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 (Parthenocarp) 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.

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).

Although oil palm was introduced to China in 1926, it has not been planted commercially because of low oil yield in China (Shi et al., 2015). Hence, China imports more than 5 million tons of palm oil every year (Xiong et al., 2009). However, such import can be reduced by developing high oil-yielding germplasms and breeding high-yield cultivars. The evaluation of factors most related to oil yield can be useful in selecting and developing germplasms with high oil yield.

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 (Owularafe 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 Parthenocarp, 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.

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), maintained at Coconut Research Institute, Chinese Academy of Tropical Agricultural Sciences, Wenchang,

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
Parthenocarp	Angola	G37–G39
	Thailand	G2
	Malaysia	G13

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China, were used in this study. The collected germplasms included three fruit forms: Dura, Tenera, and Parthenocarp (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, AFD, 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 AFD. 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:

$$\text{FOC (\%)} = \frac{(\text{M/F} \times \text{MOC} + \text{K/F} \times \text{KOC})}{100}$$

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 Origin-Pro 9.0.

Results

Cluster analysis. According to cluster analysis, three main clusters can be separated. The germplasm G2 and G13, which were Parthenocarp 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 Parthenocarp, 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 Parthenocarp

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

Fig. 1. The fruit forms of collected oil palm. (A) Dura (thick shell). (B) Tenera (thin shell). (C) Parthenocarp (without embryo and endosperm).

Fig. 2. Cluster dendrogram of 39 germplasms.

Table 2. Phenotypic variation of analyzed traits among 39 germplasms.

Traits	Mean $\pm$ SD ^a	Range	PCV (%)
FBN	9.13 $\pm$ 2.64	5–14	28.92
AFW (g)	10.22 $\pm$ 3.64	4.93–21.86	35.59
M/F (%)	74.26 $\pm$ 11.67	36.79–100	15.71
K/F (%)	8.83 $\pm$ 3.13	0–15.13	35.43
S/F (%)	15.68 $\pm$ 8.95	0–40.8	57.12
AFL (mm)	33.72 $\pm$ 3.53	25.66–40.29	10.46
AFWD (mm)	26.26 $\pm$ 2.77	20.07–33.38	10.54
AST (mm)	1.35 $\pm$ 1.06	0–4.77	78.28
MOC (%)	53.59 $\pm$ 8.31	33.56–70.48	15.50
KOC (%)	39.16 $\pm$ 6.29	25.95–52.77	16.05
FOC (%)	43.29 $\pm$ 8.42	20.44–58.62	19.44

^aResults are represented as mean $\pm$ standard deviations ($n = 3$).

PCV = phenotypic coefficient of variation; FBN = fruit bunch number; 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.

($r = -0.61^{**}$). Significant negative correlations of M/F with K/F ($r = -0.50^{**}$), S/F ($r = -0.96^{**}$), AFDW ($r = -0.35^{*}$), 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 AFDW ($r = 0.33^{*}$) 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:

$$\begin{aligned} \text{FOC} = & -18.89921 + 0.34857 \times \text{M/F} \\ & + 0.72513 \times \text{MOC} - 0.0982 \times \text{S/F} \\ & - 0.74848 \times \text{AST} \end{aligned}$$

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 statisti-

Fig. 3. Box plot showing the variation of observed traits. FBN = fruit bunch number; 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; AFDW = average fruit width; AST = average shell thickness; MOC = mesocarp oil content; KOC = kernel oil content; FOC = fruit oil content.

Fig. 4. Analysis of variance for fruit oil content (FOC) in 39 germplasms.

cal methods to determine the relationship among the agronomic traits (Obboh 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 Parthenocarp. Tenera is popular as a result of crossing between Dura $\times$ Pisifera, and hence Tenera and Dura had higher similarity as compared with Parthenocarp. Cluster analysis also indicated the close association of germplasms from different countries. Oil palm populations

Table 3. Correlation coefficients of analyzed traits.

Traits	AFW	M/F	K/F	S/F	AFL	AFWD	AST	MOC	KOC	FOC
AFW	1									
M/F	0.31	1								
K/F	-0.26	-0.50**	1							
S/F	-0.24	-0.96**	0.28	1						
AFL	0.76**	0.14	-0.29	-0.03	1					
AFWD	0.24	-0.35*	0.13	0.33*	0.08	1				
AST	0.02	-0.69**	-0.04	0.81**	0.27	0.27	1			
MOC	0.05	0.02	0.17	-0.07	-0.03	-0.06	-0.14	1		
KOC	0.30	0.08	0.16	-0.12	0.18	0.05	-0.17	0.28	1	
FOC	0.23	0.66**	-0.11	-0.69**	0.05	-0.28	-0.61**	0.74**	0.34*	1

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

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 4. The direct and indirect effects of fruit-related traits on FOC.

Traits	AFW	M/F	K/F	S/F	AFL	AFWD	AST	MOC	KOC
AFW	0.018	0.251	-0.027	-0.064	-0.008	-0.003	-0.002	0.038	0.022
M/F	0.006	0.813	-0.053	-0.255	-0.001	0.005	0.071	0.015	0.006
K/F	-0.004	-0.406	0.106	0.074	0.003	-0.001	0.004	0.128	0.011
S/F	-0.004	-0.780	0.030	0.266	0.000	-0.004	-0.082	-0.049	-0.008
AFL	0.014	0.115	-0.030	-0.007	-0.011	-0.001	-0.027	-0.020	0.013
AFWD	0.004	-0.284	0.013	0.088	-0.003	-0.014	-0.027	-0.046	0.004
AST	0.000	-0.560	-0.004	0.216	-0.009	-0.003	-0.102	-0.100	-0.012
MOC	0.001	0.016	0.019	-0.017	0.001	0.001	0.014	0.731	0.020
KOC	0.005	0.062	0.016	-0.032	0.001	-0.001	0.017	0.206	0.073

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.

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, K/F, FBN, FOC, and KOC, indicating the presence of high variability and hence there is a wider scope of selection in these traits as compared with other traits. The ANOVA with respect to FOC of 39 germplasms showed that G39 (Tenera) and G2 (Parthenocarp) had the highest FOC, suggesting that G39 and G2 might be potential candidates for FOC improvement.

Both mesocarp and kernel in oil palm are the rich sources of oil, and hence the study on mesocarp and kernel as well as the factors affecting the accumulation of the oil in these parts is relatively important. Previous studies showed that M/F in Thailand ranged from 47.90% to 73.81% (Krualee et al., 2013); however, in the present study, M/F in Hainan Island was 74.26%, although the climate conditions such as temperature and rainfall in Hainan Island were inferior to southern Thailand. Similarly, the fruit characters, including M/F, AFL, AFWD, and AST in Hainan Island were better when compared with those in Nigeria and Ghana (Owolarafe

et al., 2007; Rajanaidu et al., 1979; Sapey et al., 2012).

Interrelations of various traits in oil palm were discussed in previous studies (Obboh and Fakorede, 1990; Rios et al., 2018); however, extensive study on FOC, which is one of the major components responsible for oil yield, is still limited. Correlation analysis in this study showed a significant negative correlation of M/F with S/F, K/F, and AST. Similar reports have been presented in previous studies (Okoye et al., 2009; Patcharin et al., 2013). This negative correlation suggests that M/F is negatively influenced by S/F, K/F and AST. The increase in kernel and shell size would result in a decrease in mesocarp content (Okoye et al., 2009). In addition, FOC was positively and significantly correlated with M/F, MOC, and KOC, and negatively and significantly correlated with S/F and AST. These results suggested that increasing the M/F, MOC, and KOC will lead to higher FOC. In contrast, reducing the S/F and AST can increase the possibility of improving FOC.

Path analysis was used to determine the direct and indirect effects of various fruit components on FOC (Wright, 1921). Previous studies (Krualee et al., 2013) reported that M/F has a direct effect on oil yield per palm and also has an effect on the percentage of oil per bunch. Path analysis in the current study revealed that M/F and MOC have high positive direct effects on FOC. The direct effect of KOC on FOC was positive but with little amount. The indirect negative effect of S/F on FOC through M/F is also relatively

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
G17	47.11	48.64
G30	48.00	47.83
G22	46.89	47.76
G20	45.96	47.47
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	24.00	25.45
G19	23.64	22.07
G12	18.34	20.44

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

high. 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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