Journal of Oil Palm Research Vol. 38 (1) March 2026 p. 78–87
DOI: https://doi.org/10.21894/jopr.2024.0057

THE USE OF FACTORIAL MATING DESIGN FOR ESTIMATION OF COMBINING ABILITIES IN COMMERCIAL OIL PALMS

PATCHARIN TANYA[1]; PUNTAREE TAEPRAYOON[2]; SURAKITTI SRIKUL[3]; ANEK LIMSRIVILAI[4] and PEERASAK SRINIVES[1,5]*

ABSTRACT

This study aimed to identify the parental palms with high mean and general combining ability (GCA), and the progenies with high mean and specific combining ability (SCA) for bunch yield and bunch component traits. A total of 30 crosses were made from the elite palms of six duras *and five* pisiferas *using a factorial mating design. The progenies were transplanted in a strip-plot experimental design with three replicates. Each plot had six palms of a cross, thus making a total of 540 palms. The data on bunch yield and components were collected from 2012 to 2022. The results showed that R10/1D and R5/21P had good means and GCA for fresh fruit bunches (FFB) and bunch number (BNO) while R8/9D showed significant GCA for oil to bunch, oil yield and kernel yield. R10/5D and KA17/2P expressed high GCA for kernel to bunch and kernel yield. The cross R10/1D × R9/8P showed significant SCA for FFB (mean 262.97 kg palm^{-1} yr^{-1}) and BNO (mean 20.81 bunches palm^{-1} yr^{-1}), while R15/14D × KA17/2P for average bunch weight (mean 18.57 kg bunch^{-1}). A43/9D × R9/8P had the best SCA for oil yield (mean 82.24 kg palm^{-1} yr^{-1}), and R10/5D × KA17/2P for kernel yield (mean 18.15 kg palm^{-1} yr^{-1}).*

Keywords: *dura*, general combining ability, *pisifera*, specific combining ability, *tenera.*

Received: 18 April 2024**; Accepted:** 24 October 2024**; Published online:** 20 December 2024.

INTRODUCTION

Oil palm is the most significant oil crop worldwide. It originally came from Africa but has been widely grown in Southeast Asia, mainly in Indonesia, Malaysia, and Thailand (Corley & Tinker, 2016). Palm oil is derived from the oil palm fruits and is the primary source of vegetable oil globally. USDA (2023) estimated that the vegetable oil production and consumption would reach 88.60 and 86.87 million tonnes by 2023, while the demand for vegetable oil would increase to 240 million tonnes by 2050. The oil palm industry has expanded by increasing planted areas from 10.57 to 21.03 million hectares (FAOSTAT, 2023), causing deforestation and air pollution. However, high-yielding oil palm planting materials have been developed and used to reduce the expansion of oil palm planted areas (Arolu et al., 2016; Gingold et al., 2012; Rajanaidu et al., 2000). Oil palm germplasm is classified based on the shell gene, which controls the thickness of the shell and the presence of a fibre ring in the mesocarp. The *dura* type has a thick shell and thin mesocarp (genotype sh^+sh^+), the *pisifera* type has no shell (genotype sh^-sh^-), and the *tenera* type with a thin shell and thick mesocarp with a fibre ring (genotype sh^+sh^-). Several studies have supported

---

[1] Department of Agronomy,
Faculty of Agriculture at Kamphaeng Saen,
Kasetsart University, Kamphaeng Saen Campus,
Nakhon Pathom 73140, Thailand.

[2] Agricultural and Environmental Utilization Research Unit,
Nakhonsawan Campus, Mahidol University,
Nakhon Sawan 60130, Thailand.

[3] Agricultural Research and Development Program,
Faculty of Agriculture at Kamphaeng Saen,
Kasetsart University, Kamphaeng Saen Campus,
Nakhon Pathom 73140, Thailand.

[4] Goldentenera Company Limited, Krabi Yai,
Muang District, Krabi 81000, Thailand.

[5] Academy of Science,
The Royal Society of Thailand, Dusit,
Bangkok 10300, Thailand.

* *Corresponding author e-mail: agrpss@yahoo.com*

that the *tenera* type is more productive than the other two types (Arolu et al., 2016; Corley & Tinker, 2016; Soh et al., 2017).

The ability of a parent (*dura* or *pisifera*) that can give relatively superior or inferior progenies, when crossed with the other parents, is termed as general combining ability (GCA). A parent considered as having high GCA for a certain trait, can also have low GCA for the other traits. Another ability to be considered during the parental selection for hybrid production is specific combining ability (SCA). It is the ability of two parents that produce a cross with superior or inferior performance, when compared with the other crosses of the same experiment (Sprague & Tatum, 1942). GCA is conditioned mainly by the additive gene action, while SCA is conditioned by the non-additive ones (Griffing, 1956). Determining the GCA of each clone is a valuable tool for the plant breeder to select the *dura* or *pisifera* parents that yield superior progenies in general, whereas determining SCA helps to identify the crosses that produce desirable *tenera* for the trait.

There are several ways to estimate GCA and SCA of the genotypes and hybrids. However, plant breeders often used mating designs, especially the nested, factorial, and backcross designs (Comstock & Robinson, 1952). These designs are also known as the North Carolina Mating Design, NCM I, II, and III, respectively. The mating designs are not commonly used in oil palm breeding, partly due to the difficulty in preparing the progenies for testing. Arolu et al. (2016) used NCM I to estimate the GCA of 10 *pisifera* palms by pollinating each palm to 2-3 *duras*. Clearly that nested design can be used to estimate GCA and variance in only one side of the parents, such as the male side (*pisifera*) above. To estimate GCA (as well as genetic variation) for both male and female parents, the factorial mating design (NCM II) is usually employed. The factorial design can also reveal information for SCA of each cross combination and lead to the selection of particular parents for commercial production of superior *tenera* palm.

This study is set up to estimate the GCA of the selected *dura* and *pisifera* palms, as well as the SCA of their progenies (*tenera* palms) for bunch yield and bunch components. The parental palms would be chosen for further improvement and the best cross combination would be used for commercial production.

MATERIALS AND METHODS

Plant Materials

Thirty oil palm crosses (T11-T65) were created using a factorial mating design (North Carolina Mating Design II, NCM II) (Comstock & Robinson, 1952). There were six *dura* (female) parents (D1-D6) and five *pisifera* (male) parents (P1-P5) as shown in *Table 1.* The parents were elite palms developed during 1985–2005 by Golden Tenera Company Limited located in Krabi Province, Thailand. To obtain the clean crosses, the pollination was rigorously controlled as in the seed production steps. The female inflorescences from the *dura* palms were bagged and the male inflorescences were removed before flowering. The pollen was collected from the *pisifera* palms and refrigerated, awaiting for hand-pollination onto the intended female flowers. The pollinated inflorescence was then covered by a pollination bag, and sprayed with an insecticide to prevent possible insect pollination. The mature fruits from each bunch were processed for seeds and kept refrigerated. Germination was done when seeds from all 30 crosses were available. Before transplanting, the SSR markers were determined on the seedlings to confirm the parental genotypes were inherited in the *tenera*, by using the method described by Taeprayoon et al. (2015, 2016). The ripening fruits of the progenies were also regularly observed for shell thickness and the presence of a fibre ring during the study.

The location of the breeding farm is around 8° 14′ 0.16″ N latitude and 98° 47′ 28.69″ E longitude. The progenies were transplanted in a strip-plot (split-block) experimental design with three replications (LeClerg et al., 1966; Petersen, 1994). Each plot comprised six palms of a cross, resulting in a total of 540 palms in the experiment. All palms in the trial were transplanted in May 2009 using an equilateral triangular pattern (9 × 9 × 9 m) in a total experimental area of slightly over 4 ha.

Data Collection

Phenotypic data were collected from bunch yield and bunch components. Bunch yield comprised fresh fruit bunches (FFB) (kg palm^{-1} yr^{-1}), bunch number (BNO) (bunches palm^{-1} yr^{-1}), and average bunch weight (ABW) (kg bunch^{-1}). These traits were observed from individual palms beginning from two years and eight months after planting, twice a month for 11 consecutive years, from 2012 to 2022. Each bunch was harvested when a detached mature fruit from the bunch was found on the ground. Bunch components were determined following the method described by Rao et al. (1983). The bunches were taken for component analyses when the fruit skin was changing from black to reddish or orange during the ripening stage, generally 20–22 weeks after pollination. The data were collected by sampling a single bunch from each plot to determine the oil to bunch (OTB) (%) and the kernel to bunch (KTB) (%). Oil content was presented as oil yield

(OY) and kernel yield (KY) recorded in kg palm^{-1} yr^{-1}. Bunch analyses were performed between May 2017 to October 2018, when the palms were 8–9 years old. The data were collected on two bunches per cross, totaling 180 bunches in the experiment.

Statistical Analysis

The statistical model of an observation depicting the effects of *dura*, *pisifera*, and *tenera* (*dura* × *pisifera*) is given as Equation (1):

$$Y_{ijk} = \mu + d_i + p_j + (dp)_{ij} + e_{ijk} \qquad (1)$$

where, Y_{ijk} is the k^{th} observation on the $(i \times j)^{th}$ *tenera*, μ is the overall mean, d_i is the effect of the i^{th} *dura* parent, p_j is the effect of the j^{th} *pisifera* parent, $(dp)_{ij}$ is the interaction (specific) effect of the cross $d_i \times p_j$ and e_{ijk} is the error associated with each observation.

Each trait was subjected to an analysis of variance (ANOVA) as shown in *Table 2*. The trait means were compared by Duncan's multiple range test (DMRT). The GCA of each parent and SCA of each cross were determined and tested for significance against their standard error of estimates (Griffing, 1956). All the analyses were accomplished using the R-Stat Program (R Core Team, 2022).

RESULTS AND DISCUSSION

Analysis of Variance

The analysis of variance (ANOVA) revealed significant differences among the crosses in all traits as shown in *Table 3*. The significance of the parental effects (D and P) and their progenies (D × P) were also detected in all traits, except only for BNO in the progenies. This information revealed that the elite parental palms used in this experiment were diverse and should be investigated for combining abilities.

TABLE 1. FACTORIAL MATING USING SIX *Dura* PALMS (D1-D6) AND FIVE *Pisifera* PALMS (P1-P5) EXPRESSED AS CODE NAMES OF *Tenera*s

D×P	P1: R5/21P	P2: R3/8P	P3: R16/7P	P4: R9/8P	P5: KA17/2P
D1: R15/14D	T11	T12	T13	T14	T15
D2: A43/9D	T21	T22	T23	T24	T25
D3: R10/5D	T31	T32	T33	T34	T35
D4: R10/1D	T41	T42	T43	T44	T45
D5: A1/2D	T51	T52	T53	T54	T55
D6: R8/9D	T61	T62	T63	T64	T65

TABLE 2. AN ANALYSIS OF VARIANCE FOR FACTORIAL PROGENIES GROWN IN STRIP PLOT IN A RANDOMISED COMPLETE BLOCK DESIGN

Sources of variation (SOV)	Degrees of freedom (df)	Mean squares (MS)
Replications	r-1	MS_R
Crosses	dp-1	MS_C
Dura	d-1	MS_D
Pisifera	p-1	MS_P
Dura×*Pisifera*	(d-1)(p-1)	MS_{DP}
Error	(r-1)(dp-1)	MS_E
Total	**rdp-1**	

Notes: r - number of replication; d - number of *dura* parents; p - number of *pisifera* parents.

TABLE 3. MEAN SQUARES OF FFB, BNO, ABW, OTB, KTB, OY, AND KY OF 30 OIL PALM FACTORIAL PROGENIES, OBSERVED DURING 2012-2022

Sources of variation (SOV)	df	FFB	BNO	ABW	OTB	KTB	OY	KY
Replications	2	1588.60*	9.27**	0.53^{ns}	0.35^{ns}	0.281^{ns}	156.00*	7.01^{ns}
Crosses	29	1509.10**	21.28**	12.71**	15.73**	5.142**	169.30**	27.53**
Dura (D)	5	2385.90**	60.74**	18.67**	7.86*	7.478**	276.30**	25.16**
Pisifera (P)	4	2358.90**	68.78**	46.93**	48.77**	18.905**	133.00*	92.99**
D×P	20	1120.00**	1.92^{ns}	4.37**	11.09**	1.806**	149.80**	15.03**
Error	58	324.80	1.73	0.48	2.43	0.693	37.20	4.64
CV (%)		**8.14**	**8.04**	**5.01**	**5.16**	**17.97**	**9.14**	**20.98**

Note: FFB - fresh fruit bunches; BNO - bunch number; ABW - average bunch weight; OTB - oil to bunch; KTB - kernel to bunch; OY - oil yield; KY - kernel yield; * - significant difference at $p \leq 0.05$; ** - highly significant difference at $p \leq 0.01$; ns - non-significant.

Estimated Mean and GCA for Bunch Yield of the Parental Palms

Among the parental *dura*, R10/1D showed the highest contribution to FFB of the *tenera* at 235.67 kg palm^{-1} yr^{-1}, with a significant GCA of 14.28 kg palm^{-1} yr^{-1} (*Table 4*). Thus R10/1D showed the potential in increasing FFB in the *tenera* by the average of 14.28 kg palm^{-1} yr^{-1} when crossed with this elite *pisifera* set. In contrast, the *dura* A1/2D showed the lowest contribution to FFB of 198.09 kg palm^{-1} yr^{-1} and a negative GCA of -23.30 kg palm^{-1} yr^{-1}, meaning that this *dura* would give the progenies with the lowest FFB yield when crossed with this set of *pisifera*. R10/1D also gave the highest average BNO of 18.61 bunches palm^{-1} yr^{-1} and a significant GCA of 2.25 bunches palm^{-1} yr^{-1}. However, R10/1D had the smallest bunch of 12.76 kg bunch^{-1} with the GCA of -1.07 kg bunch^{-1}, implying that this *dura* would contribute to relatively smaller bunches to the progenies when crossed by this *pisifera* set. This is possibly due to the negative relationship between BNO and ABW (Tanya *et. al.*, 2013) as generally observed in most oil palm estates. Another promising *dura* is A43/9D which contributed to high BNO, giving the mean and GCA of 17.85 and 1.49 bunches palm^{-1} yr^{-1}, respectively.

For the *pisifera* side, R5/21P showed a contribution to the FFB of 233.82 kg palm^{-1} yr^{-1} with the GCA of 12.43 kg palm^{-1} yr^{-1}. It also contributed to high mean and GCA for BNO (17.63 and 1.27 bunches palm^{-1} yr^{-1}, respectively) (*Table 4*). However, R5/21P would give slightly smaller bunches with a negative GCA (13.40 and -0.43 kg bunch^{-1}) when crossed to this *dura* set. Another promising *pisifera* is R3/8P with the contribution to the average FFB yield of 232.19 and GCA of 10.80 kg palm^{-1} yr^{-1}. This male parent showed no contribution to BNO as its GCA for the trait was not significant. However, it would increase ABW on the average of 0.45 kg bunch^{-1} if crossed to these elite *duras*. Among the rest three *pisiferas*, R16/7P gave poor progenies for all three traits, R9/8P is a good contributor for high BNO, and KA17/2P is good for increasing the bunch size of the progenies.

Mean and SCA for Bunch Yield of the Crosses

The progenies showed the mean values for FFB, BNO, and ABW of 221.39 kg palm^{-1} yr^{-1}, 16.36 bunches palm^{-1} yr^{-1}, and 13.83 kg bunch^{-1}, respectively (*Table 5*). The crosses produced FFB from 179.82 kg palm^{-1} yr^{-1} in A1/2D × KA17/2P (T55) to 262.97 kg in R10/1D × R9/8P (T44). T44 also gave the highest SCA of 28.95 kg palm^{-1} yr^{-1}. The second highest yielding cross was R8/9 × R5/21 (T61) with an average yield of 252.40 kg palm^{-1} yr^{-1}. Another good cross giving high FFB was R10/1D × R16/7P (T43) (yield 245.18, SCA 23.23 kg palm^{-1} yr^{-1}). The FFB of these *teneras* were all higher than the selection criteria set by Malaysian Standard (SIRIM) MS 157 at 170 kg palm^{-1} yr^{-1} (Kushairi et al., 2011). The range for average BNO was from 10.29 bunches palm^{-1} yr^{-1} in T55 to 20.81 in T44. Whereas T43 gave 19.79 bunches palm^{-1} yr^{-1} with a significant SCA of 1.41 bunches palm^{-1} yr^{-1}. ABW of the crosses ranged from 10.75 kg bunch^{-1} in R10/5D × R9/8P (T34) to 18.57 kg bunch^{-1} in R15/14D × KA17/2P (T15). T15 also had a significant SCA of 1.52 kg bunch^{-1}, while T34 gave a negative SCA of -1.06 kg bunch^{-1} that contributed to the cross (*Table 5*).

TABLE 4. ESTIMATED MEAN AND GCA OF THE *Dura* AND *Pisifera* PARENTS FOR FFB, BNO AND ABW, OBSERVED DURING 2012-2022

Dura	FFB	GCA	BNO	GCA	ABW	GCA
R15/14D	222.08	0.69	15.58^{c}	-0.78*	14.53^{b}	0.70*
A43/9D	225.19	3.80	17.85^{a}	1.49**	12.68^{d}	-1.15**
R10/5D	220.25	-1.14	16.61^{b}	0.25	13.54^{c}	-0.29
R10/1D	235.67	14.28*	18.61^{a}	2.25**	12.76^{d}	-1.07**
A1/2D	198.09	-23.30**	12.87^{d}	-3.49**	15.61^{a}	1.78**
R8/9D	227.07	5.68	16.65^{b}	0.29	13.86^{c}	0.03
F-test	**ns**		**		**	
Pisifera	**FFB**	**GCA**	**BNO**	**GCA**	**ABW**	**GCA**
R5/21P	233.82	12.43*	17.63^{a}	1.27**	13.40^{c}	-0.43*
R3/8P	232.19	10.80*	16.50^{b}	0.14	14.28^{b}	0.45*
R16/7P	207.67	-13.72*	16.13^{b}	-0.23	13.02^{c}	-0.81**
R9/8P	219.75	-1.64	18.31^{a}	1.95**	12.10^{d}	-1.73**
KA17/2P	213.51	-7.88	13.23^{c}	-3.13**	16.36^{a}	2.53**
F-test	**ns**		**		**	

Note: FFB - fresh fruit bunches; GCA - general combining ability; BNO - bunch number; ABW - average bunch weight; within a column, means followed by the same letters are not significantly different according to DMRT ($p \le 0.05$);* - significant at $p \le 0.05$; ** - highly significant at $p \le 0.01$; ns - non-significant.

TABLE 5. TRAIT MEANS AND SCA OF 30 *Teneras* FOR FFB, BNO AND ABW, OBSERVED DURING 2012-2022

Crosses	*Dura* × *Pisifera*	FFB	SCA	BNO	SCA	ABW	SCA
T11	R15/14D × R5/21P	244.28^{a-e}	9.77	17.54^{b-g}	0.70	13.92^{e-i}	-0.17
T12	R15/14D × R3/8P	235.34^{a-f}	2.46	15.09^{g-l}	-0.63	15.60^{c}	0.63
T13	R15/14D × R16/7P	185.33^{hij}	-23.03*	14.28^{j-m}	-1.07	12.99^{h-m}	-0.73
T14	R15/14D × R9/8P	211.63^{e-j}	-8.82	18.36^{a-e}	0.83	11.55^{nop}	-1.25**
T15	R15/14D × KA17/2P	233.81^{a-f}	19.62	12.61^{lmn}	0.16	18.57^{a}	1.52**
T21	A43/9D × R5/21P	216.25^{c-i}	-21.36*	19.13^{a-d}	0.02	11.30^{op}	-0.95*
T22	A43/9D × R3/8P	221.91^{b-g}	-14.07	18.83^{a-e}	0.84	11.82^{m-p}	-1.31**
T23	A43/9D × R16/7P	226.72^{b-g}	15.25	16.97^{d-i}	-0.65	13.38^{f-k}	1.52**
T24	A43/9D × R9/8P	247.80^{a-d}	24.25*	18.67^{a-e}	-1.12	13.27^{f-k}	2.32**
T25	A43/9D × KA17/2P	213.23^{d-j}	-4.07	15.64^{f-k}	0.92	13.62^{f-j}	-1.59**
T31	R10/5D × R5/21P	249.24^{abc}	16.56	17.72^{b-f}	-0.15	14.06^{d-h}	0.96*
T32	R10/5D × R3/8P	237.86^{a-f}	6.82	16.89^{d-i}	0.14	14.08^{d-h}	0.10
T33	R10/5D × R16/7P	204.54^{f-j}	-1.99	17.26^{b-h}	0.88	11.91^{l-p}	-0.81
T34	R10/5D × R9/8P	182.41^{ij}	-36.2**	17.69^{b-f}	-0.87	10.75^{p}	-1.06*
T35	R10/5D × KA17/2P	227.17^{b-g}	14.81	13.46^{klm}	-0.01	16.87^{b}	0.81
T41	R10/1D × R5/21P	226.23^{b-g}	-21.86*	19.57^{abc}	-0.31	11.55^{nop}	-0.77
T42	R10/1D × R3/8P	230.93^{a-g}	-15.53	18.14^{b-f}	-0.61	12.73^{i-n}	-0.47
T43	R10/1D × R16/7P	245.18^{a-e}	23.23*	19.79^{ab}	1.41*	12.42^{j-o}	0.48
T44	R10/1D × R9/8P	262.97^{a}	28.95*	20.81^{a}	0.25	12.62^{i-n}	1.59**
T45	R10/1D × KA17/2P	213.00^{d-j}	-14.78	14.74^{i-l}	-0.74	14.45^{c-g}	-0.84*
T51	A1/2D × R5/21P	214.51^{c-j}	4.00	14.05^{j-m}	-0.08	15.28^{cd}	0.10
T52	A1/2D × R3/8P	218.22^{b-h}	9.34	12.99^{lm}	-0.01	16.81^{b}	0.76
T53	A1/2D × R16/7P	181.76^{ij}	-2.60	12.05^{mn}	-0.59	15.10^{cde}	0.3
T54	A1/2D × R9/8P	196.10^{g-j}	-0.35	14.94^{h-l}	0.13	13.19^{g-l}	-0.69
T55	A1/2D × KA17/2P	179.82^{j}	-10.38	10.29^{n}	0.56	17.67^{ab}	-0.47
T61	R8/9D × R5/21P	252.40^{ab}	12.90	17.73^{b-f}	-0.18	14.25^{d-h}	0.82
T62	R8/9D × R3/8P	248.85^{a-d}	10.98	17.06^{c-i}	0.27	14.59^{c-f}	0.29
T63	R8/9D × R16/7P	202.49^{f-j}	-10.86	16.44^{e-j}	0.03	12.28^{k-o}	-0.76
T64	R8/9D × R9/8P	217.60^{b-h}	-7.83	19.37^{a-d}	0.78	11.22^{op}	-0.91*
T65	R8/9D × KA17/2P	213.98^{c-j}	-5.20	12.62^{lmn}	-0.89	16.95^{b}	0.57
Mean		**221.39**		**16.36**		**13.83**	
%CV		**8.14**		**8.04**		**5.01**	

Note: FFB - fresh fruit bunches; SCA - specific combining ability; BNO - bunch number; ABW - average bunch weight; within a column, means followed by the same letters are not significantly different according to DMRT ($p \leq 0.05$); * - significant different at $p \leq 0.05$; ** - highly significant different at $p \leq 0.01$.

Estimated Mean and GCA for Bunch Components of the Parental Palms

In bunch components including OTB, KTB, OY, and KY, the *dura* parents were less diverse than the *pisifera* parents as they were significantly different in only KTB. R8/9D had the highest OTB of 31.59%, with a significant GCA of 1.39%. It gave an average OY of 71.29 and KY of 11.47 kg palm^{-1} yr^{-1}, with positive GCA contributing to both traits (*Table 6*). Another promising *dura*, R10/5D, was a good contributor for KTB and KY as it showed significant positive GCAs in both traits. The *pisifera* palms were more diverse as they were different in all bunch components, except OY. R16/7P and R9/8P performed well in OTB but not in OY, due mainly to their low FFB. KA17/2P was the best combiner for improving KTB and KY on the *pisifera* side.

Mean and SCA for Bunch Components of the Crosses

The means and ranges of OTB, KTB, OY and KY of the crosses were 30.20% (25.94%–33.89%), 4.63% (2.71%–7.98%), 66.74 kg palm^{-1} yr^{-1} (50.41–82.24 kg palm^{-1} yr^{-1}) and 10.26 kg palm^{-1} yr^{-1} (5.73–18.15 kg palm^{-1} yr^{-1}), respectively (*Table 7*). The crosses A43/9D × R16/7P (T23) and A43/9D × R9/8P (T24) were superior in bunch components as they showed

TABLE 6. ESTIMATED MEAN AND GCA OF THE *Dura* AND *Pisifera* PARENTS FOR OTB, KTB, OY AND KY, OBSERVED DURING 2012-2022

Dura	OTB	GCA	KTB	GCA	OY	GCA	KY	GCA
R15/14D	29.63	-0.58	4.19^{b}	-0.45*	65.59	-1.15	9.50	-0.77
A43/9D	30.28	0.08	3.76^{b}	-0.87**	68.38	1.65	8.46	-1.81**
R10/5D	30.14	-0.07	5.21^{a}	0.58*	66.25	-0.49	11.75	1.49*
R10/1D	29.72	-0.49	4.10^{b}	-0.53*	69.79	3.05	9.54	-0.72
A1/2D	29.86	-0.34	5.51^{a}	0.88**	59.14	-7.61**	10.88	0.61
R8/9D	31.59	1.39**	5.02^{a}	0.39	71.29	4.55*	11.47	1.20*
F-test	**ns**		**		**ns**		**ns**	
Pisifera	**OTB**	**GCA**	**KTB**	**GCA**	**OY**	**GCA**	**KY**	**GCA**
R5/21P	27.57^{c}	-2.63**	4.89^{b}	0.26	64.47	-2.27	11.49^{b}	1.23*
R3/8P	30.23^{b}	0.03	4.46^{b}	-0.17	70.28	3.54*	10.41^{b}	0.14
R16/7P	31.69^{a}	1.49**	4.36^{b}	-0.27	65.81	-0.94	9.03^{c}	-1.24*
R9/8P	31.50^{a}	1.29*	3.31^{c}	-1.32**	68.92	2.18	7.24^{d}	-3.03**
KA17/2P	30.02^{b}	-0.18	6.14^{a}	1.51**	64.24	-2.50	13.17^{a}	2.91**
F-test	*		**		**ns**		**	

Note: OTB - oil to bunch; GCA - general combining ability; KTB - kernel to bunch; OY - oil yield; KY - kernel yield; within a column, means followed by the same letters are not significantly different according to DMRT ($p \leq 0.05$); * - significant difference at $p \leq 0.05$; ** - highly significant difference at $p \leq 0.01$; ns - non-significant.

well-balanced in all four components with mainly positive SCA effects. R8/9D × R16/7P (T63), although gave the highest mean and SCA in OTB (33.89% and 0.82%), showed low means and/or negative SCA for the other components. Thus, T23 and T24 are good choices for commercial production of *tenera* clones with superior bunch components. Some crosses can be chosen to produce specific components such as the cross R10/5D × KA17/2P (T35) that gave the highest mean in both KTB (7.98%) and KY (18.15 kg palm^{-1} yr^{-1}). T35 expressed high positive SCA in both components.

Discussion

To the available information, this study was the first to use a factorial mating design (also known as North Carolina Mating Design II, NCM II) to create a population of *dura* × *pisifera* (D × P) in oil palm. Although Constantin et al. (2016) evaluated combining ability and genetic variance in introgressed Cameroon oil palms using NCM II, the authors used six *dura* female palms and six *tenera* male palms to produce only 21 (rather than 36) progenies. This was considered an incomplete factorial mating with limited use in a breeding program. They managed to analyse for GCA of the parents and SCA of the crosses without demonstrating the mean trait values for us to compare. Unlike these D × P, their D × T progenies were still segregating in shell thickness giving 1/2 $sh^{+}sh^{+}$ (thick shell *dura*) and 1/2 $sh^{+}sh^{-}$ (thin shell *tenera*), thus requiring further selection and could not be used as a new cultivar.

Noh et al. (2012) used a nested mating design (NCM I) to investigate GCA in a set of *pisifera* parents. This mating design led to the investigation of trait means and GCA on one side of the parents (*pisifera* in their case) because the other parents (*dura*) were randomly taken from the population. The data collected from their progenies during 1998–2004 showed that the estimated values of FFB in their *pisifera* ranged from 121.93–143.5 kg palm^{-1} yr^{-1} with the mean of 131.62 kg palm^{-1} yr^{-1}, BNO ranged from 8.00–9.46 bunches palm^{-1} yr^{-1} with the mean of 8.66 bunches palm^{-1} yr^{-1}, and ABW ranged from 14.40–17.27 kg bunch^{-1} with the mean 15.60 kg bunch^{-1}. The estimated values of five *pisiferas* used in this study (*Table 4*) were higher in FFB and BNO but less ABW than those reported by Noh et al. (2012). The *pisifera* OTB in the current study had an estimated average of 30.20%, ranging from 27.57%–31.69% (*Table 6*), which was higher than their report at the average of 24.91% and range of 23.33%–26.50%. The *pisifera* in this study tended to have less KTB at the range of 3.31%–6.14% compared to their range of 4.86%–6.25%. The *pisifera* in this study had the highest GCA for FFB at 12.43 kg palm^{-1} yr^{-1} (*Table 4*), similar to the highest GCA of Noh et al. (2012) at 12.28 kg palm^{-1} yr^{-1}. The highest GCA for OTB were also comparable, 1.49% in the current study vs. 1.59% in the study by Noh et al. (2012). The highest GCA for KTB in this experiment was 1.51% (*Table 6*) compared to their GCA at 0.57%. Noh et al. (2012) could not analyse the GCA of the *dura* parents nor the SCA of the crosses as the mating design does not allow them to do so.

Arolu et al. (2016) used NCM I to help select good combiners in a *pisifera* set based on data collected from 2001–2014. The palm progenies were obtained from 10 Nigerian *pisiferas* randomly crossed to 24

TABLE 7. TRAIT MEANS AND SCA OF 30 *Teneras* FOR OTB, KTB, OY AND KY, OBSERVED DURING 2012-2022

Crosses	*Dura* × *Pisifera*	OTB	SCA	KTB	SCA	OY	SCA	KY	SCA
T11	R15/14D × R5/21P	25.94^{l}	-1.05	4.56$^{c\text{-}j}$	0.12	63.31$^{d\text{-}h}$	0.00	11.17$^{b\text{-}g}$	0.45
T12	R15/14D × R3/8P	30.60$^{b\text{-}i}$	0.95	4.39$^{d\text{-}j}$	0.38	72.03$^{a\text{-}d}$	2.90	10.33$^{b\text{-}h}$	0.70
T13	R15/14D × R16/7P	30.25$^{c\text{-}i}$	-0.86	3.12^{jk}	-0.79*	56.06^{hi}	-8.60*	5.80^{i}	-2.46*
T14	R15/14D × R9/8P	30.81$^{b\text{-}h}$	-0.11	3.17^{ijk}	0.31	65.29$^{c\text{-}h}$	-2.47	6.73^{hi}	0.26
T15	R15/14D × KA17/2P	30.51$^{c\text{-}i}$	1.07	5.68^{bcd}	-0.01	71.26$^{a\text{-}e}$	8.17*	13.45^{bcd}	1.05
T21	A43/9D × R5/21P	28.37$^{g\text{-}l}$	0.73	3.17^{ijk}	-0.85*	61.22$^{d\text{-}i}$	-4.88	6.90^{ghi}	-2.78*
T22	A43/9D × R3/8P	29.03$^{e\text{-}k}$	-1.27	3.19^{ijk}	-0.40	64.41$^{c\text{-}h}$	-7.51*	7.10^{ghi}	-1.50
T23	A43/9D × R16/7P	33.63^{ab}	1.87*	4.21$^{d\text{-}k}$	0.73	76.25^{abc}	8.80*	9.61$^{d\text{-}i}$	2.40*
T24	A43/9D × R9/8P	33.25^{abc}	1.69*	3.42^{ijk}	0.98*	82.24^{a}	11.68**	8.51$^{e\text{-}i}$	3.08**
T25	A43/9D × KA17/2P	27.07^{jkl}	-3.02**	4.81$^{c\text{-}i}$	-0.46	57.79^{ghi}	-8.09*	10.17$^{b\text{-}h}$	-1.19
T31	R10/5D × R5/21P	30.71$^{b\text{-}h}$	3.21**	5.32$^{b\text{-}g}$	-0.14	76.49^{abc}	12.53**	13.21^{bcd}	0.24
T32	R10/5D × R3/8P	28.60$^{f\text{-}l}$	-1.57*	5.71^{bcd}	0.67	67.98$^{b\text{-}h}$	-1.80	13.59^{bcd}	1.70
T33	R10/5D × R16/7P	28.99$^{e\text{-}k}$	-2.63**	3.92$^{f\text{-}k}$	-1.02*	59.36$^{e\text{-}i}$	-5.95	8.06e-i	-2.45*
T34	R10/5D × R9/8P	32.33$^{a\text{-}d}$	0.91	3.11^{jk}	-0.78*	59.23$^{e\text{-}i}$	-9.19*	5.73i	-2.99*
T35	R10/5D × KA17/2P	30.04$^{d\text{-}j}$	0.08	7.98^{a}	1.26**	68.15$^{b\text{-}h}$	4.42	18.15a	3.50**
T41	R10/1D × R5/21P	27.61$^{i\text{-}l}$	0.53	4.21$^{d\text{-}k}$	-0.14	62.57$^{d\text{-}h}$	-4.94	9.64d-i	-1.13
T42	R10/1D × R3/8P	30.62$^{b\text{-}i}$	0.88	3.63$^{h\text{-}k}$	-0.29	70.72$^{a\text{-}f}$	-2.60	8.39e-i	-1.28
T43	R10/1D × R16/7P	30.94$^{a\text{-}g}$	-0.25	4.39$^{d\text{-}j}$	0.57	75.71^{abc}	6.86*	10.70$^{b\text{-}h}$	2.41*
T44	R10/1D × R9/8P	27.81$^{h\text{-}l}$	-3.19**	2.71^{k}	-0.06	72.75$^{a\text{-}d}$	0.79	7.16^{ghi}	0.64
T45	R10/1D × KA17/2P	31.57$^{a\text{-}f}$	2.04*	5.53$^{b\text{-}f}$	-0.07	67.16$^{c\text{-}h}$	-0.12	11.81$^{b\text{-}f}$	-0.64
T51	A1/2D × R5/21P	26.19^{kl}	-1.04	6.45^{b}	0.69	56.21^{hi}	-0.64	13.84^{bcd}	1.74
T52	A1/2D × R3/8P	30.48$^{c\text{-}i}$	0.59	4.59$^{c\text{-}j}$	-0.75	66.63$^{c\text{-}h}$	3.96	9.96$^{c\text{-}i}$	-1.05
T53	A1/2D × R16/7P	32.40$^{a\text{-}d}$	1.05	6.51^{b}	1.28**	58.95$^{f\text{-}i}$	0.75	11.89$^{b\text{-}e}$	2.26*
T54	A1/2D × R9/8P	32.34$^{a\text{-}d}$	1.18	3.86$^{g\text{-}k}$	-0.32	63.46$^{d\text{-}h}$	2.15	7.60$^{f\text{-}i}$	-0.25
T55	A1/2D × KA17/2P	27.90$^{g\text{-}l}$	-1.79*	6.12^{bc}	-0.90*	50.41^{i}	-6.22	11.08$^{b\text{-}g}$	-2.70*
T61	R8/9D × R5/21P	26.58^{kl}	-2.38**	5.59$^{b\text{-}e}$	0.32	66.95$^{c\text{-}h}$	-2.06	14.17^{bc}	1.48
T62	R8/9D × R3/8P	32.04$^{a\text{-}e}$	0.42	5.23$^{b\text{-}h}$	0.39	79.87^{ab}	5.05	13.03^{bcd}	1.43
T63	R8/9D × R16/7P	33.89^{a}	0.82	3.98$^{e\text{-}k}$	-0.76	68.48$^{b\text{-}g}$	-1.87	8.06$^{e\text{-}i}$	-2.16*
T64	R8/9D × R9/8P	32.41$^{a\text{-}d}$	-0.47	3.56^{ijk}	-0.13	70.50$^{a\text{-}f}$	-2.96	7.70$^{e\text{-}i}$	-0.74
T65	R8/9D × KA17/2P	26.58^{kl}	1.61*	6.71^{ab}	0.19	70.62$^{a\text{-}f}$	1.84	14.35^{b}	-0.02
Mean		**30.20**		**4.63**		**66.74**		**10.26**	
%CV		**5.16**		**17.97**		**9.14**		**20.98**	

Note: OTB - oil to bunch; SCA - specific combining ability; KTB - kernel to bunch; OY - oil yield; KY - kernel yield; within a column, means followed by the same letters are not significantly different according to DMRT ($p \leq 0.05$); * - significant difference at $p \leq 0.05$; ** - highly significant difference at $p \leq 0.01$.

Deli *duras*. They found FFB, BNO, ABW, OTB, KTB, OY and KY ranging from 173.80–211.46 kg palm^{-1} yr^{-1} (average 191.92 kg palm^{-1} yr^{-1}), 15.29–18.88 bunches palm^{-1} yr^{-1} (average 16.71 bunches palm^{-1} yr^{-1}), 10.28–12.79 kg bunch^{-1} (average 11.53 kg bunch^{-1}), 25.15%–29.41% (average 27.58%), 3.00%–5.24% (average 3.94%), 44.06–60.24 kg palm^{-1} yr^{-1} (average 53.72 kg palm^{-1} yr^{-1}) and 5.94–9.39 kg palm^{-1} yr^{-1} (average 7.62 kg palm^{-1} yr^{-1}). The range and average values of their traits were mainly lower than those in this research (*Table 4* and *6*). As usual, the nested mating design allowed them to only examine the merits of the male parents. Arolu et al. (2016) finally identified four *pisifera* palms based on their performances and GCA of FFB, OY and palm height. More comparisons on the results from this experiment with those from the NMC I experiment conducted by Rafii et al. (2002) showed that the calculated values for their *pisifera* parents in OTB, KTB, OY, and KY ranged from 22.25%–23.77% (average 22.73%), 4.67%–5.51% (average 5.15%), 22.10–42.55 kg palm^{-1} yr^{-1} (average 34.37 kg palm^{-1} yr^{-1}) and 5.27–9.74 kg palm^{-1} yr^{-1} (average 7.69 kg palm^{-1} yr^{-1}), respectively. Their OTB, OY and KY were lower than those reported in this study, while KTB was rather comparable (*Table 6*).

In the current study, the *dura* and *pisifera* parents were obtained from selfing a diverse set of commercial *tenera* oil palms. Lim et al. (2003) chose the female parents from D × T and the male parents from T × T based on bunch and fruit traits. Their *dura* and *pisifera* parents showed lower OTB (26.50%) but higher KTB (7.00%) as compared to the materials used in this study (*Table 6*). Teo et al. (2004) conducted progeny testing using a diverse source of *pisifera* originating from Binga (Congo), Ekona (Cameroon), and URT (Ulu Remis *tenera*) hybridised with Deli, African, and African × Deli *dura*s. They reported that FFB, BNO, ABW, OTB, KTB, and OY of the progenies were in the range of 93.0–146.0 kg palm^{-1} yr^{-1}, 12.0–20.2 bunches palm^{-1} yr^{-1}, 6.1–9.3 kg bunch^{-1}, 20.60%–26.40%, 3.70%–6.90% and 21.8–38.6 kg palm^{-1} yr^{-1}, respectively. Their *duras* showed FFB, BNO, and ABW in the range of 101.7–143.3 kg palm^{-1} yr^{-1}, 11.9–19.4 bunches palm^{-1} yr^{-1}, and 6.4–8.5 kg bunch^{-1}, respectively. These values, except for KTB, were generally lower than those of the *dura*s in this study (*Table 6*). Junaidah et al. (2011) evaluated D × P progenies for eight years to measure FFB, BNO, ABW, OTB, KTB, OY and KY. They reported the ranges and means of the traits at 165.74–175.34 kg palm^{-1} yr^{-1} (average 172.54 kg palm^{-1} yr^{-1}), 11.27–13.43 bunches palm^{-1} yr^{-1} (average 12.80 bunches palm^{-1} yr^{-1}), 13.16–14.88 kg bunch^{-1} (average 13.64 kg bunch^{-1}), 26.45%–29.50% (average 28.72%), 3.58%–4.95% (average 4.60%), 6.22–7.20 t ha^{-1} yr^{-1} (average 6.95 t ha^{-1} yr^{-1}) and 0.87–1.15 t ha^{-1} yr^{-1} (average 1.11 t ha^{-1} yr^{-1}), respectively. Their values are generally lower than those of D × P progenies in the current study (*Table 5* and *7*). Marhalil et al. (2013) recorded bunch yield and bunch components of 11 D × P for seven consecutive years. They found the maximum BNO of 16.10 bunches palm^{-1} yr^{-1} which was similar to this study. However, their FFB, ABW, OTB, OY and KY were less than those of the progenies in this study, except for only KTB (*Table 5* and *7*). Arolu et al. (2017) tested 34 D × P progenies for six consecutive years, their FFB and ABW were lower than the current study with rather similar values in BNO. Their results for OTB, KTB, OY and KY were less than, but the maximum of OTB (31.00%) and KTB (5.21%) were similar to the current results. Swaray et al. (2020) performed a study on 24 D × P crosses developed from 10 origins and found that Deli Ulu Remis × Nigeria recorded the highest FFB (184.62 kg palm^{-1} yr^{-1}) and BNO (22.91 bunches palm^{-1} yr^{-1}), while Deli Banting × AVROS had the highest ABW (10.36 kg bunch^{-1}). Their materials had lower FFB and ABW but more BNO as compared to this study. The yield components positively determining FFB are BNO and ABW, however BNO is negatively correlated with ABW (Tanya et al., 2013).

Based on the above results, the current study has made full use of trait means, GCA, and SCA in choosing suitable parents for production of superior *tenera* hybrids and for further genetic improvement. This D × P factorial population has a major advantage over the populations obtained from the other mating designs as it can be used to concurrently estimate the means of traits, GCA of both *dura* and *pisifera* parents and SCA of the progenies. Pictures of fruits and palms of some selected elite parents and crosses are shown in *Figure 1*.

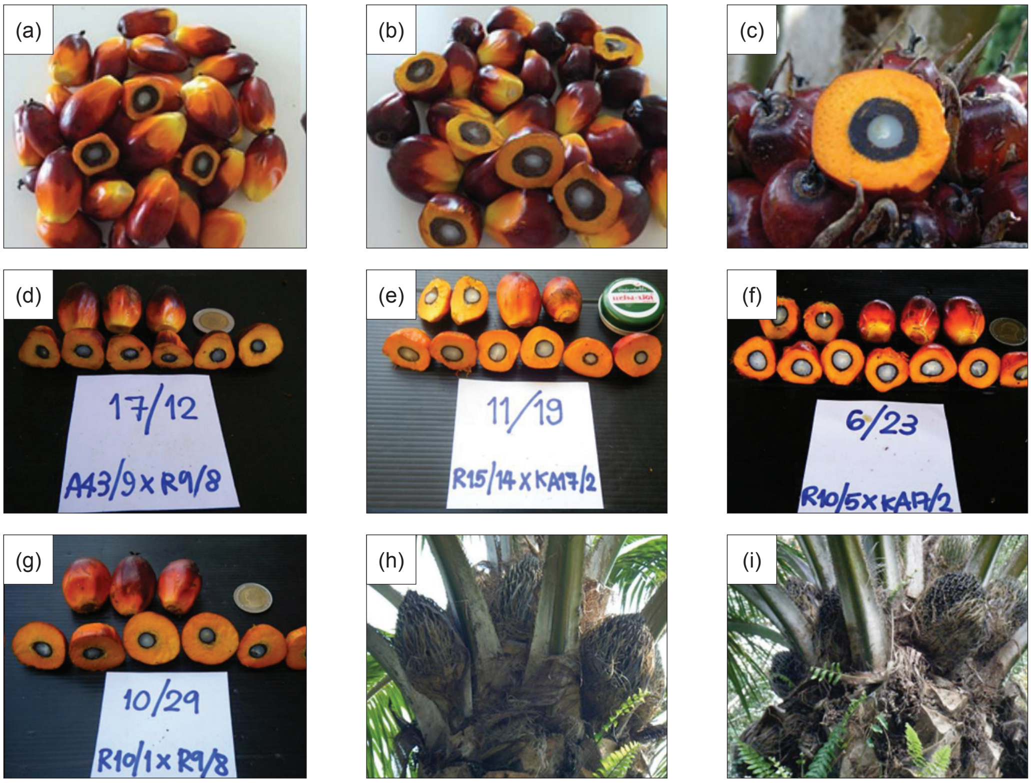

Figure 1. Fruit cross-section of (a) R10/1D, (b) R10/5D, and (c) A43/9D; four elite teneras *(d) A43/9D × R9/8P, (e) R15/14D × KA17/2P, (f) R10/5D × KA17/2P, and (g) R10/1D × R9/8P. Two types of* pisifera *palms were used in this experiment, (h) female sterile type (R5/21P, R16/7P, KA17/2P), and (i) female infertile type (R3/8P, R9/8P).*

CONCLUSION

The use of factorial mating design (NCM II) has several advantages over the other mating designs in oil palm breeding, as it can help select the desirable parental palms based on trait means and GCAs. Yet, it can earmark the superior cross combinations for commercial seed production based on trait means and SCAs of the progenies. The elite parents R10/1D and R5/21P were identified as having good GCA for FFB and BNO, while R8/9D showed high GCA for OTB, OY and KY. R3/8P showed good GCA for FFB and ABW, while A43/9D and R9/8P for BNO. R10/5D and KA17/2P were high in GCA for KTB and KY. These parents were chosen by the company for further improvement. Among the crosses, R10/1D × R9/8P showed significant SCA for FFB, BNO, and ABW, whereas R15/14D × KA17/2P gave high SCA for ABW and OY. A43/9D × R9/8P and R10/5D × KA17/2P had the best SCA for OY and KY, respectively. A43/9D × R9/8P also showed significant SCA in all traits under study, except only for BNO. As the result, superior parental palms were successfully identified for government registration and commercial production.

ACKNOWLEDGEMENT

This research was partially supported by the Center of Excellence on Biotechnology of Oil Palm for Renewable Energy, Ministry of Higher Education, Science, Research and Innovation and the Center of Advanced Study on Agriculture and Food of Kasetsart University, Bangkok, Thailand (project no. CASAF 148).

REFERENCES

Arolu, I. W., Rafii, M. Y., Marjuni, M., Hanafi, M. M., Sulaiman, Z., Rahim, H. A., Abidin, M. I. Z., Amiruddin, M. D., Din, A. K., & Nookiah, R. (2017). Breeding of high yield and dwarf oil palm planting materials using Deli *dura* × Nigerian *pisifera* population. *Euphytica, 213*, 154. https://doi.org/10.1007/s10681-017-1943-z

Arolu, I. W., Rafii, M. Y., Marjuni, M., Hanafi, M. M., Sulaiman, Z., Rahim, H. A., Kolapo, O. K., Abidin, M. I. Z., Amiruddin, M. D., Kushairi, A., & Rajanaidu, N. (2016). Genetic variability analysis and selection of pisifera palms for commercial production of high-yielding and dwarf oil palm planting materials. *Industrial Crops and Products, 90*, 135–141. https://doi.org/10.1016/j.indcrop.2016.06.006

Comstock, R. E., & Robinson, H. F. (1952). Estimation of the average dominance of genes. In J. W. Gowen (Ed.), *Heterosis* (pp. 494–516). Iowa State College Press.

Constantin, M., Sobir, Syukur, M., Suwarno, W. B., & Ntsefong, G. N. (2016). Evaluation of combining ability and genetic variance in introgressed widikum *Elaeis guineensis* Jacq. of Cameroon using North Carolina II mating design. *International Journal of Development Research, 6*(8), 9275–9281.

Corley, R. H. V., & Tinker, P. B. (2016). *The oil palm* (5th ed.). Wiley-Blackwell.

Food and Agriculture Organization. (FOASTAT). (2023). *FAOSTAT statistical database*. https://www.fao.org/faostat/en/#data/QC

Gingold, B., Rosenbarger, A., Muliastra, Y. I. K. D., Stolle, F., Sudana, I. M., Manessa, M. D. M., Murdimanto, A., Tiangga, S. B., Madusar, C. C., & Douard, P. (2012). *How to identify degraded land for sustainable palm oil in Indonesia* (Working Paper). World Resources Institute (WRI) & Sekala. https://www.wri.org/research/how-identify-degraded-land-sustainable-palm-oil-indonesia

Griffing, B. (1956). Concept of general and specific combining ability in relation to diallel crossing systems. *Australian Journal of Biological Sciences, 9*(4), 463–493.

Junaidah, J., Rafii, M. Y., Chin, C. W., & Salleh, G. (2011). Performance of *tenera* oil palm population derived from crosses between Deli *dura* and *pisifera* from different sources on inland soils. *Journal of Oil Palm Research, 23*(3), 1210–1221.

Kushairi, A., Mohd Din, A., & Rajanaidu, N. (2011). Oil palm breeding and seed production. In M. B. Wahid, Y. M. Choo, & K. W. Chan (Eds.), *Further advances in oil palm research* (Vol. 1, pp. 47–101). Malaysian Palm Oil Board (MPOB).

LeClerg, E. L., Leonard, W. H., & Clark, A. G. (1966). *Field plot technique*. Burgess Publishing Co.

Lim, C. C., Teo, K. W., Rao, V., & Chia, C. C. (2003). Performances of some *pisiferas* of Binga, Ekona, URT and Angolan origins: Part 1 – Breeding background and fruit bunch traits. *Journal of Oil Palm Research, 15*(1), 21–31.

Marhalil, M., Rafii, M. Y., Afizi, M. M. A., Arolu, I. W., Noh, A., Mohd Din, A., Kushairi, A., Norziha, A., Rajanaidu, N., Latif, M. A., & Malek, M. A. (2013). Genetic variability in yield and vegetative traits in elite germplasm of MPOB-Nigerian *dura* × AVROS *pisifera* progenie. *Journal of Food, Agriculture & Environment, 11*(2), 515–519.

Noh, A., Rafii, M. Y., Saleh, G., Kushairi, A., & Latif, M. A. (2012). Genetic performance and general combining ability of oil palm Deli *dura* × AVROS *pisifera* tested on inland soils. *The Scientific World Journal, 2012*, 1–8. https://doi.org/10.1100/2012/792601

Petersen, R. G. (1994). *Agricultural field experiments: Design and analysis*. CRC Press.

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rafii, M. Y., Rajanaidu, N., Jalani, B. S., & Kushairi, A. (2002). Performance and heritability estimations on oil palm progenies tested in different environments. *Journal of Oil Palm Research, 14*(1), 15–24.

Rajanaidu, N., Kushairi, A., Rafii, M., Mohd Din, A., Maizura, I., & Jalani, B. S. (2000). Oil palm breeding and genetic resources. In Y. Basiron, B. S. Jalani, & K. W. Chan (Eds.), *Advances in oil palm research* (Vol. 1, pp. 171–237). Malaysian Palm Oil Board (MPOB).

Rao, V., Soh, A. C., Corley, R. H. V., Lee, C. H., Rajanaidu, N., Tan, Y. P., Chin, C. W., Lim, K. C., Tan, S. T., Lee, T. P., & Ngui, M. (1983). *A critical reexamination of the method of bunch quality analysis in oil palm breeding* (PORIM Occasional Paper No. 9). Palm Oil Research Institute of Malaysia (PORIM).

Soh, A. C., Mayes, S., & Roberts, J. (2017). *Oil palm breeding: Genetics and genomics*. CRC Press.

Sprague, G. F., & Tatum, L. A. (1942). General vs. specific combining ability in single crosses of corn. *Journal of the American Society of Agronomy, 34*(10), 923–932.

Swaray, S., Din Amiruddin, M., Rafii, M. Y., Jamian, S., Ismail, M. F., Jalloh, M., Marjuni, M., Mustakim Mohamad, M., & Yusuff, O. (2020). Influence of parental *dura* and *pisifera* genetic origins on oil palm fruit set ratio and yield components in their D × P progenies. *Agronomy, 10*(1793), 1–30. https://doi.org/10.3390/agronomy10111793

Taeprayoon, P., Tanya, P., Lee, S. H., & Srinives, P. (2015). Genetic background of three commercial oil palm breeding populations in Thailand revealed by SSR markers. *Australian Journal of Crop Science, 9*(4), 281–288.

Taeprayoon, P., Tanya, P., Kang, Y. J., Limsrivilai, A., Lee, S. H., & Srinives, P. (2016). Genome-wide SSR marker development in oil palm by Illumina HiSeq for parental selection. *Plant Genetic Resources, 14*(2), 157–160. https://doi.org/10.1017/S1479262115000143

Tanya, P., Hadkam, Y., Taeprayoon, P., & Srinives, P. (2013). Estimates of repeatability and path coefficient of bunch and fruit traits in Bang Boet *dura* oil palm. *Journal of Oil Palm Research, 25*(1), 108–115.

Teo, K. W., Rao, V., Chia, C. C., & Lim, C. C. (2004). Performance of some *pisiferas* of Binga, Ekona, URT, and Angolan origins: Part 2 – Fruit bunch yields, vegetative growth, and physiological traits. *Journal of Oil Palm Research, 16*(1), 22–38.

United States Department of Agriculture. (USDA). (2023). *Oilseeds: World markets and trade*. Foreign Agricultural Service. https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf