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ORIGINAL PAPER

# Development of a method for measuring oil content in oil palm mesocarp using a single-outlet piston press: a feasibility study

**Tanakorn Tantanawat[1] · Siwaporn Srimongkol[1] · Rattanapon Yuttawiriya[1] · Arkom Haewchin[1] · Tongpool Sangkapes[1] · Ekkachart Hattha[1]**

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**Abstract**
In this paper, we proposed a mechanical extraction method using a newly designed single-outlet piston press for measuring oil content in oil palm mesocarp. The aim of this study was to evaluate the feasibility of the proposed method, which was expected to help facilitate and fulfill the development of other methods for assessing oil palm ripeness and, in some scenarios, to be directly used at oil palm trading sites. The six steps of the proposed method include sampling, drying, shredding, digesting, pressing, and interpreting. A prototype of a single-outlet piston press was constructed and integrated with other equipment to form a prototype of a measurement system. The effects of two factors, including bunch zone and sample form, were studied. Bunch zones were equatorial zone and apical zone, while sample forms were chopped mesocarp and capillaceous mesocarp. A full factorial design of experiments having four treatments was used in the study. For each treatment, we established a calibration equation that related the oil content measured by using the proposed method to the oil content measured by using a standard soxhlet extraction method. The study revealed that only the factor of sample form significantly affected the calibration equation. It suggested that higher measurement precision could be achieved by using capillaceous mesocarp. In this case, the maximum standard deviation of the predicted oil content within the range of predicted value from 50 to 82% was calculated to be 2.66%, which was approximately 3.2% of the maximum predicted value in the studied range.

**Keywords** Oil content · Oil palm · Quality · Ripeness · Mesocarp

## Introduction

Ripeness of oil palm fresh fruit bunches (FFB) is an important quality factor affecting not only the production cost of palm oil mills but also the productivity of the overall palm oil supply chain. It may be defined as the accumulation of oil in a single fruit, and thus in a whole bunch [1]. Assessing and controlling FFB ripeness may be performed either before or after harvesting. After being harvested, FFBs are sold to palm oil mills, either directly or indirectly through collecting centers. At trading sites, even though FFB price is based on ripeness, FFB producers usually give priority to the weight, rather than the ripeness, of FFBs being sold each lot. One of the reasons is because weight is measured by standard equipment, while ripeness, though standard guidelines exist, is evaluated roughly and subjectively by human. Controlling the ripeness of FFBs becomes even more difficult for cases when FFBs are from estates not sharing proprietorship with palm oil mills [2]. The lack of objective assessment for FFB ripeness has been keeping palm oil industry away from the maximum possible productivity, especially for cases when majority of FFB producers are independent smallholders.

Various techniques for evaluating FFB ripeness, as well as automatic FFB grading systems, have been proposed and studied. Most of them, if not all, are non-destructive evaluation (NDE), in comparison to their soxhlet extraction method counterpart [3], which is standard but destructive, time consuming, and, therefore, not practical for FFB trading. While a soxhlet extraction method measures oil content in oil palm mesocarp directly, NDE techniques measure oil content indirectly based on datasets containing pairs of device signals

✉ Siwaporn Srimongkol
siwapors@mtec.or.th

[1] National Metal and Materials Technology Center (MTEC), National Science and Technology Development Agency (NSTDA), 114 Thailand Science Park, Paholyothin Road, Khlong Nueng, Khlong Luang, Pathum Thani 12120, Thailand

and oil content. Therefore, the quality of database used in the evaluation system to interpret the signals obtained from devices will influence the performance and applicability of the system.

Among major classes of techniques, optical methods have been widely studied. In this class of techniques, FFB ripeness evaluation based on machine color vision is the most popular one [4–10]. Methods based on color vision, however, encounter practical problems when fruit damages or inconsistent light sources are present [11]. In addition, oil palms of different types identified by *VIRESCENS* gene exhibit different color changing behaviours upon ripening [12], making it unreliable to use a color vision system. Other optical methods such as near infrared (NIR) and ultraviolet (UV) are also promising [13, 14]. They, however, require frequent calibration, high initial cost, and high maintenance cost [15]. For NIR technique, it is difficult to differentiate ripeness stages of *oleifera* type of oil palms [16]. In addition, the measurement is affected by the tilting angle of camera and the distance of the bunch from camera [17], adding complication to the system in order to overcome the problem. The UV technique, on the other hand, is sensitive to sunlight, which causes alteration to the measurement [15]. Other optical methods including fluorescence [11] and laser light [18] were also investigated, but the systems were not very economical. All these limitations make it difficult, though not impossible, to implement optical methods for FFB trading. Mohd Hazir and Mohamed Shariff [9] emphasized that developing a database of optical characteristics for various types of oil palms was a key to improve the accuracy and efficiency of FFB grading systems.

For non-optical methods, techniques based on nuclear magnetic resonance (NMR) [19, 20] were studied. Junaidah demonstrated that NMR technique could provide very accurate and reliable measurement, which could replace standard soxhlet extraction method in laboratory to avoid concerns about toxicity from chemicals. The lengthy sample preparation and the high cost of devices, however, prevent this technique from being used for FFB trading. Besides NMR, some researchers explored techniques based on capacitance [21], inductance [22], microwave [23, 24], and ultrasonic [25]. The results showed that the proposed techniques had potential for the applications in FFB ripeness evaluation, but some practical issues and limitations needed to be addressed.

All mentioned NDE techniques have high potential for rapid and convenient assessment of FFB ripeness. Aside from an issue about a system cost that some techniques may have, they all require database, which are constructed either from oil content in mesocarp measured by a standard soxhlet extraction method or from ripeness stages classified by human judgement. Training a system to classify FFB ripeness stages based on human judgement is an inexpensive and practical approach, but the system will achieve the measurement resolution at most as high as that obtained by human grading. This is considered as an underutilization of measurement devices. On the other hand, calibrating a system with oil content measured by soxhlet extraction method is costly and time-consuming, which limits the amount of calibration data when budget is limited. This system, possibly with insufficient or inappropriate calibration data, therefore, is not reliable in situations when FFBs of various types are present. The problem related to database may be one of the factors preventing widespread use of the mentioned NDE techniques, while a system cost is another factor.

Due to a reliability problem for low-cost NDE systems and a budget problem for high-cost NDE and soxhlet extraction systems, a mechanical extraction method using a single-outlet piston press for measuring oil content in oil palm mesocarp sample was proposed. This method can be used for two different objectives. One is to support the development of NDE techniques. Since the proposed method is more economical than a standard soxhlet extraction method, it allows more quantitative datasets to be obtained and added to database during the development of NDE techniques, thus improving the quality and utilizing full potential of NDE systems. The other objective of using the proposed method is to directly use it at FFB trading sites for assessing FFB ripeness. This is an alternative solution for cases when budget is a limiting factor, especially for some small FFB collecting centers and palm oil mills. The proposed method is expected to help promote objective FFB grading even when facing with budget constraint. Although the concept of mechanical extraction is common in production scale, it has never been demonstrated for its preciseness and practicality for a grading purpose. This work was, therefore, to prove the concept and evaluate the feasibility of the proposed method.

## Materials and methods

### Prototype of a mesocarp collector

Since the proposed method is based on mechanical extraction, mesocarp samples are required for the measurement. In order for the method to be practical, a simple mesocarp collector shown in Fig. 1 was designed and built. As seen from Fig. 2, this mesocarp collector provides a quick and easy-to-use interface between FFBs and the measurement process being developed. By piercing a palm fruit with the mesocarp collector, a piece of sampled mesocarp can be obtained in the form of cylindrical shape as shown in Fig. 3, which is ready for further processing.

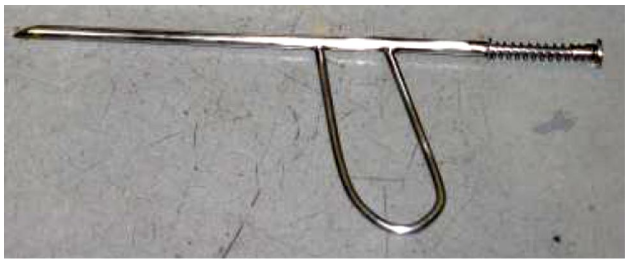

**Fig. 1** A prototype of a mesocarp collector

**Fig. 2** Piercing a palm fruit with the mesocarp collector

**Fig. 3** Sampled mesocarp obtained in the form of cylindrical shape

## Prototype of a single-outlet piston press

A newly designed single-outlet piston press as shown in Figs. 4 and 5 is the result of attempts to recover the oil in mesocarp samples as much as possible while minimizing the required amount of samples. The press consists of a

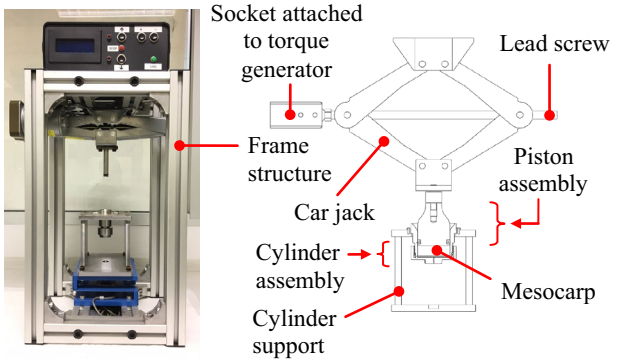


**Fig. 4** Overall structure of a single-outlet piston press

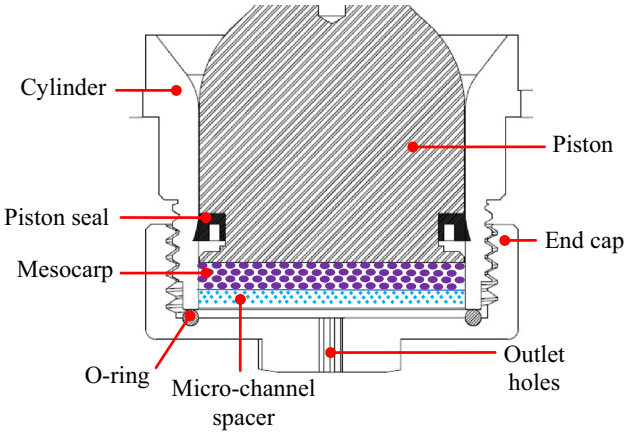


**Fig. 5** Components of a piston assembly and a cylinder assembly

frame structure, a car jack, a piston assembly, a cylinder assembly, and a cylinder support. The frame structure holds the cylinder support on the bottom and holds the car jack on the top. The end of the car jack is attached with the piston, while the cylinder with the end cap screwed from underneath sits on the cylinder support. The microchannel spacer, a specially selected wire mesh whose functions include both allowing radial flow of oil and filtering solids when subjected to high compression, sits on the top of the end cap inside the cylinder. A sample of oil palm mesocarp is put in the cylinder between the piston and the microchannel spacer. The end cap is removable for changing the sample, replacing microchannel spacer, and cleaning the cylinder. O-ring is installed between the end cap and the cylinder, while the piston seal is installed between the piston and the cylinder to prevent oil leakage at component interfaces. Compression on the sample is generated by turning a lead screw of a car jack, by using either a torque wrench or a motor with a force controller.

## Prototype of a measurement system

The concepts of a mechanical extraction method for measuring oil content in oil palm mesocarp started with the principles of the processes used in palm oil mills. Key steps were identified to be sterilization, digestion, extraction, and clarification. After oil is extracted from mesocarp samples, oil content can be calculated as a percentage. However, since most of the processes used in production scale are of wet type where steam is injected into the system during sterilization, steps for removing water from oil are required, making the overall process complicated and difficult to scale down for the purpose of sample measurement. The well-known existing processes, therefore, had to be redesigned so that no water was injected into the system. The goal was to reduce the number of steps as much as possible. In addition, the process must run in a batch mode for the purpose of measurement, in contrast to a continuous mode for the purpose of large scale production. The greatest challenge is to reduce the required amount of each sample as much as possible to minimize the destructive effect of mesocarp sampling while keeping measurement variation as small as possible.

Based on the proposed concepts, the prototypes of mesocarp collector and single-outlet piston press, along with commercial integrated to form measurement processes based on mechanical extraction (see Fig. 6). Different variations of the processes were designed and a few runs of ad hoc testing were performed. Some possible processes sharing common steps were obtained as shown in Fig. 7. All of them consist of sampling, drying, transforming, digesting, pressing, and interpreting, arranged exactly in this order. Each process had details different from others, which were described by two factors including the bunch zone for collecting samples and the form of mesocarp used for pressing. The bunch zone, which may affect the ripeness uniformity of the samples, and

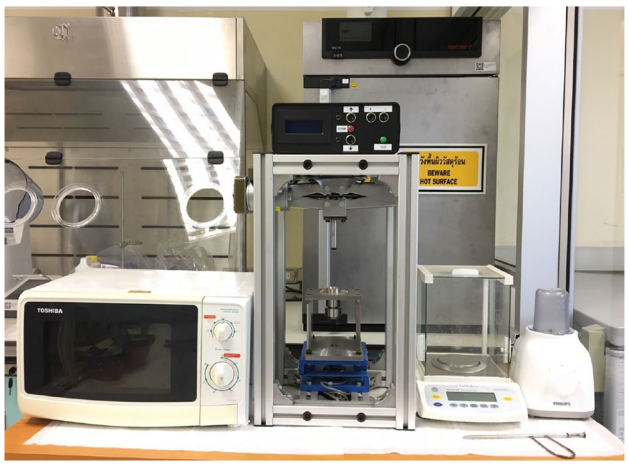

**Fig. 6** Equipment of measurement processes

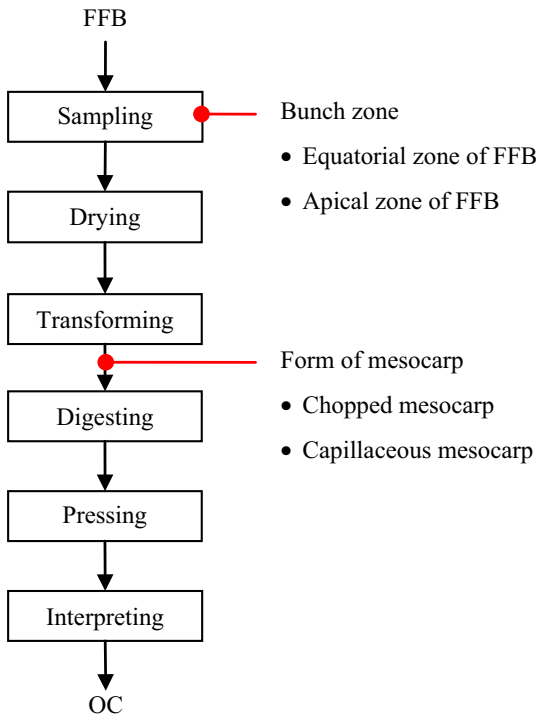


**Fig. 7** Common steps and possible variations of process design

hence measurement variation, could be equatorial zone or apical zone, while the form of mesocarp, which may affect the amount of extracted oil, could be chopped mesocarp or capillaceous mesocarp. These two factors, which may affect the measurement performance, were systematically studied and the results are presented in the following sections.

## Design of experiments

The experiments were planned based on a full factorial design. Because there were two factors, each having two levels, the experiments consisted of four treatments whose levels of the factors are shown in Table 1. For each treatment, the values of oil content from nine FFBs of various ripeness stages were measured using the proposed mechanical extraction method and a standard soxhlet extraction method. A calibration curve for the two methods was obtained using

**Table 1** Experimental plan based on a full factorial design of experiments

| Treatment | Factor | |
|---|---|---|
| | Bunch zone | Mesocarp form |
| Tr. 1 | Equatorial zone | Chopped mesocarp |
| Tr. 2 | Apical zone | Chopped mesocarp |
| Tr. 3 | Equatorial zone | Capillaceous mesocarp |
| Tr. 4 | Apical zone | Capillaceous mesocarp |

a linear regression model and a standard error of estimate (*SEE*) [26], which was a dependent variable of the experiments, was calculated. Because the objective of the experiments was to evaluate the feasibility of the proposed method and the resources were limited, only one repeat of calibration curve was done for each treatment. Each zone in each FFB was, however, split into three samples whose values of oil content were measured independently, thus giving three repeats of measurement.

Due to the limitation of the blender used in these experiments, the whole fruits had to be used to obtain capillaceous mesocarp and thus the fruits had to be sampled out of FFBs before mesocarp was taken from the fruit samples. The experimental procedure, therefore, had to be adjusted, which made it slightly different from the process designed. The factors being investigated (i.e. bunch zone and mesocarp form), however, were strictly kept as specified in the design of experiments. In order to minimize the effects of sample variation, fruit samples were taken from FFBs according to the sampling plan described in the next section. The experiments then proceeded through the experimental procedure shown in Fig. 8. All measured values of oil content, taking into account residual oil remaining in a mesocarp container, were calculated based on dry basis [27] according Eq. 1.

$$OC = \frac{W_{extracted\_oil} + W_{residual\_oil}}{W_{dried\_mesocarp}} \times 100 \quad (1)$$

where $OC$ is dried-basis percentage of oil content in mesocarp, $W_{extracted\_oil}$ is weight of oil extracted by pressing mesocarp sample, $W_{residual\_oil}$ is weight of oil remaining in mesocarp container and $W_{dried\_mesocarp}$ is weight of dried mesocarp sample before extraction.

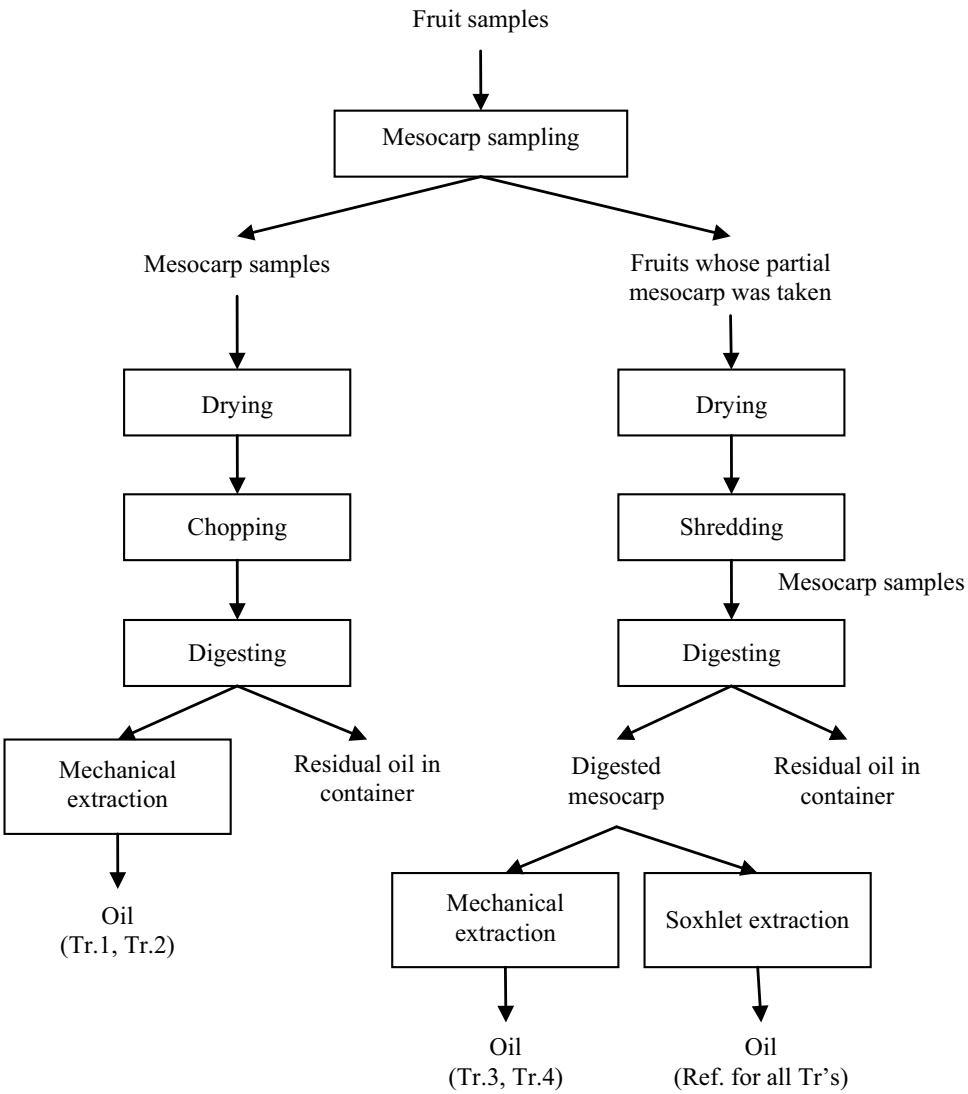


**Fig. 8** Experimental procedure used to run the design of experiments consisting of four treatments

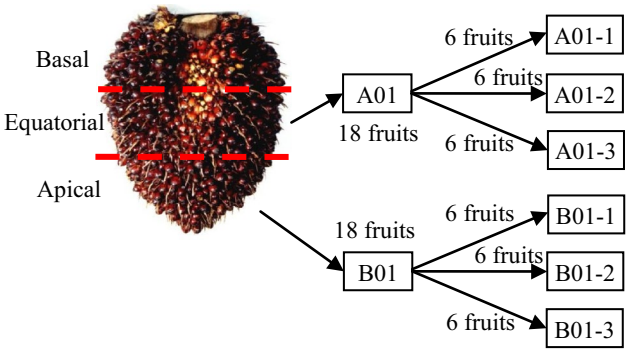


**Fig. 9** Sampling procedure and sample naming convention for each FFB

### Sampling plan

Each FFB was split into three zones: basal, equatorial, and apical, as shown in Fig. 9. Fruits from different zones were separated and fruits from the same zone of each FFB were mixed thoroughly. 18 fruits were then randomly chosen from the equatorial zone (labelled A) and the apical zone (labelled B). Fruits from each zone were then split into three fruit samples to represent three repeats. This sampling procedure was repeated for all nine FFBs, giving the total of 54 fruit samples. Each fruit sample then undertook the experimental procedure shown in Fig. 6.

### Mechanical extraction for chopped mesocarp

For Treatment 1 and Treatment 2, mesocarp samples were taken from fruit samples by using the mesocarp collector. Each mesocarp sample was laid on a Petri dish, which was used as a mesocarp container, and then dried in a microwave oven set to 800 W for 7 min. The dried mesocarp sample was chopped to have approximately 0.5 cm in length as can be seen from Fig. 10. About 2.5 g of chopped mesocarp sample was then digested in a microwave oven set to 800 W for 2 min and then immediately pressed it by the single-outlet piston press. A torque wrench was used to control the maximum applied torque of 20.3 N m. A small tube was used to receive the extracted oil. Oil content evaluated by this mechanical extraction process was calculated from Eq. 2.

$$OC = \frac{\left(W_{TC} - W_T\right) + \left(W_{DC} - W_D\right)}{W_P} \times 100 \quad (2)$$

where $OC_M$ is dried-basis percentage of oil content measured by mechanical extraction, $W_{TC}$ is weight of extracted oil including its container (tube), $W_T$ is weight of oil container (tube), $W_{DC}$ is weight of residual oil including its container (Petri dish), $W_D$ is weight of mesocarp container (Petri dish) and $W_P$ is weight of dried mesocarp sample before extraction.

**Fig. 10** A chopped mesocarp sample having approximately 0.5 cm in length

### Mechanical extraction for capillaceous mesocarp

For Treatment 3 and Treatment 4, fruit samples whose some mesocarp was already taken were put in aluminium cans and then dried in a hot air oven set to 100 °C for 24 h. Each dried fruit sample was shredded in a blender so that capillaceous mesocarp was obtained as can be seen from Fig. 11. Mesocarp remaining attached to the fruit sample had to be observed in order to stop shredding before cracking nuts. The capillaceous mesocarp of 2.5 g from each fruit sample was digested in a microwave oven set to 800 W for 2 min and then immediately pressed it by the single-outlet piston press. A torque wrench was used to control the maximum applied torque of 20.3 N m. Oil content evaluated by this mechanical extraction process was calculated from Eq. 2.

### Soxhlet extraction

For each fruit sample, after completing the procedure described in "Mechanical extraction for capillaceous mesocarp", capillaceous mesocarp of 1.5 g was taken for measuring oil content by using soxhlet extraction. In this study, an automatic soxhlet extraction system as shown in Fig. 12 was used. The solvent was n-Hexane, and the rinsing time was set to 90 min. With the available system, two samples can only be tested for each run. After the process of soxhlet extraction was completed, the samples were put in fume hood to let n-Hexane

**Fig. 11** A capillaceous mesocarp sample

**Fig. 12** An automatic soxhlet extraction system

completely evaporate. Oil content evaluated by soxhlet extraction was calculated from Eq. 3 [3].

$$OC_S = \frac{W_{BC} - W_B}{W_P} \times 100 \tag{3}$$

where $OC_S$ is dried-basis percentage of oil content measured by soxhlet extraction, $W_{BC}$ is weight of extracted oil including its container (beaker) and boiling chips, $W_B$ is weight of oil container (beaker) including boiling chips, and $W_P$ is weight of dried mesocrp sample before extraction.

## Results and discussion

### Regression analysis of original data (with outliers)

The values of oil content obtained from mechanical extraction having conditions specified in each treatment were plotted against those obtained from soxhlet extraction. Because statistical regression assumes that a measurement error of independent variable is negligible, the measured values from soxhlet extraction were plotted on x-axis and those from mechanical extraction were plotted on y-axis. The relationship between the two quantities was assumed to be linear, which could be represented by a regression model shown in Eq. 4.

$$OC_M = a \cdot OC_S + b \tag{4}$$

where $OC_M$ is dried-basis percentage of oil content measured by mechanical extraction, $OC_S$ is dried-basis percentage of oil content measured by soxhlet extraction, $a$ is model parameter (slope) estimated from the data, $b$ is model parameter (intercept) estimated from the data.

The model parameter $a$ and $b$ were estimated by applying a linear least squares method on the data obtained from each treatment, giving a calibration equation. The data points, along with the corresponding calibration equations, correlation coefficients ($r$), and standard errors of estimate ($SEE$), are shown in Figs. 13, 14, 15 and 16.

### Regression analysis of data without outliers

Since the regression models are sensitive to outliers, residual analysis was performed and Tukey's fences, as mentioned

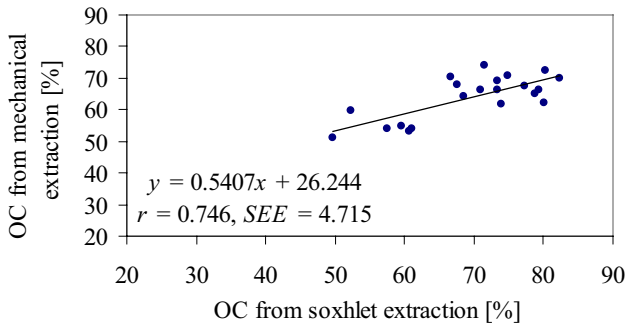


**Fig. 13** Treatment 1 (equatorial zone, chopped mesocarp)

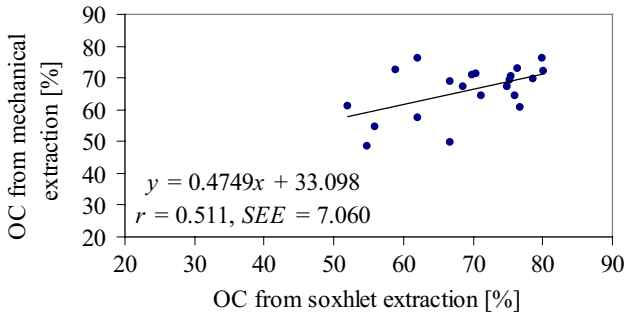


**Fig. 14** Treatment 2 (apical zone, chopped mesocarp)

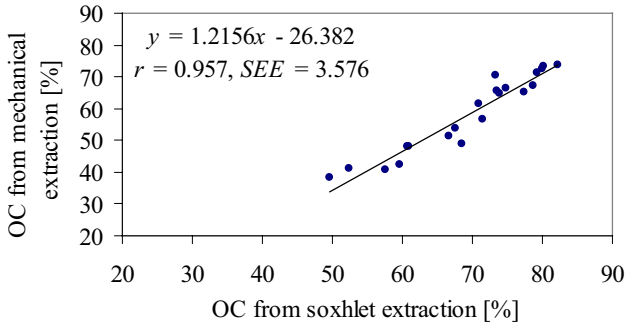


**Fig. 15** Treatment 3 (equatorial zone, capillaceous mesocarp)

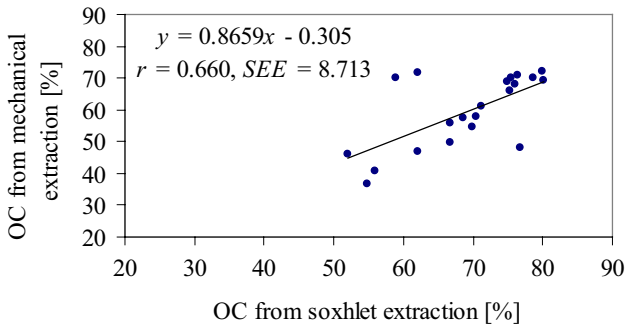


**Fig. 16** Treatment 4 (apical zone, capillaceous mesocarp)

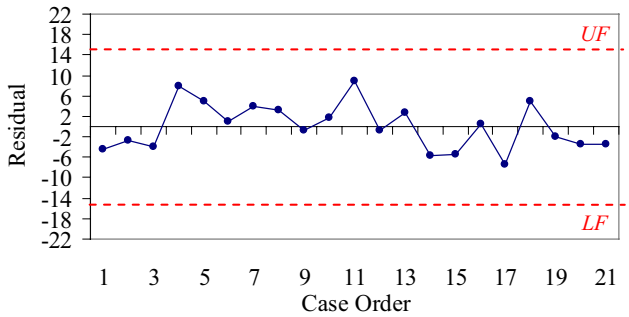


**Fig. 17** Treatment 1: $LF = -14.3041$, $UF = 14.1207$

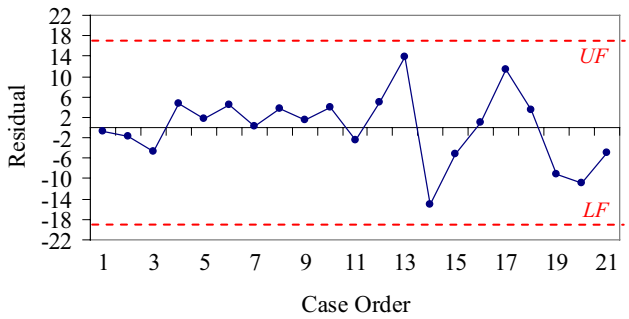


**Fig. 18** Treatment 2: $LF = -18.1368$, $UF = 17.3811$

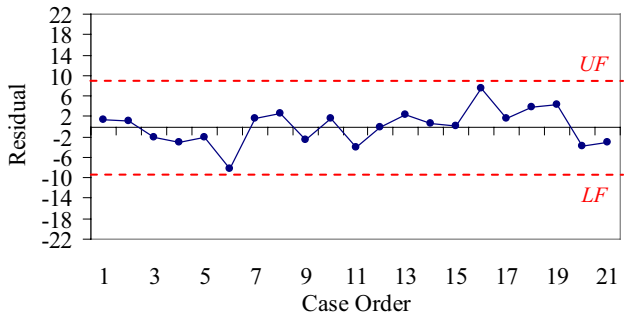


**Fig. 19** Treatment 3: $LF = -9.4036$, $UF = 8.6079$

in Schwertman and Silva [28], were applied to identify possible outliers. The lower fence (*LF*) and the upper fence (*UF*) were calculated from Eqs. 5 and 6.

$$LF = Q_1 - 1.5.IQR \tag{5}$$

$$UF = Q_3 + 1.5.IQR \tag{6}$$

where $Q_1$ is the first quartile of the residuals, $Q_3$ is the third quartile of the residuals, *IQR* is interquartile range equal to $Q_3 - Q_1$. The data points whose residuals were outside the lower and upper fences were considered as possible outliers. These possible outliers in each treatment were removed and regression analysis was performed again on the updated set of data points. The process of estimating model parameters, identifying outliers, and removing outliers repeated until all possible outliers were removed. The results revealed four possible outliers in Treatment 4. After removing these possible outliers, residual plots of all treatments with lower and upper fences are shown in Figs. 17, 18, 19 and 20, confirming that all possible outliers have been removed.

The data points of Treatment 4, along with the corresponding calibration equation, are plotted as shown in Fig. 21. The correlation coefficients (*r*) and standard errors of estimate (*SEE*) of four treatments without outliers are shown in Figs. 22 and 23.

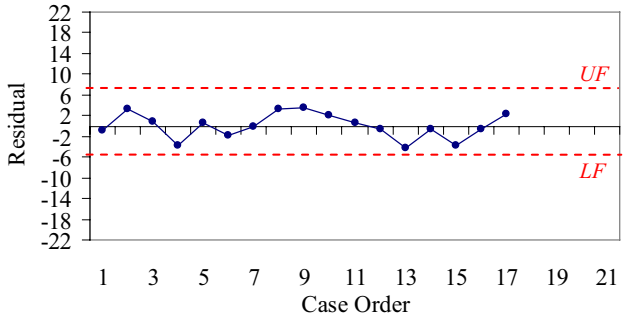


**Fig. 20** Treatment 4: $LF = -5.653$, $UF = 6.695$

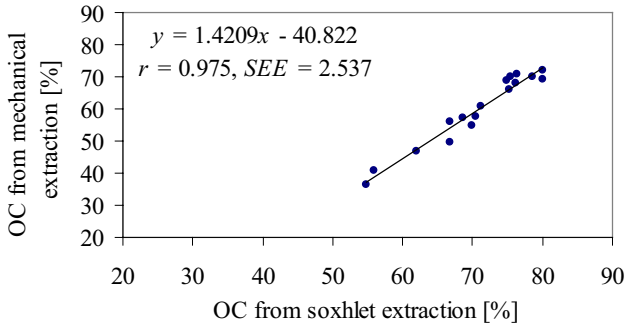


**Fig. 21** Treatment 4 without four possible outliers

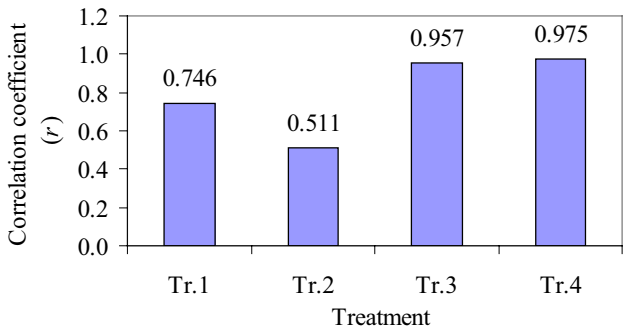


**Fig. 22** Comparison of correlation coefficients from all treatments without outliers

## Tests of differences in calibration equations

The effects of the factors being investigated (bunch zone and mesocarp form) on a calibration equation were assessed by statistical tests. In this study, the tests of difference in correlation coefficients ($r$) were performed using available online software [29], while the tests of difference in model parameters $a$ (Slope) and $b$ (Intercept) were performed based on the method explained by Frost [30]. Since each test could only be applied to compare a pair of calibration equations,

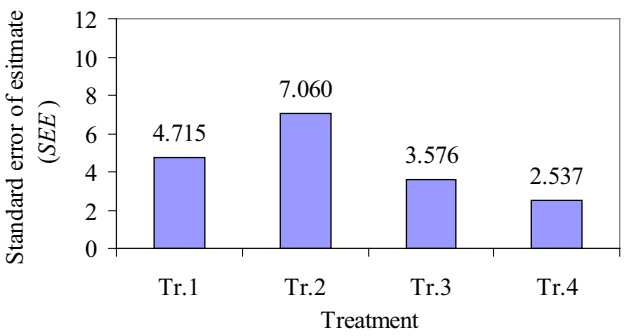


**Fig. 23** Comparison of standard errors of estimate from all treatments without outliers

six pairs of calibration equations derived from the combination of four treatments were tested. The results of testing the difference in correlation coefficients are shown in Table 2, while the results of testing the difference in model parameters $a$ and $b$ are shown in Tables 3 and 4, respectively.

It is seen from the results that four pairs of calibration equations, including Tr.1/Tr.3, Tr.1/Tr.4, Tr.2/Tr.3, and Tr.2/Tr.4, have significant differences in correlation coefficients, model parameter $a$, and model parameter $b$ (p values are less than 0.05). On the other hand, two pairs of calibration equations, including Tr.1/Tr.2 and Tr.3/Tr.4, were not found to have any significant differences regarding correlation coefficients, model parameter $a$, and model parameter $b$. The effects of two factors (bunch zone and mesocarp form) on a calibration equation, therefore, can be depicted as shown in Fig. 24 where arrows represent differences in calibration equations between a pair of treatments. The results imply that the mesocarp form has significant effects on a calibration equation, while the bunch zone does not.

## Regression analysis of combined bunch zones

To investigate the relationship between oil content measured from mechanical extraction and oil content measured from soxhlet extraction without differentiating the bunch zones of collected mesocarp samples, the original data from Treatment 1 and Treatment 2 were combined to give data for Treatment A (chopped mesocarp), while the original data from Treatment 3 and Treatment 4 were combined to give data for Treatment B (capillaceous mesocarp). Possible outliers were then checked and removed again using Tukey's fences. The results revealed four possible outliers in Treatment B. After removing these possible outliers, the residual plots of data points from Treatment A and Treatment B, along with the upper and the lower fences, are shown in Figs. 25 and 26, respectively, confirming that all possible outliers have been removed.

**Table 2** Results of testing the difference in correlation coefficients ($r$)

| Equation pairs | A<br>B | Tr. 1<br>Tr. 2 | Tr. 1<br>Tr. 3 | Tr. 1<br>Tr. 4 | Tr. 2<br>Tr. 3 | Tr. 2<br>Tr. 4 | Tr. 3<br>Tr. 4 |
|---|---|---|---|---|---|---|---|
| Equation A | $r_A$ | 0.746 | 0.746 | 0.746 | 0.511 | 0.511 | 0.957 |
| | $n_A$ | 21 | 21 | 21 | 21 | 21 | 21 |
| Equation B | $r_B$ | 0.511 | 0.957 | 0.975 | 0.957 | 0.975 | 0.975 |
| | $n_B$ | 21 | 21 | 17 | 21 | 17 | 17 |
| | p value | *0.2304* | ***0.0046*** | ***0.0006*** | ***0.0001*** | ***0.0000*** | *0.4391* |

Values in italics indicate that all the p values are statistically significant

Values in bolditalic indicate that only the p values less than 0.05 are statistically significant

**Table 3** Results of testing the difference in model parameter $a$ (Slope)

| Equation pairs | A<br>B | Tr. 1<br>Tr. 2 | Tr. 1<br>Tr. 3 | Tr. 1<br>Tr. 4 | Tr. 2<br>Tr. 3 | Tr. 2<br>Tr. 4 | Tr. 3<br>Tr. 4 |
|---|---|---|---|---|---|---|---|
| Intercept | Coeff | 26.2438 | 26.2438 | 26.2438 | 33.0976 | 33.0976 | − 26.3823 |
| | p value | 0.0117 | 0.0005 | 0.0003 | 0.0023 | 0.0023 | 0.0000 |
| Input ($x$) | Coeff | 0.5407 | 0.5407 | 0.5407 | 0.4749 | 0.4749 | 1.2156 |
| | p value | 0.0005 | 0.0000 | 0.0000 | 0.0023 | 0.0022 | 0.0000 |
| *Tr* | Coeff | 6.8538 | − 52.6262 | − 67.0654 | − 59.4800 | − 73.9192 | − 14.4392 |
| | p value | 0.6435 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.1184 |
| *x·Tr* | Coeff | − 0.0658 | 0.6749 | 0.8801 | 0.7407 | 0.9459 | 0.2052 |
| | p value | *0.7560* | ***0.0000*** | ***0.0000*** | ***0.0005*** | ***0.0002*** | *0.1161* |

Values in italics indicate that all the p values are statistically significant

Values in bolditalic indicate that only the p values less than 0.05 are statistically significant

**Table 4** Results of testing the difference in model parameter $b$ (Intercept)

| Equation pairs | A<br>B | Tr. 1<br>Tr. 2 | Tr. 1<br>Tr. 3 | Tr. 1<br>Tr. 4 | Tr. 2<br>Tr. 3 | Tr. 2<br>Tr. 4 | Tr. 3<br>Tr. 4 |
|---|---|---|---|---|---|---|---|
| Intercept | Coeff | 28.3072 | 2.7866 | 5.3767 | 4.9732 | 7.8126 | − 31.2484 |
| | p value | 0.0004 | 0.6547 | 0.4588 | 0.5347 | 0.4160 | 0.0000 |
| Input ($x$) | Coeff | 0.5110 | 0.8782 | 0.8409 | 0.8814 | 0.8404 | 1.2856 |
| | p value | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| *Tr* | Coeff | 2.2925 | − 5.7116 | − 5.1516 | − 8.1239 | − 7.5499 | − 0.0014 |
| | p value | *0.2181* | ***0.0011*** | ***0.0056*** | ***0.0002*** | ***0.0015*** | *0.9989* |

Values in italics indicate that all the p values are statistically significant

Values in bolditalic indicate that only the p values less than 0.05 are statistically significant

The data points of Treatment A and Treatment B, along with the corresponding calibration equations, correlation coefficients ($r$), and standard errors of estimate *(SEE*), are plotted as shown in Figs. 27 and 28. The results show that Treatment A has a correlation coefficient of 0.611 and standard error of estimate of 5.975, while Treatment B has a correlation coefficient of 0.962 and standard error of estimate of 3.187. It can be obviously seen that Treatment A gave only moderate relationship ($0.5 < r < 0.7$) between the values of oil content obtained from mechanical extraction and those obtained from soxhlet extraction, while Treatment B gave almost perfect linear relationship ($r$ approaching 1.0). In addition, the standard error of estimate is reduced by almost a factor of two when switching from Treatment A to Treatment B. Therefore, Treatment B, which is when the form of mesocarp samples is capillaceous mesocarp, provides a higher precision of oil content measurement where the calibration equation is shown in Eq. 7.

$$OC_M = 1.2856 \cdot OC_S - 31.249 \tag{7}$$

where $OC_M$ is dried-basis percentage of oil content measured by mechanical extraction and $OC_S$ is dried-basis percentage of oil content measured by soxhlet extraction.

The results of regression statistics shown in Table 5 confirm the significance of the estimated parameters.

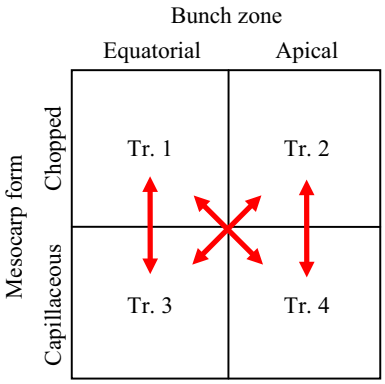


**Fig. 24** Differences in the resulting calibration equations due to the effects of bunch zone and mesocarp form

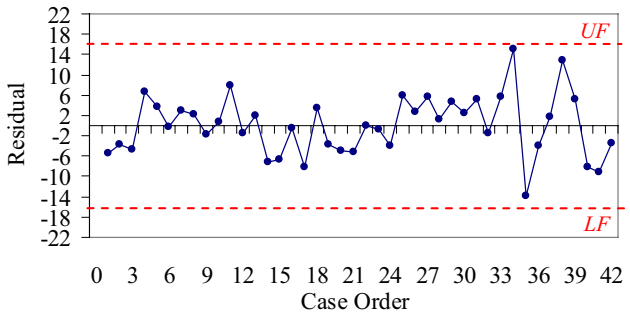


**Fig. 25** Treatment A: $LF = -15.531$, $UF = 15.426$

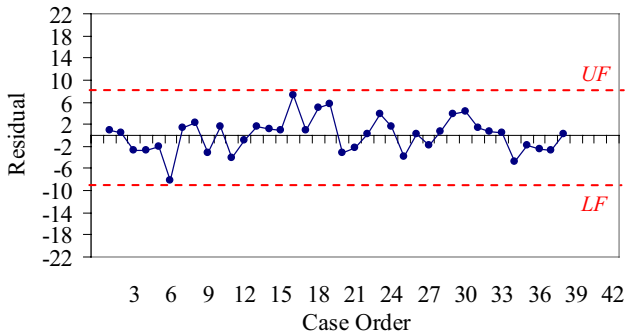


**Fig. 26** Treatment B: $LF = -8.446$, $UF = 7.437$

## Standard deviation of predicted oil content

When using the calibration equation to determine the oil content of an unknown sample, the calibration equation is used in reverse. In other words, the measured value of oil content obtained from mechanical extraction ($OC_M^*$) is substituted into Eq. 7 and the predicted value of oil content obtained from soxhlet extraction ($OC_S^*$) is solved. For the convenience of calculation, the *original calibration equation* is rearranged as shown in Eq. 8, which is referred to as a *reversed calibration equation*.

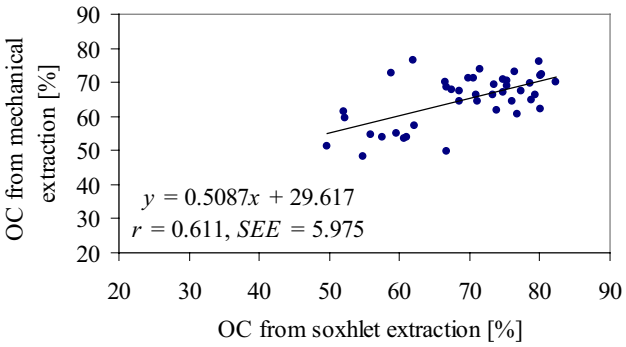


**Fig. 27** Treatment A (chopped mesocarp)

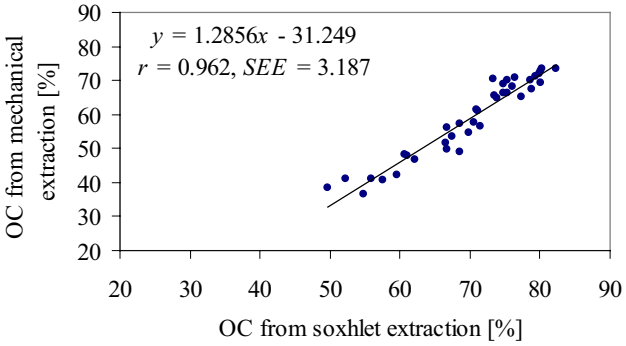


**Fig. 28** Treatment B (capillaceous mesocarp)

**Table 5** Regression statistics of treatment B

| | Estimate | SE | t stat | p value |
|---|---|---|---|---|
| *a* | 1.2856 | 0.0607 | 21.1880 | 6.4243E−22 |
| *b* | − 31.249 | 4.2834 | − 7.2952 | 1.3509E−08 |

$$OC_S^* = 0.7778 \cdot OC_M^* + 24.307 \tag{8}$$

The standard deviation of predicted value ($S_x$), also called standard deviation about regression, can be calculated from Eq. 9 [31].

$$S_x = \frac{SEE}{a}\sqrt{1 + \frac{1}{n} + \frac{\left(OC_M^* - \overline{OC_M}\right)^2}{a^2 \sum \left(OC_{S,i} - \overline{OC_S}\right)^2}} \tag{9}$$

where $S_x$ is the standard deviation of predicted oil content, *SEE* is *SEE* calculated when constructing the original calibration equation, $OC_M^*$ is $OC_M$ of unknown sample whose oil content is being measured, $\overline{OC_M}$, is average value of $OC_M$

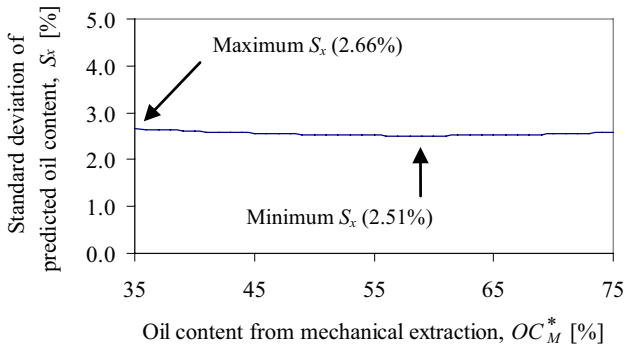


**Fig. 29** Standard deviation of predicted value as a function of measured response

used in constructing the original calibration equation, $OC_{S,i}$ is $OC_S$ of each data point used in constructing the original calibration equation, $\overline{OC_S}$ is average value of $OC_S$ used in constructing the original calibration equation, $a$ is model parameter (slope) of the original calibration equation, and $n$ is the number of data points used in constructing the original calibration equation.

In this case, $SEE$ is 3.187, $\overline{OC_M}$ is 58.85, $\overline{OC_S}$ is 70.08, $a$ is 1.2856, and $n$ is 38. The standard deviation of predicted value $S_x$, therefore, can be plotted as a function of the measured response $OC^*_M$ as shown in Fig. 29.

From the analysis, it was found that the minimum and maximum $S_S$ within the range of $OC^*_S$ from 50% to 82% ($OC^*_M$ from 35% to 75%) were 2.51% and 2.66%, respectively. The maximum standard deviation of $OC^*_S$ was calculated to be 3.2% of the maximum $OC^*_S$. In other words, the maximum standard deviation of the predicted oil content was approximately 3.2% of the maximum predicted value from 50% to 82%.

## Conclusion

In this work, the method of measuring oil content in oil palm mesocarp based on a newly designed single-outlet piston press has been demonstrated to be technically feasible. Two factors including bunch zone and sample form were investigated using a full factorial design of experiments. After removing all possible outliers, the study revealed that only sample form significantly affected the calibration equation. The best method was to use samples in the form of capillaceous mesocarp collected from either equatorial or apical zone. The calibration equation was found to be $OC_M = 1.2856 \cdot OC_S - 31.249$ whose correlation coefficient and standard error of estimate were 0.962 and 3.187, respectively. Based on this calibration equation, the reversed calibration equation can be written as $OC^*_S = 0.7778 \cdot OC^*_M + 24.307$ whose maximum standard deviation of the predicted oil content was calculated to be 2.66% within the range of predicted value from 50% to 82%, which was approximately 3.2% of the maximum predicted value in the studied range. The method proposed in this work may be used to efficiently expand the database and improve the reliability of NDE techniques for FFB ripeness assessment or to be directly implemented at FFB trading sites for FFB ripeness control. Further research should focus on obtaining more data from various types of oil palms to refine the calibration equation. In addition, equipment design is an important aspect that should receive more attention to make the method more practical.

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## Compliance with ethical standards

**Conflict of interest** Tanakorn Tantanawat declares that he has no conflict of interest. Siwaporn Srimongkol declares that she has no conflict of interest. Rattanapon Yuttawiriya declares that he has no conflict of interest. Arkom Haewchin declares that he has no conflict of interest. Tongpool Sangkapes declares that he has no conflict of interest. Ekkachart Hattha declares that he has no conflict of interest.

**Ethical approval** This article does not contain any studies with human participants or animals performed by any of the authors.

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