Analysis on Fruit Oil Content and Evaluation on Germplasm in Oil Palm

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Abstract. Fruit oil content (FOC) is one of the most important commercial traits in oil palm; however, extensive study on related traits is still limited. The present study was conducted to analyze the relationship between FOC and fruit-related traits, as well as to predict the oil palm germplasm for potential improvement. In this study, a total of 11 traits, including fruit bunch number (FBN), average fruit weight (AFW), mesocarp-to-fruit ratio (M/F), kernel-to-fruit ratio (K/F), shell-to-fruit ratio (S/F), average fruit length (AFL), average fruit width (AFWD), average shell thickness (AST), mesocarp oil content (MOC), kernel oil content (KOC), and FOC were analyzed in 39 germplasms collected from seven different countries in Asia and Africa. Different statistical analyses were conducted to evaluate the relationship between FOC and fruit-related traits. Correlation analysis showed that FOC was positively and significantly correlated with M/F, MOC, and KOC, whereas negatively and significantly correlated with S/F and AST. Likewise, path analysis indicated that M/F and MOC have high positive direct effect on FOC, whereas S/F and AST have high negative direct and indirect effects on FOC. Furthermore, regression analysis showed significant correlation between predicted and observed FOC. In conclusion, FOC was mainly determined by M/F, MOC, S/F, and AST, and the FOC prediction in this study was reliable for germplasm evaluation. In addition, G39 (Tenera) and G2 (Parthenocarpy) have the highest FOC with 58.62% and 57.68%, respectively, indicating that they might be potential candidates for FOC improvement. These results could be applicable to oil palm breeding programs.

Materials and Methods

Plant materials. A total of 39 oil palm germplasm materials (9 years old), representing seven countries in Africa and Southeast Asia (Table 1), were used, and 11 fruit-related traits among these germplasms were observed and then analyzed using cluster, analysis of variance (ANOVA), correlation, path, and regression analysis, respectively. Furthermore, FOC prediction was constructed and validated for germplasm evaluation. The expected results could be applicable to oil palm breeding programs.

African oil palm (Elaeis guineensis Jacq.) is an important woody oil crop that is widely cultivated in tropical regions all over the world (Adjei-Nsiah et al., 2012; Gutiérrez-Vélez et al., 2011; Murphy, 2009, 2014; Sayer et al., 2012). Oil palm originates from Africa, but Malaysia introduced oil palm in the 1900s and quickly developed oil palm plantations. Indonesia, Malaysia, and Thailand are currently the most important oil palm plantation regions in the world (Corley and Tinker, 2015). Current yields have generally reached 4 to 6 tons per hectare, which led to a rapid expansion in the tropics of Asia, Africa, and South America. Supply of palm oil and palm kernel oil accounted for 39.7% of vegetable oil around the world (U.S. Department of Agriculture, 2018). Palm oil and palm kernel oil are crucial raw materials for the food industry, chemical industry, and biodiesel (Edem, 2002; Kalam and Masjuki, 2002; Mba et al., 2015). Generally, oil palm fruit can be divided into exocarp, mesocarp, endocarp (shell), and kernel (Corley and Tinker, 2015). The fruit components, including fruit weight, fruit size, M/F, K/F, and S/F, might be crucial for FOC in oil palm germplasm. The AFW of high-yielding Thai and Nigerian cultivars is ~7.57 g (Owolarafe et al., 2007; Patcharin et al., 2013; Rajanaidu et al., 1979); however, high variations were observed in M/F, S/F, and K/F (Krualee et al., 2013; Patcharin et al., 2013; Rajanaidu et al., 1979; Sapey et al., 2012). Mesocarp and kernel of the fruit are the richest sources of oil, and it is relatively important to increase the oil content of mesocarp and kernel of existing germplasms in China. To our knowledge, previous studies (Krualee et al., 2013; Mathews et al., 2004; Okoye et al., 2009; Rafii et al., 2013) mainly focused on oil yield from the whole bunch of the oil palm fruits. Although the fruit components of oil palm have been extensively studied, investigations on FOC are still limited. Breeders often use different statistical analyses to estimate the interrelation among the agronomic traits (Boo et al., 1990). Hierarchical cluster analysis shows the similarity of the samples (Peeters and Martinelli, 1989). Path analysis serves as a great tool to evaluate the relationship among agronomic traits (Krualee et al., 2013; Patcharin et al., 2013; Zeng et al., 2016).

In the present study, a total of 39 germplasms, including Dura, Tenera, and Parthenocarpy, collected from seven different countries in Asia and Africa were used, and 11 fruit-related traits among these germplasms were observed and then analyzed using cluster, analysis of variance (ANOVA), correlation, path, and regression analysis, respectively. Furthermore, FOC prediction was constructed and validated for germplasm evaluation. The expected results could be applicable to oil palm breeding programs.

Table 1. Origin and fruit forms of collected materials.

| Fruit form | Origin | Germplasm |
|------------|--------|-----------|
| Dura       | Malaysia | G11     |
|            | Nigeria  | G29, G31 |
|            | Cameroon | G34     |
| Tenera     | Thailand | G1, G3–G8 |
|            | Malaysia | G9, G10, G12, G14–G23 |
|            | Indonesia| G24–G28 |
|            | Nigeria  | G30     |
|            | Cameroon | G32, G33 |
|            | Ghana    | G35, G36 |
|            | Angola   | G37–G39 |
| Parthenocarpy | Thailand | G2     |
|            | Malaysia | G13     |
China, were used in this study. The collected germplasms included three fruit forms: Dura, Tenera, and Parthenocarpy (Fig. 1). Each germplasm has only one tree; fully matured fruits (fall off easily from bunch according to the oil palm harvesting standards) from each germplasm were collected for the following analyses.

**Studied traits.** The following traits were investigated: FBN (number of bunches/tree/year), AFW, M/F, K/F, S/F, AFL, AFWD, AST, MOC, KOC, and FOC. Three fresh fruit bunches per germplasm were selected and 20 healthy fruits from each bunch were randomly chosen to measure AFW, AFL, and AFWD. The fruits were then cut vertically and dissected to measure AST, M/F, S/F, and K/F. Then, MOC and KOC were determined through Soxhlet extraction using hexane as a solvent. The experiment included three biological replicates for each trait, and FOC was calculated using the following formula:

\[
\text{FOC} \% = \left( \frac{M/F \times MOC + K/F \times KOC}{100} \right)
\]

**Statistical analyses.** Phenotypic coefficient of variation (PCV), one-way ANOVA, correlation coefficients, path analysis, and regression analysis were calculated using SAS Statistical Package Program version 9.1 (SAS Institute, Inc., Cary, NC) (Each, 2006; Ziegel, 1996). The diagrams for cluster analysis, box plot, and ANOVA were generated by OriginPro 9.0.

**Results**

**Cluster analysis.** According to cluster analysis, three main clusters can be separated. The germplasm G2 and G13, which were Parthenocarpy from Thailand and Malaysia, were in one cluster, and G11, G29, G19, G12, and G31, which included Dura and Tenera from Malaysia and Nigeria, were grouped in one cluster. The remaining 32 germplasms, which consisted of 31 Tenera from seven different countries and one Dura from Cameroon, formed the largest cluster. Clustering analysis showed that Tenera and Dura were more closely related than to Parthenocarpy, and the overall results indicated the close association of germplasm from different countries (Fig. 2).

**Phenotypic variation of analyzed traits.** The PCVs ranged from 10.46% to 78.28%. The highest PCV was recorded for AST (78.28%) followed by S/F (57.12%), AFW (35.59%), K/F (35.43%), FBN (28.92%), FOC (19.44%), and KOC (16.05%), whereas the lowest PCV was observed in AFL (10.46%) (Table 2, Fig. 3). Most of the traits varied largely, indicating that germplasms collected from seven countries had abundant diversity.

With respect to FOC, ANOVA showed that FOC from 39 germplasms was significantly different \((P < 0.0001)\). The lowest FOC was observed in G12 (20.44%), whereas the highest values were represented by G39 (58.62%), which was Tenera from Angola, and G2 (57.68%), which was Parthenocarpy from Thailand (Fig. 4). Germplasms G39 and G2 had the potential of breeding high oil-yielding varieties.

**Correlation among analyzed traits.** Correlation analysis showed that FOC was positively and significantly correlated with MOC \((r = 0.74**\)), M/F \((r = 0.66**\)) and KOC \((r = 0.34*)\), whereas negative and significant correlations of FOC were observed with S/F \((r = -0.69**)\) and AST.


\[ r = -0.61^{**} \]. Significant negative correlations of M/F with K/F \((r = -0.50^{**})\), S/F \((r = -0.96^{**})\), AFWD \((r = -0.35^{*})\), and AST \((r = -0.69^{**})\) was also found in this study. Positive and significant correlation existed between AFW and AFL \((r = 0.76^{**})\). In addition, S/F was positively and significantly correlated with AFWD \((r = 0.33^{*})\) and AST \((r = 0.81^{**})\) (Table 3). Accordingly, FOC may be related mostly with MOC, M/F, KOC, S/F, and AST.

**Path analysis.** The direct and indirect effects of various traits on FOC were estimated using path analysis. Results showed that M/F (0.813) had the highest positive direct effect on FOC followed by MOC (0.731). The positive direct effect of KOC (0.073) on FOC was little and ignorable. Although the direct effect of S/F (0.266) on FOC was not obvious, S/F had considerable negative indirect effect on FOC through M/F (−0.780). Similarly, AST had negative direct (−0.102) and indirect effects on FOC through M/F (−0.560). The effects of other traits on FOC were ignorable because of the little amount and also the correlation was not significant (Table 4), indicating that FOC was mainly determined by M/F, MOC, S/F, and AST.

**Regression analysis between FOC and fruit-related traits.** Regression analysis was conducted to evaluate the relationship between FOC and M/F, MOC, S/F, and AST. The regression equation used for the prediction of FOC values was as follows:

\[
\text{FOC} = -18.89921 + 0.34857 \times \text{M/F} + 0.72513 \times \text{MOC} - 0.0982 \times \frac{\text{S/F}}{\text{M/F}} - 0.74848 \times \text{AST}
\]

Results showed that the correlation coefficient between predicted and observed FOC was significant \((r = 0.99)\) (Table 5). It indicated that it is reliable to predict FOC by using the regression equation. Among all these germplasms, G39 was found to have the highest FOC and followed by G2, which was in agreement with the observations (Fig. 4).

**Discussion**

Oil palm is the highest oil-yielding crop among oleaginous crops and producing 4 to 6 tons of oil per hectare on average. With the increasing population and oil consumption, it is estimated that the demands for edible oil will hit 240 million tons by 2050 (Barcelos et al., 2015). To overcome such exigencies for edible oil, it is necessary to improve the FOC of the potential oil palm cultivars through effective breeding programs. There is an enormous potential for increasing oil yield of more than 10 tons per hectare by selecting traits most related to oil yield in breeding programs. Evaluation and selection of potential oil palm individuals from the existing germplasm is important to achieve high oil yields, such as 11 to 18 tons per hectare. Breeders often use different statistical methods to determine the relationship among the agronomic traits (Oboh and Fakorede, 1990).

In the current study, interrelation among different traits as well as direct and indirect effects of specific traits on FOC was estimated using different statistical analyses. Hierarchical cluster analysis shows the relationship among the samples (Ene et al., 2016). Clustering analysis in this study revealed that Tenera and Dura were more closely related than to Parthenocarpy. Tenera is popular as a result of crossing between Dura × Pisifera, and hence Tenera and Dura had higher similarity as compared with Parthenocarpy. Cluster analysis also indicated the close association of germplasms from different countries. Oil palm populations
from Africa were introduced to many places by humans (Hayati et al., 2004), and it is most likely that there is no dramatic variation during its spreading to Asia from Africa.

The CV determines the relative amount of variability among the traits (Sharma, 1988). The amount of variability present determines the potential in trait selection. The traits with greater variability have the higher potential to discriminate among treatments (Khan et al., 2009). The results of the PCV in the current study showed that the highest PCV was recorded for AST followed by S/F, AFW, and AFL. AFW and AFL are important in oil palm breeding programs.

Table 3. Correlation coefficients of analyzed traits.

| Traits | AFW | M/F | K/F | S/F | AFL | AFWD | AST | MOC | KOC | FOC |
|--------|-----|-----|-----|-----|-----|------|-----|-----|-----|-----|
| AFW    | 1   | 0.31| 0.31| 0.26| 0.10| 0.15 | 0.08| 0.16| 0.23| 0.10|
| M/F    | 0.14| 0.00| 0.14| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|
| K/F    | 0.15| 0.00| 0.14| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|
| S/F    | 0.08| 0.00| 0.08| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|
| AFL    | 0.10| 0.00| 0.10| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|
| AFWD   | 0.15| 0.00| 0.14| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|
| AST    | 0.08| 0.00| 0.08| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|
| MOC    | 0.16| 0.00| 0.15| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|
| KOC    | 0.23| 0.00| 0.22| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.00| 0.00|

Note: Data in bold represent direct effect of each trait on FOC, whereas others represent indirect effect. AFW = average fruit weight; M/F = mesocarp-to-fruit ratio; K/F = kernel-to-fruit ratio; S/F = shell-to-fruit ratio; AFL = average fruit length; AFWD = average fruit width; AST = average shell thickness; MOC = mesocarp oil content; KOC = kernel oil content; FOC = fruit oil content.

**Correlation is significant at 0.05 level; ***Correlation is significant at 0.01 level.

Footnote: Data in bold represent direct effect of each trait on FOC, whereas others represent indirect effect. AFW = average fruit weight; M/F = mesocarp-to-fruit ratio; K/F = kernel-to-fruit ratio; S/F = shell-to-fruit ratio; AFL = average fruit length; AFWD = average fruit width; AST = average shell thickness; MOC = mesocarp oil content; KOC = kernel oil content; FOC = fruit oil content.

**Table 5. Prediction values and observation values of collected germplasm.**

| Germplasm | Prediction value | Observation value |
|-----------|------------------|-------------------|
| G39       | 57.40            | 58.62             |
| G2        | 57.78            | 57.68             |
| G36       | 52.89            | 53.93             |
| G13       | 54.80            | 53.57             |
| G25       | 52.60            | 52.17             |
| G32       | 51.81            | 51.72             |
| G23       | 50.93            | 51.31             |
| G27       | 49.14            | 50.76             |
| G24       | 47.28            | 47.08             |
| G37       | 48.64            | 46.68             |
| G15       | 45.32            | 45.83             |
| G5        | 45.26            | 45.52             |
| G26       | 44.85            | 45.00             |
| G18       | 43.64            | 44.96             |
| G9        | 44.79            | 44.54             |
| G38       | 44.12            | 44.17             |
| G7        | 43.74            | 43.67             |
| G6        | 42.35            | 43.41             |
| G14       | 43.96            | 43.4              |
| G10       | 41.54            | 41.82             |
| G4        | 42.68            | 41.46             |
| G3        | 40.97            | 41.17             |
| G28       | 41.46            | 40.63             |
| G1        | 41.36            | 40.47             |
| G34       | 38.63            | 40.14             |
| G35       | 41.05            | 39.88             |
| G16       | 39.84            | 38.22             |
| G33       | 37.26            | 38.00             |
| G11       | 39.83            | 37.83             |
| G8        | 37.80            | 36.17             |
| G21       | 36.63            | 35.35             |
| G29       | 34.17            | 33.63             |
| G31       | 34.06            | 25.45             |
| G20       | 34.06            | 22.07             |
| G17       | 18.34            | 20.44             |

Note: Correlation coefficient between observation and prediction value = 0.99114, $P < 0.001$.

Furthermore, the high negative direct and indirect effects of AST on FOC were also observed in this study. The results of path analysis were in agreement with that of correlation analysis. Regression analysis also confirmed that FOC was positively related to M/F and MOC, and negatively related to S/F and AST. The significant correlation ($r = 0.99$) between predicted and observed FOC in regression analysis suggested that this regression equation is reliable for evaluation on FOC in oil palm germplasms. These observations revealed that M/F, MOC, S/F, and AST strongly influence FOC and hence should be preferably used as selection criteria for development of high-yield oil palm cultivars.

In conclusion, FOC was mainly determined by M/F, MOC, S/F, and AST, and the FOC prediction in this study was reliable for germplasm evaluation, which could be applicable in oil palm breeding programs.

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