y = 0.0501x + 12.845$
$R^2 = 0.1363$

(e) $y = 0.0663x^2 - 3.3421x + 43.889$
$R^2 = 0.093$

(f) $y = 9.3632x^5 - 1201.7x^4 + 61521x^3 - 2E+06x^2 + 2E+07x - 1E+08$
$R^2 = 0.8122$

(g) $y = -6E-07x^3 + 0.0002x^2 - 0.0211x + 0.9714$
$R^2 = 0.2723$

(h) $y = 0.0015x^3 - 0.6139x^2 + 78.573x - 2743.7$
$R^2 = 0.1793$

(i) $y = 0.0663x^2 - 3.3421x + 43.889$
$R^2 = 0.093$

(j) $y = 0.2064x - 4.0487$
$R^2 = 0.6732$
In addition, when the ratio of oil content and moisture content of FFB samples was regressed to FFB surface temperature (T) (figure 2i), and FFB spectrum (figure 2j) the later produce less promising result. Temperature of an object is depending on its thermal capacity. Reduction of water composition in a product will affect its behavior when exposed to external energy. The phenomenon was observed in this study. The relationship between T and ratio of oil and moisture content was explained by a model where:

\[
\frac{OC}{MC} = 0.2064T - 4.0487
\]  

(23)

The model produced a high coefficient of determination (R²) of 0.6732. The model correlation was strong, and in the statistical term, the goodness of fit of this model can be considered to fully produce prediction approximate of the real \( \frac{OC}{MC} \) data. However, when the relationship between FFB spectrum (R, G, and B) and \( \frac{OC}{MC} \) was modeled by a multiple-regression, the result was poor. Of three FFB spectrum (R, G, and B), only redness (R) was producing highest coefficient of determination (R²) of 0.2723. The \( \frac{OC}{MC} \) can be determined by this model according to Eq. 24.

\[
\frac{OC}{MC} = -6E-07(R^3) + 0.0002(R^2) - 0.0211(R) + 0.9714
\]  

(24)

Based on the performance of both model (Eq. 23 and Eq. 24), FFB surface temperature can be used to properly predict the \( \frac{OC}{MC} \) of the samples. The result suggest, FFB color is not fully suitable to be used as independent variable for estimating the FFB \( \frac{OC}{MC} \).

4. Conclusion

In this study the thermal and optical features of oil palm FFB were used to model optimum harvest window prediction. The study employed the use of hybrid-camera which can observe the FFB in multispectral-regime. Models were developed to explain the relationship of fruit appearance and thermal capacity with various parameters such as ripeness, moisture and oil content, DOBI, carotene, and ratio of oil and moisture. Linear and multiple-regression were used to develop the model.

FFB ripeness can be modeled according to its surface temperature (T) and Green spectrum (G) with model performance (R²) of 0.8344 and 0.5155 respectively. The optimum harvest window for FFB was established based on these models. The FFB is best harvested when the fruits age was between 156 DAA and 166 DAA. Furthermore, models to predict FFB quality based on its surface temperature and color spectrum were established. The surface temperature of FFB, can be used to develop models for predicting FFB carotene content, as well as the ratio of oil and moisture in fruits mesocarp. The models produce R² of 0.8122 and 0.6732. Nonetheless, both thermal and optical properties of FFB did not have strong relationship for modeling one FFB quality parameter, DOBI. The best model for DOBI prediction was by employing the blueish spectrum of FFB. Yet, the model only obtained R² of 0.3735.

Since most of FFB harvest and quality parameters can be predicted by this study, it opens the opportunity to introduce the method of harvest prediction in oil palm plantation. Moreover, the prototype develop in this study was able to better identify changes in FFB physical and thermal characteristics upon maturation and ripening. Harvest errors can be reduced by using this tool to minimize the potential economic losses from oil palm plantations. The output of this study can be used to design a similar system for other plantation commodities. In conclusion, 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.
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