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Growth and yield performance of Bambara groundnut advanced line and introduced accessions grown in the rainy season in the South of Thailand

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Abstract Result showed that the days to 50% flowering among four bambara groundnut genotypes ranged from 31.75 days to 34.25 days and days to harvest ranged from 93 days to 125 days. TVsu 89 had the lowest days to 50% flowering of 31.75 days and days to harvest of 93 days. TVsu 89 had lower agronomic traits than check variety (Songkhla 1), but it was not different from check variety for fresh pod yield and dry pod yield. Correlation analysis indicated that harvest index was positively and significantly associated with fresh pod yield and dry pod yield.

Keywords: Cropping system, Correlation, Early maturity, Rubber plantation, Physiological traits

Introduction

Bambara groundnut (*Vigna subterranean* (L.) Verdc) is a leguminous species in fabaceae family (Rachie, 1979). The plant is native to sub-saharan (Mayes *et al*., 2019) and the madagascar islands in West Africa (Hepper, 1963). Its exact area of origin in Africa has however been a subject of debate (Temegne *et al*., 2018). Bambara groundnut may be introduced to Southeast Asia (Thailand) from West Africa via East Africa (Rungnoi *et al*., 2012). In Thailand, it was first found that in the southern border area in 1931. The crop is known under different local names such as kajapo, ficus beans, single beans, panyi beans, bo beans. Therefore, it is most commonly planted in Songkhla, Narathiwat, Yala, Pattani, Phatthalung, Krabi, Trang, Nakhon Si Thammarat, and Surat Thani.

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The smallholder farmers in the South of Thailand have grown bambara groundnut as a cash crop in intercropping system with rubber trees and fruit crops during the first and second years of plantation. The most abundant nutrient in bambara groundnut is carbohydrate (55.6-67.1%) and amylose content of its starch ranges between 15.7 to 35.3%, while dietary fibre content can be up to 10.3% (Halimi *et al*., 2019; Marcel *et al*., 2014). According to Mbagwu *et al*. (2011), seed of bambara groundnut contained lipid (7.84%), protein (18.65%), potassium (3.15%), phosphorus (1.74%), calcium (0.35%) and manganese (0.39%), and it also contained other phytochemicals such as alkaloids (0.40%), flavonoids (0.29%) and saponins (0.43%). Marcel *et al*. (2014) reported that seeds of bambara groundnut contained phenols (0.60%), carotenoids (0.26%) and anthocyanins (1.00%).

Climate change is one factor driving the spread of pests and diseases. The use of late maturing varieties is at risk for disease infestation in the late growing cycle, and the use of early maturing varieties can avoid disease and pest infestation. Therefore, improvement of early maturing varieties is important to reduce crop lost from the impact of climate instability and destruction of diseases and pests (Kongnakhon *et al.*, 2016b).

There are two varieties of bambara groundnut of in the South of Thailand including a local variety and Songkhla 1. The local variety is expected to be the first introduced variety with maturity of 150-180 days, while Songkhla 1 is a released variety with maturity of 110-120 days (Suwanprasert, 2005). The use of late maturing varieties is at risk not only for disease and pest infestation but also weed competition. Early maturing varieties are advantageous and more suitable for many cropping systems, and allow farmers to grow more than one crops in early rainy season and late rainy season (Petthong *et al*, 2016). TVsu 1221 and TVsu 89 were introduced from Nigeria, and SK1-15 is an advanced breeding line from our bambara groundnut breeding program for early maturity. TVsu 1221 and TVsu 89 give a good yield and agronomic traits comparable to Songkhla 1 (Kongnakhon *et al.*, 2016a; Kongnakhon *et al.*, 2016b). The objective was to compare the new breeding lines and the old variety of bambara groundnut for growth and yield in Songkhla province.

Materials and methods

Location and experimental design

Randomized complete block design was performed with four replications and treatments were one variety, 2 accessions and 1 advanced breeding line. The experimental site was Songkhla agricultural research and development centre, Hatyai district, Songkhla province, Thailand (Lat 7.017141, Long 100.504695) in the rainy season during May 2021 to September 2021.

Bambara groundnut var. Songkhla 1 is released variety popularly cultivated in Thailand. The former name of Songkhla 1 is TVsu 922, which was kindly donated from IITA in 1989. This variety has high yield and late maturity, and used as a standard check. Two accessions consisted of TVsu 1221 and TVsu 89, which were kindly donated from IITA in 2003. SK1-15 is an advanced breeding line of our breeding program for early maturity. Three genotypes including two accessions and one advanced breeding line had good yield comparable to Songkhla 1, which was used as the check variety, and they have potential for possible release. TVsu 1221, TVsu 89 and SK1-15 had been evaluated for yield and agronomic traits according to the evaluation system of bambara groundnut breeding program in Thailand. Although they passed the evaluation at advanced levels, the recorded data were focused on yield and yield components. This study was carried out to evaluate other important traits for use as the necessary information for varietal register and crop modelling.

Crop management

Soil in the field was collected and analyzed for physical and chemical properties. The soil texture was loamy clay, and it was acidic with a pH range between 4.58 and 4.66. The electrical conductivity of the soil was 0.06 dS/m. Conventional tillage was practiced for soil preparation by ploughing two times followed by harrowing once. Bambara groundnut was planted on flat soil at a spacing of 50 cm between rows and 40 cm between the plants within rows on May 11, 2021. The crop was planted at the seed rate of 3 seeds per hill, and the seedlings were thinned to obtain 2 seedlings per hill at 14 days after planting. Evaluation of germination was carried out at 14 days after planting. The plot size was 4.8×5 m, and there were 16 plots totally. Weed control was practiced for both chemical and manual weeding methods. For chemical weed control, alachlor, a pre-emergence herbicide, was sprayed on the soil at the rate of 3.75 l ha^{-1} after planting. Manual weeding was carried out by hoeing at 3 weeks after planting. Sprinkler irrigation system was installed to supplied water to the crop to avoid water deficit. However, it was rarely used because of good distribution of rainfall. Compound fertilizer of N–P–K (15:15:15) was applied to the crop at the rate of 187.5 kg ha^{-1} at 3 weeks after planting. Ridging was practiced by piling soil up around the base of a plants after fertilizer application. Carbaryl, an insecticide, was sprayed on the crop to control subterranean ants at pod setting stage.

Data collection

Data were recorded for plant height and canopy diameter at 25 days after planting (DAP), 50 DAP, 75 DAP and harvest from 12 plants in each plot. Plant height was measured from ground level to the highest point of leaf tip. Canopy size was measured at the widest point of the canopy. Days to 50% flowering was recorded from 0 day after planting to the day, when 50% of the plants in each plot were blooming. Twelve plants in each plot were harvested. The plants, which were used for measurement of plant height and canopy diameter, were the same plants, which were harvested. The plants were cut at ground level, and leaves were separated from the stems. Leaves were measured of leaf area using disc borer method. Leaves were cut with a disc borer, and 40 leaves discs of each plant in each plot were used for measurement of specific leaf area.

Leaf area index (LAI) was calculated as follows;

LAI = LA/GA where, LA is the leaf area and GA is the land area.

Specific leaf area (SLA) was calculated according to the formula below;

SLA = LA/LW where, LA is the leaf area and LW is the leaf dry weight.

Pods were separated from the plants at harvest time. All parts of the plants were weighted after separation into parts to avoid water loss. All parts of the plants were oven-dried at 65-70 ℃ for 72 hours to determine dry weight.

Crop growth rate (CGR) was calculated according to the equation below;

CGR = 1/GA × [(W2- W1)/(T2-T1)] where, GA is the land area, W2 and W1 are dry weights of plant at time T2and T1, respectively.

Data analysis

Data were subjected to analysis of variance (ANOVA) using MSTAT-C software program from Michigan State University (Bricker, 1989). Duncan's Multiple Range Test (DMRT) was used to compare means at 0.05 probability level. Correlation coefficients were analysed by Microsoft Excel.

Results

Field emergence, days to 50% flowering and days to harvest

Significant differences (P≤0.05 and P≤0.01) among four genotypes of bambara groundnut were observed field emergence and days to 50% flowering (Table 1). Percentages of field emergence of four genotypes ranged between 84.27% and 98.78%. Songkhla 1 was highest for these traits, and it was significantly higher than SK1-15, whereas TVsu 1221 and TVsu 89 were intermediate between Songkhla 1 and SK1-15, and they were not significantly different from Songkhla 1 and SK1-15. Days to flowering were between 31.75 and 34.25 days. TVsu 1221 and SK1-15 were similar for this trait, and they were significantly higher than Songkhla 1 and TVsu 89. Days to harvest was not analyzed statistically because all plots of the same genotype were harvest on the same day. It was apparent that TVsu 89 was early mature (93 days), whereas Songkhla 1, TVsu 1221 and SK1-15 were late mature (124-125 days).

Table 1. Means for field emergence, days to 50% flowering and days to harvest of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	Field emergence (%)	Days to 50 % Flowering (DAP)	Days to harvest (DAP)[1/]
Songkhla 1	98.78[a]	32.00[b]	124
TVsu 1221	90.56[ab]	34.25[a]	124
TVsu 89	93.01[ab]	31.75[b]	93
SK1-15	84.27[b]	34.25[a]	125
F-test	*	**	-
C.V. (%)	5.96	1.90	-

DAP = day after planting, * and **= significantly different at $P < 0.05$ and significantly different at $P < 0.01$, respectively, Means within the same column followed by the same letter are not significantly different by DMRT.[1/] All plots of the same genotype were harvested at the same time.

Plant height

Plant height was measured at 25 days after planting (DAP), 50 DAP, 75 DAP and harvest. Plant height increased with time from 25 DAP to harvest in all genotypes (Table 2). Significant differences P≤0.01 among bambara groundnut genotypes were observed for plant height at 25 DAP, 50 DAP and harvest. The ranks for plant height were different across times of evaluation, indicating the interaction between time and variety for this trait. SK1-15 was consistently tallest at 25 DAP, 50 DAP, 75 DAP and harvest, whereas TVsu 89 was consistently shortest. Plant heights at harvest ranged between 34.86 cm in TVsu 89 and 44.92 cm in SK1-15.

Table 2. Means for plant height at 25 days after planting (DAP), 50 DAP, 75 DAP and at harvest of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	**Plant Height (cm)**			
	25 DAP	50 DAP	75 DAP	At harvest
Songkhla 1	26.80[a]	28.14[b]	38.76	40.68[ab]
TVsu 1221	23.93[ab]	30.26[b]	43.01	44.05[a]
TVsu 89	21.26[b]	30.25[b]	34.02	34.86[b]
SK1-15	25.47[a]	37.07[a]	40.12	44.92[a]
F-test	**	**	ns	**
C.V. (%)	5.90	8.14	11.96	8.24

DAP = day after planting, ns and ** = non significant and significantly different at $P < 0.01$, respectively, Means within the same column followed by the same letter are not significantly different by DMRT.

Canopy diameter

Canopy diameter increased with time from 25 DAP to harvest in all genotypes (Table 3). Bambara groundnut genotypes were significantly different ($P \leq 0.05$ and $P \leq 0.01$) for canopy diameter at 25 DAP, 50 DAP, 75 DAP and harvest. There was the interaction between bambara groundnut genotype and time for canopy size as the ranks of the genotypes were different across times. SK1-15 had the largest canopy across times, whereas TVsu 89 had the smallest canopy across times. At harvest, canopy size of SK1-15 was 72.50 cm, and canopy size of TVsu 89 was 52.79 cm, which were significantly different.

Table 3. Means for canopy diameter at 25 days after planting (DAP), 50 DAP, 75 DAP and at harvest of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	**Canopy diameter (cm)**			
	25 DAP	50 DAP	75 DAP	At harvest
Songkhla 1	39.79[a]	46.08[b]	62.77[ab]	61.81[b]
TVsu 1221	35.58[b]	49.94[b]	72.10[a]	70.61[a]
TVsu 89	30.70[c]	46.90[b]	52.88[b]	52.79[c]
SK1-15	38.98[ab]	66.02[a]	74.84[a]	72.50[a]
F-test	**	**	*	**
C.V. (%)	4.89	6.92	12.52	4.76

DAP = day after planting, * and **= significantly different at $P < 0.05$ and significantly different at $P < 0.01$, respectively, Means within the same column followed by the same letter are not significantly different by DMRT

Leaf area index

Leaf area indexes increased with times from 25 DAP to 75 DAP, when leaf area indexes were highest in all genotypes, and leaf area indexes reduced at harvest (Table 4). Significant differences ($P \leq 0.05$) among the genotypes were found at 25 DAP and 50 DAP. The ranks of the genotypes changed across times, indicating the interaction between genotype and time. At 75 DAP, SK1-15 had the highest leaf area index (9.30), whereas TVsu 89 had the lowest leaf area index (3.59) although they were not significantly different. At harvest, Songkhla 1 had the highest leaf area index (5.00), and TVsu 89 had the lowest leaf area index (3.23) although they were not significantly different.

Table 4. Means for leaf area index (LAI) at 25 days after planting (DAP), 50 DAP, 75 DAP and at harvest of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	Leaf area index (LAI)			
	25 DAP	50 DAP	75 DAP	At harvest
Songkhla 1	0.22^{ab}	2.88^{a}	5.63	5.00
TVsu 1221	0.15^{b}	$2.76a^{b}$	4.32	3.56
TVsu 89	0.41^{a}	1.47^{b}	3.59	3.23
SK1-15	0.36^{a}	3.41^{a}	9.30	4.81
F-test	*	*	ns	ns
C.V. (%)	42.18	31.62	50.03	29.86

DAP = day after planting, ns and * = non significant and significantly different at $P < 0.05$, respectively, Means within the same column followed by the same letter are not significantly different by DMRT

Specific leaf area

Bambara groundnut genotypes were significantly different ($P \leq 0.05$ and $P \leq 0.01$) for specific leaf area at 25 DAP, 75 DAP and harvest (Table 5). In general, specific leaf area seemed to reduce with times from 25 DAP to harvest. There was interaction between bambara groundnut genotype and time as the ranks of the genotypes changed across times. TVsu 89 has the highest specific leaf area at 25 DAP (409.85 cm^2 g^{-1}) and 75 DAP (278.35 cm^2 g^{-1}), whereas SK1-15 had the highest specific leaf area at 50 DAP (361.04 cm^2 g^{-1}). All bambara groundnut genotypes had the lowest specific leaf area at harvest.

Table 5. Means for specific leaf area (SLA) at 25 days after planting (DAP), 50 DAP, 75 DAP and at harvest of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	Specific leaf area (SLA) (cm^2 g^{-1})			
	25 DAP	50 DAP	75 DAP	At harvest
Songkhla 1	315.19^{ab}	329.72	260.24^{b}	156.48^{a}
TVsu 1221	229.90^{b}	304.16	105.16^{c}	82.22^{b}
TVsu 89	409.85^{a}	257.31	278.35^{ab}	97.39^{b}
SK1-15	340.67^{ab}	361.04	340.01^{a}	113.22^{ab}
F-test	*	ns	**	*
C.V. (%)	22.64	17.19	17.95	27.67

DAP = day after planting, ns = non significant, * and **= significantly different at $P < 0.05$ and significantly different at $P < 0.01$, respectively, Means within the same column followed by the same letter are not significantly different by DMRT

Crop growth rate

Significant differences (P≤0.05 and P≤0.01) among bambara groundnut genotypes were found for crop growth rate at 50 to 75 DAP and 75 DAP to harvest (Table 6). Crop growth rates increased with times, but the peak times were different among genotypes. TVsu 1221 and SK1-15 had peak time at 50 DAP to 75 DAP, whereas Songkhla 1 and TVsu 89 had peak time at 75 DAP to harvest. TVsu 1221 had the highest crop growth rate (25.91 g m^{-2} d^{-1}) at 50 DAP to 75 DAP, whereas TVsu 89 had the highest crop growth rate (24.00 g m^{-2} d^{-1}) at 75 DAP to harvest.

Table 6. Means for crop growth rate (CGR) at planting (PT) to 25 days after planting (DAP), 25 DAP to 50 DAP, 50 DAP to 75 DAP and 75 DAP to harvest of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	CGR (g m^{-2} d^{-1})			
	PT to 25 DAP	25 to 50 DAP	50 to 75 DAP	75 to harvest
Songkhla 1	0.67	6.13	9.78^{b}	11.31^{a}
TVsu 1221	0.66	6.78	25.91^{a}	3.20^{b}
TVsu 89	0.75	5.59	6.32^{b}	24.00^{a}
SK1-15	0.72	7.02	17.09^{ab}	5.04^{ab}
F-test	ns	ns	*	**
C.V. (%)	36.14	44.33	57.43	50.25

PT = planting, DAP = day after planting, ns = non significant, * and **= significantly different at $P < 0.05$ and significantly different at $P < 0.01$, respectively, Means within the same column followed by the same letter are not significantly different by DMRT

Total dry weight

Total dry weight increased with times from 25 DAP to harvest in all bambara groundnut genotypes (Table 7). However, significant differences among bambara groundnut genotypes were found at 75 DAP and harvest only. TVsu 1221 also had the highest total dry weight (8.34 t ha^{-1}) at 75 DAP followed by SK1-15 (6.21 t ha^{-1}). TVsu 1221 also had the highest total dry weight (9.90 t ha^{-1}) at harvest followed by Songkhla 1 (9.69 t ha^{-1}) and SK1-15 (8.68 t ha^{-1}), respectively. TVsu 89 had the lowest total dry weight at 75 DAP (3.17 t ha^{-1}) and harvest (7.49 t ha^{-1}). At harvest, TVsu 1221 and SK1-15 were not significantly different from check variety, whereas TVsu 89 was significantly lower than check variety.

Fresh pod yield, dry pod yield and harvest index

Bambara groundnut genotypes were not significantly different for fresh pod yield and dry pod yield (Table 8). Fresh pod yields ranged between 1.47 and 2.42 t ha^{-1}, and dry pod yield ranged between 0.51 and 0.79 t ha^{-1}. TVsu 1221 had the highest fresh pod yield (2.42 t ha^{-1}) and dry pod yield (0.79 t ha^{-1}), whereas SK1-15 had the lowest fresh pod yield (1.47 t ha^{-1}) and dry pod yield (0.51 t ha^{-1}). Bambara groundnut genotypes were not significantly different for harvest index. The range of harvest indexes was between 0.05 and 0.15. TVsu 1221 had the highest harvest index, whereas the others had low harvest index (0.05 and 0.06).

Table 7. Means for total dry weight at 25 days after planting (DAP), 50 DAP, 75 DAP and at harvest of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	**Total dry weight (t ha^{-1})**			
	25 DAP	50 DAP	75 DAP	At harvest
Songkhla 1	0.18	1.70	4.14^{b}	9.69^{a}
TVsu 1221	0.17	1.86	8.34^{a}	9.90^{a}
TVsu 89	0.19	1.59	3.17^{b}	7.49^{b}
SK1-15	0.18	1.94	6.21^{a}	8.68^{ab}
F-test	ns	ns	*	*
C.V. (%)	36.14	39.62	33.72	11.60

DAP = day after planting, ns and *= non significant and significantly different at $P < 0.05$, respectively, Means within the same column followed by the same letter are not significantly different by DMRT

Table 8. Means for fresh pod yield, dry pod yield and harvest index of four bambara groundnut genotypes grown in the rainy season 2021

Genotype	Fresh pod yield (t ha^{-1})	Dry pod yield (t ha^{-1})	Harvest index
Songkhla 1	1.58	0.73	0.05
TVsu 1221	2.42	0.79	0.15
TVsu 89	1.74	0.60	0.06
SK1-15	1.47	0.51	0.05
F-test	ns	ns	ns
C.V. (%)	28.13	26.96	78.42

ns = non significant

Correlation

Plant height, canopy diameter, days to 50% flowering and days to harvest were inter-correlated, and the correlation coefficients ranged from 0.78 to 0.90 (Table 9). The significant correlation coefficients would be meaningful if they are higher than 0.50. Fresh pod yield, dry pod yield and harvest index were also inter-correlated, and the correlation coefficients ranged between 0.84 and 0.95. It is surprising that growth traits were not correlated with pod yield and harvest index. Leaf area index had significant correlation coefficients with plant height, days to harvest and specific leaf area, whereas total dry weight had significant correlation coefficients with plant height, days to harvest and crop growth rate.

Discussion

Field emergence, days to 50% flowering and days to harvest

Field emergence is important for plant population density and crop establishment in the field, and, ultimately, it affects crop performance. In this study, Songkhla 1 was the best genotype for field emergence, and other genotypes were in a range of commercial seed quality, which is higher than 80%. However, the seedlings were thinned to obtain uniform population density, and field emergence was expected to affect the experiment. This legume has slow germination of about 2 weeks (Nordin and Singh, 2015), and the seed is at risk for soil born damage under unfavorable condition. Therefore, good germination is a criterion for selection. According to Nordin and Singh (2015) high temperatures (30-35 ℃) and low temperatures (lower than 20 ℃) reduced seed germination. Sowing depth was greatly reduced field germination, and sowing at 1 cm below the soil surface had the best field germination (Olayinka *et al.,* 2016).

Table 9. Correlation coefficients among traits under study of bambara groundnut grown in the rainy season in the South, Thailand, at harvest

	Correlation coefficient (r)									
	Height	CD	DF	DH	LAI	SLA	CGR	DW	Fpod	Dpod
CD	0.90**									
DF	0.82**	0.86**								
DH	0.86**	0.89**	0.78**							
LAI	0.56*	0.38^{ns}	0.35^{ns}	0.51*						
SLA	0.21^{ns}	0.03^{ns}	-0.12^{ns}	0.22^{ns}	0.80**					
CGR	-0.24^{ns}	-0.45^{ns}	0.32^{ns}	-0.36^{ns}	-0.09^{ns}	-0.08^{ns}				
DW	0.58*	0.44^{ns}	0.45^{ns}	0.62*	0.37^{ns}	0.13^{ns}	0.50*			
Fpod	-0.14^{ns}	-0.00^{ns}	0.19^{ns}	-0.00^{ns}	-0.16^{ns}	-0.32^{ns}	0.10^{ns}	0.05^{ns}		
Dpod	-0.24^{ns}	-0.04^{ns}	0.04^{ns}	0.03^{ns}	-0.22^{ns}	-0.28^{ns}	0.00^{ns}	-0.01^{ns}	0.89**	
H I	-0.39^{ns}	-0.18^{ns}	-0.12^{ns}	-0.14^{ns}	-0.24^{ns}	-0.22^{ns}	-0.11^{ns}	-0.26^{ns}	0.84**	0.95**

CD = canopy diameter, DF = days to flowering, DH = days to harvest, DW = total dry weight, Fpod = fresh pod, Dpod = dry pod
ns = non significant, * and ** = significant at $P < 0.05$ and < 0.01, Degree of freedom (n-2) = 14

Days to flowering is related to days to maturity. According to Gao *et al*. (2020), flowering of bambara groundnut started at 30-45 days and continued until harvest. The podding in bambara groundnut started within 5-8 days of flowering and took about 40 days for development and maturity (Singh and Basu, 2005). In this study, TVsu 89 had the lowest days to 50% flowering and it also had the lowest days to harvest. Therefore, days to harvest is also related to the time required for pod filling.

Plant height and canopy diameter

Bambara groundnut is an herbaceous annual leguminous plant with about 0.3 m tall creeping stems at ground level (Mabhaudhi and Modi, 2013). In this study, plant heights at harvest ranged between 34.86 cm and 44.92 cm, which were somewhat taller than those reported in the literature. Only TVsu 89 has shorter plant similar to those reported in the literature. The differences in the results would be due to the effect of environment. Bambara groundnut grown in Thailand would have higher rainfall and more fertile soil than those grown in Africa. Additionally, irrigation was available and drought was not a problem. In this study, canopy diameters at harvest were highest, ranging from 52.79 cm and 72.50 cm. According to Gao *et al*. (2020), growth habits of bambara groundnut genotypes were classified into three types including bunch, semi-bunch and spreading. Therefore, canopy sizes were different depending in part on plant types. Onwubiko *et al.* (2010) reported that canopy sizes of bambara groundnut varieties were in a range of 18 cm to 28 cm. Canopy sizes in this study were larger than those reported in previous study.

Leaf area index and specific leaf area

Leaf area index is a physiological trait related to growth and yield. The crop should be of the optimum leaf area index to obtain optimum yield. In this study, maximum leaf area indexes were at 75 DAP in all genotypes. The range of leaf area indexes at the peak (75 DAP) in this study was between 3.59 and 9.30. The lower range of leaf area indexes of bambara groundnut genotypes grown under irrigation was also reported in previous study (2.50 and 4.25) (Mabhaudhi and Modi, 2013). Similarly, Karunaratne *et al*. (2010) found that leaf area indexes of bambara groundnut genotypes ranged between 1.00 and 5.20, and Mabhaudhi and Modi (2013) reported that the range of leaf area index was between 3.00 and 8.00. Leaf area indexes in this study were somewhat in the high range compared to bambara groundnut genotypes grown in Africa.

Higher leaf area index in this study would be due to high rainfall in the South of Thailand.

Specific leaf area is related to leaf thickness, and it is also related to chlorophyll content in leaf and leaf photosynthesis. Low specific leaf area indicates high leaf mass and high chlorophyll content, and the genotypes with low specific leaf area should grow better than the genotypes with high specific leaf area. In this study, the highest specific leaf areas at peak times were in a range between 304.16 cm^2 g^{-1} and 409.85 cm^2 g^{-1}. TVsu 89 had peak specific leaf area as early as 25 DAP, and others had peak specific leaf area at 50 DAP. Specific leaf area of bambara groundnut was highest (140 cm^2 g^{-1}) at 25 days after sowing, when it was grown in sole and intercropping systems with rice, and it reduced until (Andika *et al*., 2009). Specific leaf areas in this study were higher than specific leaf area of bambara groundnut genotypes reported in previous study.

Crop growth rate

Crop growth rate indicates growth characteristic of a variety and it is also related to yield performance. In this study, two genotypes of bambara groundnut (TVsu 1221 and SK1-15) had peak crop growth rate at 50 to 75 DAP, and two genotypes (Songkhla 1 and TVsu 89) had peak crop growth rate at 75 to harvest. Crop growth rates at peak times were in a range between 11.31 g m^{-2} d^{-1} and 25.91 g m^{-2} $d^{-1.}$ Under drought stress and well-watered conditions, Madukwe *et al*. (2011) reported that crop growth rates of bambara groundnut genotypes were between 0.2 g m^{-2} d^{-1} and 1.2 g m^{-2} d^{-1}, depending on water supply to the crop. Sesay *et al.* (2010) found that crop growth rates were also dependent on planting date. The crop planted in December had the highest crop growth rate during 25 to 125 days (4.0 g m^{-2} d^{-1}), whereas the crop planted in February had the lowest crop growth rate (1.3 g m^{-2} d^{-1}). Therefore, comparison of crop growth rates among different study is difficult because there are many factors affecting crop growth rates. However, crop growth can be an important trait related to yield.

Total dry weight

Total dry wight is important for yield as it is the accumulation of assimilates that can be divided into economic yield. In this study, total dry weights were highest at harvest. This would be due to indeterminate growth of the crop. TVsu 1221, SK1-15 and control had similar total dry weights (9.90 t ha^{-1}, 8.68 t $ha^{-1}$and 9.69 t ha^{-1}), whereas TVsu 89 had the lowest total dry weight (7.49 t ha^{-1}).To the best of our knowledge so far, most (if not all) studies on dry matter of bambara groundnut were reported on grams per plant, and direct comparison is impossible. However, growth of bambara groundnut is similar to that of groundnut. According to Inban *et al*. (2022), groundnut genotypes grown in Thailand had total dry weights ranging from 10.53 t ha^{-1} to 13.03 t ha^{-1}. Although it is difficult to compare because total dry weight is affected by many growing conditions, it seemed likely that total dry weights in this study were rather low, and improvement of total dry weight may increase yield.

Fresh pod yield, dry pod yield and harvest index

TVsu 1221 had the highest fresh pod yield and the highest dry pod yield, whereas SK1-15 had the lowest fresh pod yield and the lowest dry pod yield. Dry pod yields in this study ranged from 0.51 t ha^{-1} to 0.79 t ha^{-1}. Mkandawire and Sibuga (2002) reported that the highest pod yield of bambara groundnut was 0.80 t ha^{-1}. Pod yields in this study were similar to pod yields of bambara groundnut genotypes grown in Africa. However, harvest indexes in this study were very low, ranging from 0.05 to 0.15. According to Mkandawire and Sibuga (2002), the highest harvest index was 75.0, while Gao *et al*. (2020) found that harvest index of bambara groundnut ranged between 0.20 and 0.60. The difference in harvest index, although pod yields were similar, should be because of excessively high total dry weight (9.69 t ha^{-1}) in this study. Shading and long-day length also caused low harvest index (Brink, 1999).

Correlation

Yield is always important for crop breeding, and suitable maturity is necessary for bambara groundnut to integrate into cropping systems. Study on the relationships among traits helps plant breeders to design suitable breeding strategies to achieve their goals. The goal of this study is to select bambara groundnut genotypes with acceptable yield and early maturity. Days to harvest was positively correlated with plant height, canopy diameter, days to 50% flowering, leaf area and total dry weight. Therefore, the genotypes with early maturity should be of low values for these traits. In previous study, days to 50% flowering (−0.350) showed a negative and significant relationship with yield (Khan *et al*., 2022). Maturity was not correlated with yield or even negatively correlated with yield might be caused by indeterminate nature of the crop, and shoot might be a stronger sink for assimilates than developing pod. In this study, only harvest index was closely associated with fresh pod yield and dry pod yield. According to Norman and Chongo (1992) biomass production and harvest index had positive and highly significant correlation with grain yield and most of the traits, indicating that they may be used as additional indices to improve yield. The discrepancy of the results of different studies would be due to the differences in environments and varieties used in the experiments. Bambara groundnut in this study was planted in The South, Thailand, where excessive rainfall usually occurs, but the crop planted in Africa is at risk to drought stress. In this study, TVsu 89 was earlier mature than other genotypes and its yield was comparable to the standard check. It is promising for release. However, further investigations in more details are still required.

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