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PATH ANALYSIS AND PRELIMINARY YIELD TRIALS OF BAMBARA GROUNDNUT *(Vigna subterranean* L. Verdc.) IN MADURA DRY LAND, INDONESIA

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SUMMARY

The development of promising bambara groundnut cultivars through the selection of local land races was initiated a decade ago in various regions of Indonesia. The preliminary trials of the potential lines that provide a sustainable base should be carried out before a cultivar is finally released. This research aimed to evaluate the performance of the selected potential lines of bambara groundnut during July 2019 to December 2019 in farmers' fields and outside the central area for bambara groundnut cultivation in Madura (Desa Bandungan, Pakong Sub-District of Pamekasan Regency), Madura Island, Indonesia. This study was performed with eight potential lines and two local lines by using a randomized complete block design and three replications. Results revealed significant genetic variability among the genotypes. When grown outside the central area of bambara groundnut cultivation, the highest yielding potential line was GSG 1.1.1 from Gresik Regency and BBL 2.1.1 and BBL 6.1.1 selected from Lamongan Regency, Indonesia. Path coefficient analysis revealed that four characters had a positive direct effect on the pod weight yield of bambara groundnut, i.e., the number of internodes, length of the leaves, width of the leaves, and weight of the wet stover. However, only three morphological characters, i.e., leaf length, leaf width, and wet stover weight, were found to be highly effective for selection of high-yielding bambara groundnut genotypes. These traits are suggested to be considered as selection criteria in improving the seed yield of bambara groundnut.

Keywords: Path coefficient analysis, potential lines, genetic variability, planting season, morphological and yield traits, *Vigna subterranean* L.

Key findings: Three potential lines were identified by the evaluation of the selected genotypes of bambara groundnut through path analysis in Madura dry land, Indonesia. The four characters that had a positive direct effect on the pod weight yield of bambara groundnut were the number of internodes, length of the leaves, width of the leaves, and weight of the wet stover.

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INTRODUCTION

Bambara groundnut (*Vigna subterranea* L.) is used for human and animal consumption and is the third most important legume after groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) (Omoikhoje, 2008). It is a rich source of protein, and its seeds are valued for their nutritional and economic importance. In Indonesia, the current potential yield of bambara groundnut in farmers' fields is very low. Farmers grow diversified landraces of bambara groundnut in the country. A previous study demonstrated that bambara groundnut landraces with various seed colors produced seed yields ranging from 0.7 tons ha^{-1} to 2.0 tons ha^{-1} (Redjeki, 2003). According to Kouassi and Zoro-Bi (2010), bambara groundnut can achieve a potential seed yield of 4.0 tons ha^{-1} under optimal growing environmental conditions. Advanced lines of bambara groundnut were developed through conventional breeding via screening and purification followed by the selection of the germplasm collected from various regions of Indonesia. The obtained potential lines are expected to be developed into new cultivars or utilized as parental genotypes in bambara groundnut crossing programs.

Genetic diversity within lines and populations is fundamental for breeding and germplasm conservation programs (Ogundele *et al*., 2017). As such, knowing the genetic diversity of breeding materials is pertinent to avoid the risks related to increased uniformity in elite germplasm and to ensure long-term selection gain because a cross between the limited number of elite lines puts the lines at risk of losing their genetic diversity. A breeding program for the improvement of bambara groundnut germplasm was started in 2012. Single-seed descent is the selection method that is used to select pure lines to accelerate the generation of new advanced lines with low diversity within each homogenous line or pure lines with high diversity among the potential lines of bambara groundnut. The said selection method is expected to provide additional opportunities for obtaining new bambara groundnut cultivars. The evaluation of diversity and resilience to drought in selected potential lines has also been carried out.

Genetic variability, which could be helpful for the improvement of the genetic performance of any crop species, is largely preserved in the form of local landraces and selected germplasm (Mwale *et al*., 2007). A significant magnitude of genetic diversity has been maintained in the landraces of bambara groundnut under low-input farming systems (Massawe *et al*., 2002). Fatimah (2019) found that each potential line of bambara groundnut was uniform as indicated by the observed low coefficient of genetic variability (CGV) and somewhat low coefficient of phenotype variability (CPV) for all quantitative traits determined on the basis of the criteria developed by Murdianingsih *et al*. (1990). Bambara groundnut lines with low CGV and CPV have relatively narrow genetic variability and phenotypic performance and are therefore considered to relatively homogeneous (Rachmawati *et al*., 2014). Past studies based on the basis of morphological markers and RAPD molecular markers revealed great genetic variability in 12 potential lines of bambara groundnut (Fatimah *et al*., 2018).

Studies on the drought resistance and potential yield of five drought-resistant genotypes have illustrated the opportunities for the development of advanced and potential lines of bambara groundnut with high-yielding potential (Fatimah *et al*., 2020). These five potential lines, which resulted from a series of studies, showed a potential for release as new superior bambara groundnut cultivars.

In bambara groundnut and in other crops, seed yield is a complex trait that is reliant on a number of variables. Studies on the direct and indirect effects of morphological and yield-related traits provide the basis for successful breeding programs aiming to increase seed yield. Path coefficient analysis measures the direct and indirect effects for one variable on another and permits the separation of the correlation coefficient into the components of direct and indirect effects (Dewey and Lu, 1959). Based on the above description, the main aim of the present research was to evaluate the seed yield of the selected germplasm of bambara groundnut in Madura dry land, Indonesia.

MATERIALS AND METHODS

This research was conducted during the dry season outside the areas of bambara groundnut cultivation centers in Madura. A growth rate of above 80% was observed for the 600 planted plants. Several diseases, including dwarf disease characterized by rolled and curled leaves, were suspected to be caused by the pepper yellow leaf curl virus, which is known as leaf curl disease. This disease was suspected to be transmitted by the whitefly *Bemisia tabaci* (Genn), which originated from the tobacco plants around the research area. Other diseases attacking bambara groundnut plants were leaf spot caused by *Cercospora* sp. and wilt disease, which is suspected to be caused by soil fungus originating from the spores of *Sclerotium rolfsii*. The plants that were affected by this virus were removed manually to prevent the infection of the other plants and to control disease. Fungal attacks were addressed by applying the fungicide Dithane™ with the active ingredient permethrin. The insect pests that were observed to attack bambara groundnut crops included grasshoppers (*Valanga nigricornis*) and ants (*Hymenoptera* sp.). However, the pest attacks during the study were not excessively severe such that chemical pest control was not undertaken.

Genetic material and procedure

This research was conducted during July 2019 to December 2019 at farmer fields and outside the central area for bambara groundnut cultivation in Madura (Desa Bandungan, Pakong Sub-District of Pamekasan Regency), Madura Island, Indonesia. The location had an altitude of ±250 m above sea level and ultisol soil type. Eight selected potential lines and two nonselected local land races from the bambara groundnut cultivation centers in Gresik Regency and Bangkalan Regency of Madura were used in the study (Table 1). Fertilizers, i.e., urea, SP-36, and KCL, were used at the rates of 50, 100, and 100 kg ha^{-1} (Redjeki, 2003). All the bambara groundnut genotypes were planted with a randomized complete block design (RCBD). The treatment consisted of eight selected potential lines and two local lines as the control. Each was repeated three times, resulting in 30 experimental units. A total of 20 plants were planted for each experimental unit.

Table 1. Bambara groundnut genotypes used in this study.

No.	Code	Line name	Line origin
1.	G1	Local Madura	Bangkalan Madura, East Java, Indonesia
2.	G2	Local Gresik	Gresik, East Java, Indonesia
3.	G3	BBL 6.1.1	Lamongan, East Java, Indonesia
4.	G4	GSG 1.1.1	Gresik, East Java, Indonesia
5.	G5	CKB 1	Bangkalan Madura, East Java
6.	G6	TKB 1	Bangkalan Madura, East Java
7.	G7	GSG 2.4	Gresik, East Java
8.	G8	BBL 2.1.1	Lamongan, East Java
9.	G9	GSG 3.1.2	Gresik, East Java
10.	G10	1JLB 1	Bangkalan Madura, East Java

The size of each experimental unit was 60 cm × 300 cm, and the distance between beds was 50 cm. Each planting hole was planted with one seed with a depth of approximately 5 cm. Fertilization involved three kinds of fertilizers: urea (50 kg ha^{-1}), SP-36 (100 kg ha^{-1}), and KCl (100 kg ha^{-1}). Fertilization was conducted three times: 1/3 dose at the time of planting, 1/3 dose at second fertilization (plants aged 21 days after planting [DAP]), and 1/3 dose when the plants began to flower at 40 DAP.

Data recorded

The traits comprising plant growth and yield traits, such as plant height, crown diameter, petiole length, internode length, number of leaves, terminal leaf width, and terminal leaf length, were observed at 10 weeks after planting (WAP). The traits observed during harvesting included number of branches, number of segments, number of pods, weight of wet pods, weight of wet stover, pod width, pod length, dry pod weight, dry seed weight, number of seeds, seed weight, shell weight, shelling percentage, seed length, seed width, seed productivity, dry pod harvest index, and seed harvest index. The crop ages at different stages, i.e., germination, flowering, and at harvesting, were also observed.

Data analysis

Quantitative traits were analyzed by using analysis of variance (ANOVA) at the 5% level of probability with Microsoft Excel on the basis of RCBD with three replications. ANOVA revealed the significant effect of the bambara groundnut genotype treatments on growth and yield traits on the basis of Duncan's multiple range test (DMRT) at the 5% level of probability. The predicted genetic parameters included the values of genetic, phenotypic, and environmental variances in reference to Singh and Chaudhary (1979). The heritability values and coefficient of genetic variability were also calculated in reference to Singh and Chaudhary (1979) as follows:

$$\mathrm{CV}\ (\text{coefficient of variatio}\square) = \frac{\sqrt{\mathrm{KTg}}}{\bar{x}} = \frac{\mathrm{M1}}{\bar{x}}$$

$$H^2_{bs}\ (\text{broadsense heritability}) = \frac{\sigma^2 g}{\sigma^2 p}$$

$$\mathrm{CGV}(\text{coefficient of genetic vari}\square\text{tion}) = \frac{\sqrt{\sigma^2 g}}{\bar{x}} x100\%$$

Broad-sense heritability was grouped in accordance with Elrod and Stansfield (2002):

$0.05 < H^2_{bs} < 1.00$ = high
$0.20 < H^2_{bs} < 0.05$ = moderate
$H^2_{bs} < 0.20$ = low

The relationship among morphological traits and the direct and indirect effects of morphological traits on yield traits were tested through path coefficient analysis by using Statistical Package for the Social Sciences software in accordance with Al-Jibouri *et al*. (1958), Dewey and Lu (1959), and Singh and Chaudhary (1979).

RESULTS

ANOVA revealed that the bambara groundnut lines had a significant effect on the traits, i.e., age at germination, flowering, and harvesting; number of leaves; leaf width and terminal leaf length at 10 weeks of age; number of pods; wet pod weight; wet stover weight; pod width; pod length; dry pod weight; dry stover weight; number of seeds; seed weight; shell weight; shelling percentage; seed length; seed width; seed productivity; dry pod harvest index; and seed harvest index (Table 2). However, the bambara groundnut genotypes had no effect on the following traits: plant height, crown diameter, petiole length, internode length, number of branches, number of internodes, and pod length.

Table 2. Means; F-value; genetic, environmental, and phenotypic variances; coefficients of genetic variation and variation; and heritability values of bambara groundnut genotypes.

Characters	Mean	F-value	Δ^2g	δ^2e	δ^2p	GCV (%)	CV (%)	h^2
Age at germination	13.08	2.78*	3.61	6,07	9.68	52.54	18.83	0.37
Age at flowering	50.79	6.67*	20.63	10.92	31.55	63.73	6.51	0.65
Age at harvesting	136.31	3.60*	31.60	36.42	68.02	48.14	4.43	0.46
Number of leaves at 10 WAP	55.58	2.59*	32.57	61.64	94.21	76.55	14.13	0.35
Plant Height at 10 WAP (cm)	24.77	0.86 ^{ns}	-0.21	4.57	4.36	0.00	8.63	-0.05
Crown diameter at 10 WAP (cm)	58.42	2.26 ^{ns}	15.39	36.61	52.00	51.33	10.36	0.30
Petiole Length at 10 WAP (cm)	16.71	1.18 ^{ns}	0.10	1.72	1.82	7.78	7.85	0.06
Terminal leaf length at 10 WAP (cm)	8.30	5.80*	0.26	0.16	0.42	17.62	4.83	0.62
Leaf width at 10 WAP (cm)	2.39	3.00*	0.02	0.02	0.04	8.38	6.64	0.40
Internode length at 10 WAP (cm)	1.89	0.98 ^{ns}	(0.00)	0.04	0.04	0.00	10.41	0.00
Number of branches	9.43	1.84 ^{ns}	0.49	1.76	2.26	22.90	14.09	0.22
Number of internodes	7.00	2.01 ^{ns}	0.20	0.61	0.81	17.10	11.14	0.25
Number of pods per plant	62.33	2.62*	148.16	274.07	422.22	154.17	26.56	0.35
Wet pod weight per plant (g)	102.61	4.05*	707.40	696.88	1404.28	262.57	25.73	0.50
Dry pod weight per plant (g)	43.95	3.91*	86.52	89.27	175.79	140.31	21.50	0.49
Number of seeds per plant	63.27	2.63*	153.02	279.66	432.68	155.52	26.43	0.35
Wet stover weight per plant (g)	82.24	4.21*	2305.68	2155.24	4460.92	529.48	56.45	0.52
Dry stover weight per plant (g)	38.21	2.94*	204.61	315.77	520.39	231.42	46.51	0.39
Seed weight per plant (g)	33.27	2.85*	32.16	52.05	84.21	98.33	21.69	0.38
Shell weight per plant (g)	8.00	2.97*	3.18	4.84	8,02	63.10	27.51	0.40
Shelling Percentage (%)	0.23	2.59*	0.0011	0.0021	0.0032	6.96	19.85	0.35
Net wet pod weight/plot (g)	1492.63	1.11 ^{ns}	6282.96	168308.85	174591.81	205.17	27.49	0.04
Net dry pod weight/plot (g)	648.67	1.76 ^{ns}	4865.70	19236.23	24101.93	273.88	21.38	0.20
Seed weight/plot (g)	498.07	2.69*	5808.21	10291.29	16099.50	341.49	20.37	0.36
Pod length (cm)	18.60	2.24 ^{ns}	0.13	0.31	0.44	8.37	3.02	0.29
Pod width (cm)	14.98	4.22*	0.18	0.16	0.34	10.86	2.71	0.52
seed length (g)	13.27	3.13*	0.05	0.07	0.13	6.31	2.05	0.42
seed width (g)	10.04	3.02*	0.03	0.05	0.08	5.79	2.23	0.40
Wet pod productivity (tons/ha)	6.22	1.11 ^{ns}	0.11	2.92	3.03	13.24	27.49	0.04
Dry pods productivity (tons/ha)	2.70	1.76 ^{ns}	0.08	0.33	0.42	17.68	21.38	0.20
Dry seed productivity (tons/ha)	2.08	2.69*	0.10	0.18	0.28	22.04	20.37	0.36
Dry pod harvest index (%)	0.45	2.63*	0.0019	0.0034	0.0053	6.47	13.16	0.35
Seed harvest index (%)	0.43	2.59*	0.0001	0.0002	0.0003	1.65	3.44	0.35

Notes: * = significant at the level of 5%, ns = not significant.

The values of genetic diversity among 10 bambara groundnut potential lines were also calculated on the basis of the means, genetic diversity coefficient, and genetic variance of each quantitative trait (Table 2). In accordance with Moedjiono and Mejaya (1994), the traits with coefficients of genetic diversity ranging from 0% to 25% were categorized as low, those with coefficients of genetic diversity of 25% to 50% as somewhat low, those with coefficients of genetic diversity of 50% to 75% as fairly high, and those with coefficients of genetic diversity of 75% to 100% as high. Broad-sense heritability was also formulated to determine whether trait diversity was more influenced by genetic or environmental effects. The diversity found in the traits was not due to the genetic role of the tested bambara groundnut lines as indicated by the moderate value of heritability of the four diverse production traits (h^2 = 0.2 to 0.5). The moderate heritability values indicated that the genetic role will appear only under the appropriate environmental conditions. The summary of the ANOVA, genetic diversity values, and estimated heritability values are provided in Table 2.

The bambara groundnut genotypes showed diversity for the traits of the generative phase and yield but not for some vegetative traits (Table 2). The diversity among the bambara groundnut potential lines was used as the basis for the development of superior bambara groundnut cultivars via the purification and selection of local land races. Subsequently, such an approach makes obtaining a large number of candidate superior cultivars possible.

Genotypes age at germination, first flowering, and harvest

Early-age bambara groundnut genotypes were selected by observing the age at germination, first flowering, and harvest in accordance with the research of Jambormias *et al*. (2013). The results revealed that bambara groundnut lines had significant diversity for age traits (Table 3). For the tested bambara groundnut genotypes, the age at germination ranged from 10.43 DAP to 16.50 DAP with an average of 13.08 DAP. Overall, all of the potential lines had a lower age at germination than the average value, and only two potential lines, i.e., CKB-1 and GSG 2.4, had a greater age at germination than the average age value. The potential line JLB-1 originating from the island of Madura was the genotype with the lowest age at germination (10.43 DAP), and the potential line GSG2.4 derived from Gresik was observed with the highest age at germination (16.50 DAP).

The ages at first flowering of the tested bambara groundnut lines ranged from 43.88 DAP to 59.28 DAP with an average of 50.79 DAP (Table 3). Similar to the age at germination, almost all the potential lines tested had a lower age at flowering than the average value. However, three potential lines, i.e., CKB-1, GSG 2.4, and BBL 2.1.1, had a greater age at first flowering than the average age. The potential line BBL 6.1.1 was reported with the lowest age at flowering (43.88 DAP) and the local land Madurese lines was the genotype with the highest age at flowering (59.28 DAP).

Among the tested potential lines of bambara groundnut, the age at harvesting ranged from 126.96 DAP to 147.76 DAP with an average age of 136.31 DAP (Table 3). Almost all the tested potential lines had lower age at harvesting than the average value, and two potential lines, namely, TKB-1 and JLB-1, had a greater age at harvesting than the average value. The potential line GSG 1.1.1 was observed with the lowest age at harvesting (126.96 DAP). However, the local line Gresik was reported with the highest age at harvesting (147.76 DAP).

Vegetative traits

The recorded vegetative traits were plant height, crown diameter, petiole length, terminal leaf length, terminal leaf width, number of leaves, number of branches, and number of internodes. Except for the number of branches and internodes, vegetative traits were observed at 10 WAP. The numbers of branches and internodes were recorded at the harvesting time. The average data of the traits are shown in Table 4.

The results illustrated that the tested bambara groundnut lines lacked diversity for plant vegetative traits. However, diversities were recorded for the traits, i.e., number of leaves, terminal leaf length, and terminal leaf width (Table 4).

The terminal leaf length of the tested bambara groundnut lines ranged from 7.46 cm to 9.24 cm with an average of 8.30 cm. The line with the highest terminal leaf length was GSG 2.4 (9.24 cm) selected from the local line Gresik. However, this line was not different from the local Gresik lines, i.e., GSG 1.1.1, CKB-1, GSG 3.1.2, and JLB-1. The local Madurese line (TKB-1) exhibited the shortest terminal leaf length (7.46 cm).

The terminal leaf width of the tested bambara groundnut lines, ranged from 2.18 cm to 2.70 cm with an average of 2.39 cm. The local genotype Lamongan line (BBL 2.1.1) was reported with the widest terminal leaf (2.70 cm), whereas the genotype Lamongan line (BBL 1.1.1) was observed with narrowest terminal leaf width (2.18 cm).

At the age of 10 WAP, the number of leaves of the tested bambara groundnut lines ranged from 47.33 to 69.50 with an average of 55.58. Four potential lines with more leaves than the average value included GSG 1.1.1, GSG 2.4, and GSG 3.1.2, which were selected from local

Table 3. Average age at germination, first flowering, and harvest of bambara groundnut genotypes.

Genotypes	Line Name	Age at Germination (DAP)	Age at Flowering (DAP)	Age at harvesting (DAP)
G1	Madura Local Line	16.38 b	59.28 c	144.78 b
G2	Gresik Local Line	14.25 ab	49.43 ab	147.76 b
G3	BBL 6.1.1	10.52 ab	43.88 a	128.68 ab
G4	GSG 1.1.1	10.64 ab	46.86 ab	126.96 a
G5	CKB-1	15.32 ab	53.16 ab	134.92 ab
G6	TKB-1	11.95 ab	49.07 ab	137.29 ab
G7	GSG 2.4	16.50 b	57.10 c	139.29 ab
G8	BBL 2.1.1	12.31 ab	53.69 c	130.74 ab
G9	GSG 3.1.2	12.52 ab	46.03 ab	135.30 ab
G10	JLB-1	10.43 a	49.39 ab	137.41 ab

Numbers followed by the same letters in the same variable show nonsignificant differences based on the DMRT test at the 5% probability level.
Notes: DAP = day after planting

Table 4. Average values of the number of leaves and terminal leaf length and width of bambara groundnut genotypes.

Genotypes	Line name	NL 10 WAP	LL 10 WAP	LW 10 WAP	PH 10 WAP	CD 10 WAP	PL 10 WAP	Internode length	Number of branches	Number of internodes
G1	Local Madurese line	47.33 a	8.06 ab	2.31 ab	52.61	15.77	1.71	8.76	6.63	6.63
G2	Local Gresik line	54.17 ab	8.30 bc	2.44 ab	55.61	16.77	1.83	11.93	8.26	8.26
G3	BBL 6.1.1	69.50 c	7.94 ab	2.18 a	60.22	16.18	1.84	9.56	7.28	7.28
G4	GSG 1.1.1	56.28 ab	8.71 c	2.36 ab	64.78	17.55	1.98	9.30	7.33	7.33
G5	CKB-1	48.11 ab	8.53 c	2.22 ab	56.33	17.07	1.82	8.83	6.39	6.39
G6	TKB-1	48.22 ab	7.46a	2.53 ab	52.28	15.40	1.87	8.22	6.33	6.33
G7	GSG 2.4	64.94 bc	9.24 c	2.44 ab	67.50	18.05	2.09	10.35	7.76	7.76
G8	BBL 2.1.1	55.56 ab	7.62 ab	2.70 b	54.56	16.25	1.90	9.15	6.57	6.57
G9	GSG 3.1.2	58.67 ab	8.25 bc	2.45 ab	57.17	16.83	1.83	9.26	6.69	6.69
G10	JLB-1	53.00 ab	8.90 c	2.25 ab	63.11	17.29	2.02	8.93	6.72	6.72

Numbers followed by the same letters in the same variable show nonsignificant differences based on the DMRT test at the 5% probability level.
Notes: NL = number of leaves; PH = plant height; CD = crown diameter; PL = petiole length; LL = leaf length, LW = leaf width.

Gresik lines, and one potential line BBL 6.1.1, which was selected from the local Lamongan line. Line BBL 6.1.1, which was as selected from the local Lamongan line, exhibited the highest number of leaves (69.50). However, the number of leaves of this line was not significantly different from that of GSG 2.4. The local Madurese line was recorded with the smallest number of leaves (47.33).

The plant height of the tested bambara groundnut lines ranged from 22.83 cm to 25.78 cm with an average value of 24.77 cm. Plant crown diameter ranged from 52.28 cm to 67.50 cm with an average value of 58.42 cm. Petiole length ranged from 15.40 cm to 18.05 with an average value of 16.71 cm. The internode length measured at the fourth internode ranged from 1.71 cm to 2.09 cm with an average value of 1.89 cm. The number of branches ranged from 6.33 to 8.26 with an average value of 7.00. However, the number of internodes of the tested bambara groundnut genotypes ranged from 8.22 to 11.93 with an average value of 9.43.

Seed yield and production traits

The tested bambara groundnut genotypes showed diversity for almost all yield and production traits except for the traits wet pod weight per plot, dry pod weight per plot, wet pod productivity, and dry pod productivity. The observed diversity data among the bambara groundnut tested genotypes for yield and production traits per hectare are shown in Tables 5 and 6. The wet pod weight per plot of the tested genotypes ranged from 1098.67 g to 2037.33 g with an average of 1492.63 g. Dry pod weight per plot ranged from 403.67 g to 737.33 g with an average of 648.67 g. Wet pod productivity ranged from 4.58 tons ha^{-1} to 8.49 tons ha^{-1} with an average of 6.22 tons ha $^{-1}$, and dry pod productivity ranged from 1.68 to 3.34 tons ha^{-1} with an average of 2.70 ton ha^{-1}.

The dry seed weight per plant of the bambara groundnut tested genotypes ranged from 26.53 g to 47.67 g with an average value of 33.27 g. The potential bambara groundnut line GSG 2.4, which was selected from Gresik, recorded the heaviest seeds per plant. The smaller and lightest seeds per plant was observed for the potential line CKB-1, which was selected from the local line Madurese. Seed productivity per ha ranged from 1.17 tons ha^{-1} to 2.70 tons ha^{-1} with an average value of 2.08 tons ha^{-1}. The bambara groundnut line GSG 1.1.1 was reported to have the highest seed productivity, whereas the local line Gresik showed the lowest seed productivity.

Quality traits

The quality traits of bambara groundnut were pod length, pod width, seed length, seed width, and shelling percentage (Table 7). The results showed great diversity among the tested bambara groundnut lines for the observed quality traits, except pod length. The pod lengths of the tested bambara groundnut genotypes ranged from 18.03 mm to 19.46 mm with an average value of 18.60 mm.

The pod width of the tested bambara groundnut lines ranged from 14.32 mm to 15.78 mm with an average value of 14.98 mm. The line GSG 2.4 had the widest pod (15.78 mm) and was recorded as a potential line. It was selected from the local line Gresik. However, it was significantly different from the potential line BBL 2.1.1, which was selected from Lamongan.

The seed lengths of the bambara groundnut genotypes ranged from 12.76 mm to 13.63 mm with an average value of 13.27 mm, whereas seed widths ranged from 9.63 mm to 10.34 mm with an average value of 10.04 mm. The bambara groundnut line GGG 2.4, which had the longest seeds, was selected from local line Gresik, and the widest seeds were exhibited by the potential line CKB-1 selected from Madura. GSG 3.1.2, which was selected from Gresik, exhibited the shortest seeds. The narrowest seeds were observed in the potential line BBL 2.1.1, which was selected from Lamongan.

Table 5. Average values of the yield traits of bambara groundnut genotypes.

Genotypes	Line Name	Pods plant^{-1}	Wet pod weight plant^{-1} (g)	Dry Pod weight plant^{-1} (g)	Wet Stover weight plant^{-1} (g)	Dry Stover weight plant^{-1} (g)	Seeds plant^{-1}	Shell weight plant^{-1} (g)	Seed weight plant^{-1} (g)
G1	Local Madurese line	70.94 ab	118.61 ab	42.76 a	147.19 b	60.54 b	71.92 ab	8.68 ab	30.03 ab
G2	Local Gresik line	97.05 b	166.83 c	61.40 b	210.85 c	78.22 c	98.13 b	12.43 c	42.75 bc
G3	BBL 6.1.1	50.29 ab	76.42 ab	35.10 a	42.23 a	24.50 a	50.49 ab	6.28 ab	28.04 ab
G4	GSG 1.1.1	56.34 ab	90.05 ab	41.53 a	43.35 ab	30.24 ab	56.91 ab	7.14 ab	33.63 ab
G5	CKB-1	54.65 ab	87.51 ab	36.09 a	67.43 ab	29.75 ab	55.65 ab	7.31 ab	26.53 a
G6	TKB-1	58.28 ab	96.48 ab	44.25 a	59.04 ab	30.22 ab	59.64 ab	7.57 ab	35.45 ab
G7	GSG 2.4	76.60 ab	141.31 bc	64.67 b	89.04 ab	42.57 ab	78.03 ab	11.15 bc	47.67 c
G8	BBL 2.1.1	52.95 ab	73.52 a	35.27 a	46.65 ab	27.00 ab	53.70 ab	5.96 ab	28.66 ab
G9	GSG 3.1.2	62.04 ab	97.12 ab	43.96 a	66.40 ab	31.34 ab	63.43 ab	7.53 ab	32.86 ab
G10	JLB-1	44.20 a	78.24 ab	34.46 a	50.25 ab	27.70 ab	44.79 a	5.90 a	27.04 ab

Numbers followed by the same letters in the same variable show nonsignificant differences based on the DMRT test at the 5% probability level.

Table 6. Average production of bambara groundnut genotypes.

Genotypes	Line Name	Wet pod weight plot^{-1} (g)	Dry pod weight plo^{-1} (g)	Seed weight plot^{-1} (g)	Dry pod productivity (ha^{-1})	Wet pod productivity (ha^{-1})	Seed productivity (h^{-1})	Dry pod harvest index	Seed harvest index
G1	Local Madurese line	2037.33 b	737.33 cd	516.67 bc	3.07 c	8.49 b	2.15 bc	0.54 b	0.41 a
G2	Local Gresik line	1098.67 a	403.67 a	281.67 a	1.68 a	4.58 a	1.17 a	0.55 b	0.41 ab
G3	BBL 6.1.1	1499.67 ab	689.00 bc	551.33 c	2.87 bc	6.25 ab	2.30 c	0.41 ab	0.45 b
G4	GSG 1.1.1	1736.33 ab	801.33 d	649.00 c	3.34 c	7.23 b	2.70 c	0.42 ab	0.45 b
G5	CKB-1	1484.33 ab	618.67 ab	457.33 bc	2.58 ab	6.18 ab	1.91 bc	0.45 ab	0.43 ab
G6	TKB-1	1405.33 ab	650.33 bc	523.67 bc	2.71 ab	5.86 ab	2.18 bc	0.41 ab	0.45 b
G7	GSG 2.4	1344.00 ab	606.67 ab	447.67 ab	2.53 ab	5.60 ab	1.87 ab	0.39 a	0.42 ab
G8	BBL 2.1.1	1445.33 ab	693.00 bc	563.00 c	2.89 bc	6.02 ab	2.35 c	0.43 ab	0.45 b
G9	GSG 3.1.2	1515.33 ab	688.00 bc	520.33 bc	2.87 bc	6.31 ab	2.17 bc	0.41 ab	0.43 ab
G10	JLB-1	1360.00 ab	598.67 ab	470.00 bc	2.49 ab	5.67 ab	1.96 bc	0.44 ab	0.44 ab

Numbers followed by the same letters in the same variable show nonsignificant differences based on the DMRT test at the 5% probability level.

Table 7. Average seed length, seed width, pod length, pod width, and shelling percentage of bambara groundnut genotypes.

Genotypes	Line Name	Seed length (mm)	Seed width (mm)	Pod length (mm)	Pod width (mm)	Shelling (%)
G1	Local Madurese Line	13.12 ab	9.83 ab	18.58	15.01 ab	0.30 b
G2	Local Gresik Line	13.27 ab	10.01 ab	18.60	15.12 ab	0.30 b
G3	BBL 6.1.1	13.00 ab	9.88 ab	18.19	14.78 ab	0.20 ab
G4	GSG 1.1.1	13.41 bc	10.30 c	19.01	15.45 b	0.19 a
G5	CKB-1	13.41 bc	10.34 c	18.48	14.72 ab	0.24 ab
G6	TKB-1	13.45 bc	10.12 b	18.44	14.75 ab	0.19 a
G7	GSG 2.4	13.63 c	10.18 b	19.19	15.78 b	0.26 ab
G8	BBL 2.1.1	13.08 ab	9.63 a	18.03	14.32 a	0.19 a
G9	GSG 3.1.2	12.76 a	9.94 ab	18.04	14.40 ab	0.24 ab
G10	JLB 1	13.60 c	10.18 b	19.46	15.50 b	0.23 ab

Numbers followed by the same letters in the same variable show nonsignificant differences based on the DMRT test at the 5% probability level.

The shelling percentage of the tested bambara groundnut genotypes ranged from 19% to 30% with an average value of 23%. The potential line GSG 1.1.1 recorded the lowest percentage (19%) and was selected from Gresik, whereas line TKB-1 was selected from Madura. However, the highest percentage (30%) was recorded for two local lines selected from Gresik and Madura.

Correlation among traits

The correlation coefficient (r) among the traits was calculated only for 11 morphological traits. The values of the relationships among the morphological traits of bambara groundnut are presented in Table 8. Correlation estimation among various traits is used to know the linear relationship among the traits to be evaluated. This study, the 10 vegetative traits and one yield trait (pod weight) were selected for analysis, and almost all the relationships among those traits, except for the relationship between the internode length and wet stover weight, had a positive correlation value. Gomez and Gomez (1995) stated that when two traits have close correlation values ($r = -1$ or $r = +1$), their traits are very closely related to each other. This study observed no such relationship among traits with a correlation value of $r = -1$ or $r = +1$. In this study, the highest correlation value ($r = 0.806$) was observed between wet stover weight and wet pod weight. The results further indicated that all vegetative traits were positively correlated with the wet pod weight, and six traits revealed significant positive correlation, i.e., plant height ($r = 0.429$), petiole length ($r = 0.543$), leaf length ($r = 0.575$), number of branches (r = 0.554), number of internodes ($r = 0.736$), and wet stover weight (0.806).

Path analysis

Regression and correlation analyses were performed to determine the combined and partial effects of each morphological trait with a calculated coefficient of correlation (r). Given that farmers on the island of Madura sell their bambara groundnut directly to the local markets in the form of wet pods, wet pod weight per plant was selected as the dependent variable (Y) or seed yield in the regression analysis, and the 10 morphological traits were selected as the independent variables (X). These traits included plant height, number of leaves, crown diameter at 10 WAP, number of internodes, number of branches, petiole length, internode length, terminal leaf width, terminal leaf length, and wet stover weight. Path analysis provides information on the direct and indirect effects of a trait through other traits on yield traits. The results of

Table 8. Correlation coefficients of the morphological characters of bambara groundnut genotypes.

Traits	NB	NI	NL	PH	CD	PL	IL	LL	LW	WSW	WPW
NB	1										
NI	0.784**	1									
NL	0.608**	0.524**	1								
PH	0.433*	0.532**	0.455*	1							
CD	0.437*	0.601**	0.656**	0.655**	1						
PL	0.560**	0.678**	0.611**	0.740**	0.800**	1					
IL	0.412*	0.474**	0.445*	0.532**	0.682**	0.698**	1				
LL	0.487**	0.567**	0.437*	0.580**	0.765**	0.805**	0.537**	1			
LW	0.271	0.333	0.328	0.576**	0.278	0.416*	0.405*	0.064	1		
WSW	0.507**	0.530**	0.067	0.318	0.034	0.276	−0.066	0.309	0.205	1	
WPW	0.554**	0.736**	0.238	0.429*	0.356	0.543**	0.224	0.575**	0.359	0.806**	1

Notes: NB = number of branches; NI = number of internodes; NL = number of leaves; PH = plant height; CD = crown diameter; PL = petiole length; IL = internode length; LL = leaf length, LW = leaf width; WSW = wet stover weight; WPW = wet pod weight per plant.

Table 9. Regression analysis of morphological characters against the wet pod weight per plant of bambara groundnut genotypes.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.946 [a]	0.895	0.840	18.19880

Table 10. Direct and indirect effects of morphological characters on the wet pod weight of bambara groundnut genotypes.

Morphological Characters	Number of Branches	Number of inter-nodes	Number of Leaves	Plant Height	Crown Diameter	Petiole Length	Internode Length	Leaf Length	Leaf Width	Wet Stover Weight
Direct Effects	(0.277)	0.485	(0.024)	(0.273)	(0.074)	(0.070)	(0.047)	0.529	0.350	0.536
Indirect Effects through										
Number of Branches	-	(0.217)	(0.168)	(0.120)	(0.121)	(0.155)	(0.114)	(0.135)	(0.075)	(0.140)
Number of internodes	0.380	-	0.254	0.258	0.291	0.329	0.230	0.275	0.162	0.257
Number of Leaves	(0.015)	(0.013)	-	0.455	(0.016)	(0.015)	(0.011)	(0.010)	(0.008)	(0.002)
Plant Height	(0.118)	(0.145)	(0.124)	-	(0.202)	(0.202)	(0.145)	(0.158)	(0.157)	(0.087)
Crown Diameter	(0.032)	(0.044)	(0.049)	(0.048)	-	(0.059)	(0.050)	(0.057)	(0.021)	(0.003)
Petiole Length	(0.039)	(0.047)	(0.043)	(0.052)	(0.056)	-	(0.049)	(0.056)	(0.029)	(0.019)
Internode Length	(0.019)	(0.022)	(0.021)	(0.025)	(0.032)	(0.033)	-	(0.025)	(0.019)	0.003
Leaf Length	0.258	0.300	0.231	0.307	0.405	0.426	0.284	-	0.034	0.163
Leaf Width	0.095	0.117	0.115	0.202	0.097	0.146	0.142	0.022	-	0.072
Wet Stover Weight	0.272	0.284	0.036	0.170	0.018	0.148	(0.035)	0.166	0.110	-
Total Indirect Effects	0.781	0.211	0.231	1.147	0.385	0.584	0.251	0.021	(0.004)	0.245

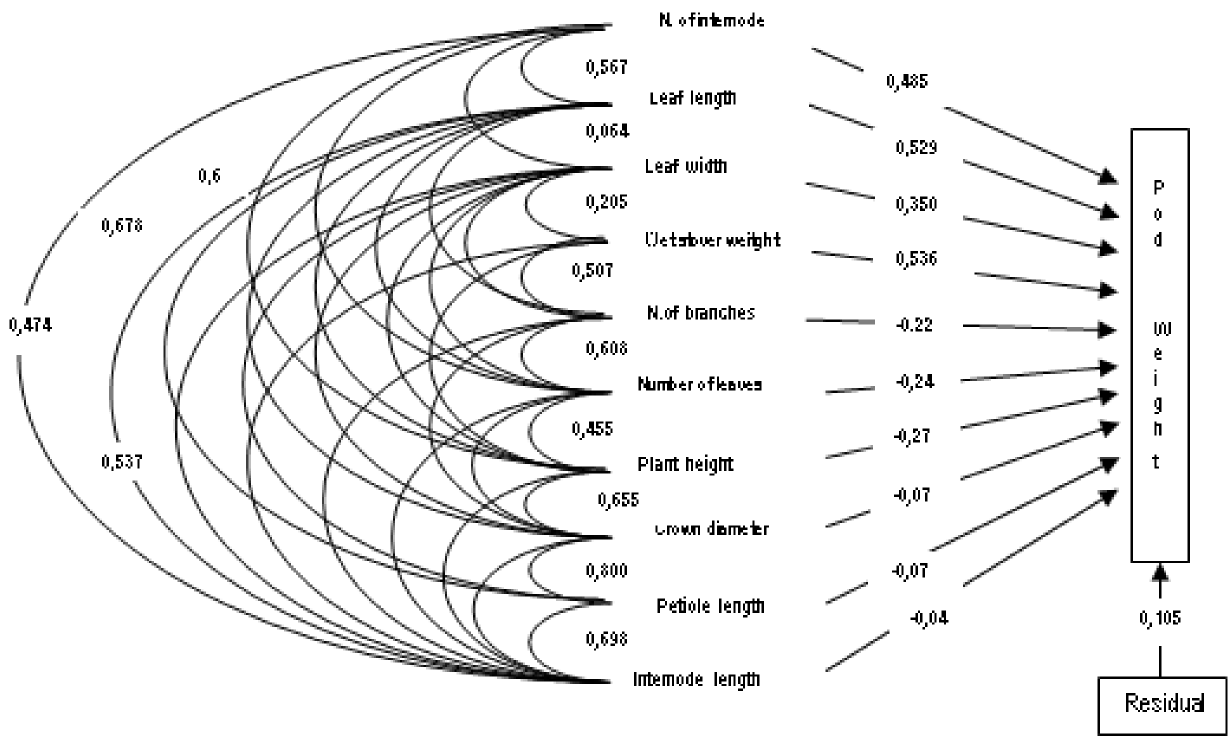

Figure 1. Path analysis diagram of vegetative characters for the wet pod weight per plant of bambara groundnut genotypes.

regression analysis and the direct and indirect relationship of morphological traits with pod weight per plant are presented in Tables 9 and 10 and Figure 1.

Path analysis showed the 10 morphological traits used for the analysis of wet pod weight per plant. These morphological traits had a very close relationship with the yield trait, i.e., wet pod weight per plant, with a R value of 0.946. This analysis provided a R^2 value of 0.895, which indicated that the 10 morphological traits tested here had an effect (89.5%) on the wet pod weight and that the remaining residue was 10.5% (*r* = 0.105).

The path analysis matrix shows the 10 vegetative and morphological traits that were analyzed. Six traits were observed to exert a negative direct effect, and four traits had a positive direct effect on the yield trait (wet pod weight). The number of branches and petiole length had a negative direct effect but an adequately large indirect effect on the resulting wet pod weight. The trait number of branches had a large indirect effect through three traits, i.e., number of internodes, leaf length, and wet stover weight. Meanwhile, petiole length had a significant indirect effect through the traits number of internodes and leaf length.

The four traits with a positive direct effect on wet pod weight were the number of internodes (0.485), leaf length (0.529), leaf width (0.350), and wet stover weight (0.536). This result revealed that the four traits strongly affected the yield of bambara groundnut, and the value of their direct effect was almost the same and equivalent to the correlation coefficient of these traits with wet pod weight. The results further indicated that for the heritability value of the four traits with a direct effect on the yield trait (wet pod weight) in bambara groundnut plantations, only three traits had high and moderate heritability values, i.e., leaf length, leaf width, and wet stover weight. Considering that the heritability of the number of internodes was low, this trait was not effective as a selection criterion for the yield of bambara groundnut genotypes.

DISCUSSION

The results revealed significant differences among the tested bambara groundnut lines for seed weight per plot, seed productivity, dry pod harvest index, and seed harvest index. However, nonsignificant differences were observed among the lines for wet pod weight, dry pod weight, wet pod productivity, and dry pod productivity. The differentiation in the observed traits of the bambara groundnut tested lines indicated differences in the genetic potential of these lines in response to environmental conditions. On the other hand, the absence of diversity in the potential lines for a trait here indicates the absence of differences in the genetic potential of those potential lines in response to environmental conditions as shown by the level of plant phenotypic expression. Massawe *et al*. (2005) stated that the genotypic diversity for various traits shows differences in the genetic potential of the genotypes as reflected by the differences in morphological, physiological, and agronomic phenotypes, such as the number of flowers, harvesting time, and pod formation. Stanfield (1983) reported that a plant trait with low and moderate values of broad-sense heritability is not necessarily passed on to the next generation because the proportion of environmental effects on the appearance of these traits is greater or equal to the genetic effects. Thus, these traits are less effective for use as criteria for selection activities.

The selected potential line GSG 1.1.1, which originated from the local land race Gresik Regency, recorded the highest seed productivity. When the said genotype was planted during the dry season, it achieved a production of 2.70 tons ha^{-1}. However, this value was not different from the productivity of the two other potential lines BBL 2.1.1 and BBL 6.1.1, which were selected from Lamongan. These results revealed that these three potential lines have a great potential for development into new superior genotypes on dry land. This study also showed that the nonselected lines of bambara groundnut had the lowest seed productivity as indicated by the local line Gresik, which had a potential yield of 1.17 tons ha^{-1}. Studies on the potential yield of bambara groundnut have been widely conducted under varied environmental conditions and have revealed the varied performance of genotypes (Akpalu *et al*., 2012; Mabhaudhi and Modi, 2013; Effa *et al*., 2016; Dias *et al*., 2018; Kevin *et al*., 2020; Tyoakoso *et al*., 2020; Obidiebube *et al*., 2020). The per hectare potential yield of bambara groundnut could exceed 5 tons ha^{-1} under optimal environmental conditions.

Vegetative traits were observed to determine the relationship between the vegetative and yield-related traits. Miladinović *et al*. (2011) reported that high-yielding cultivars can be assembled through the selection method either directly based on yield or indirectly through several other yield-related traits. This study indicated the presence of great diversity among the bambara groundnut tested lines for the traits, i.e., number of leaves, terminal leaf length, and terminal leaf width. The diversity for terminal leaf length was caused by the genetic effect as shown by the high heritability value for the said trait. However, the diversity for the number of leaves and the terminal leaf width was influenced by environmental effects because of their low heritability value (<0.5). Other morphological traits, such as plant height, crown diameter, petiole length, internode length, number of internodes, and number of branches, did not exhibit diversity.

The potential lines of bambara groundnut with a high potential yield of seeds per hectare had also large number of leaves. These findings were confirmed by three selected potential lines, namely, GSG 1.1.1, BBL 2.1.1, and BBL 6.1.1. In addition to their high potential seed yield, these lines exhibited a large number of leaves because bambara groundnut pods are located in each internode that supports the leaf stalk, which is the site of photosynthesis in plants. Thus, a high number of bambara groundnut leaves is indicative of the high potential for the production of a large number of pods and seeds. The results further revealed that the number of leaves at 10 WAP ranged from 47.33 to 69.50 with an average value of 55.58. This study, the increase in the number of leaves in the bambara groundnut genotypes did not differ from the previously reported findings of 49–193 leaves per plant (Saptadi *et al*., 2016; Fatimah *et al*., 2018; Yuliawati *et al*., 2019; Fatimah *et al*., 2020; Obidiebube *et al*., 2020).

The age at germination, first flowering, and harvest were observed to identify early-age bambara groundnut potential lines. Septeningsih and Soegianto (2013) stated that early age is an advantageous trait because crop yields would be obtained rapidly if the plants have a relatively fast harvesting age. In addition to obtaining potential homogenous lines, selection is also expected to identify and separate the potential lines with an early age. In this study, the ages of the bambara groundnut genotypes were categorized into three age groups, i.e., early age (<120 DAP), medium age (120–140 DAP), and long life (>140 DAP). The results showed that the selected potential lines of bambara groundnut had lower age at germination, first flowering, and harvesting than the unselected local lines. This situation indicated that the nonselected local lines are thought to have a mixture of lines with diverse ages. The potential bambara groundnut lines BBL 6.1.1 and GSG 1.1.1 were observed with the lowest age at harvesting.

The observation on the age at germination among the potential lines of bambara groundnut indicated that the genotypes had a relatively high age at germination with an average value of 13.08 DAP. Legwaila and Karikari (2013) and Berchie *et al*. (2010) also reported similar findings for bambara groundnut that had a relatively high age at germination that ranged from 7 days to 15 days. Therefore, the seeds are suggested to be soaked before planting to accelerate germination. However, these findings were in contrast to the results of Enen *et al*. (2016), who observed that bambara groundnut seed germination ranges from 8 DAP to 10 DAP. The results showed that the bambara groundnut lines had a relatively longer age at germination than the lines reported in several other studies.

The correlation coefficient is a statistical tool that is used to identify the relationship among variables and its strength (Heiman, 2011). Aditya *et al*. (2011) and Sarutayophat (2012) reported that the correlation coefficient is used to determine the relationship between yield-related traits and other traits that may affect yield. The results showed that the bambara groundnut line with high crowns, long petioles, wide terminal leaves, numerous branches and internodes, and high wet stover weight were thought to produce a high wet pod weight as well. The relationship between the vegetative and yield traits of bambara groundnut genotypes has also been widely reported (Shegro *et al*., 2013; Chandra, 2017; Fitriani, 2018). Specifically, wet stover weight has a significant correlation with wet pod weight (Zenabou *et al*., 2014), and leaf length and width are significantly positively correlated with pod number (Unigwe *et al*., 2016; Belel, 2018; Onwubiko *et al*., 2019; Yuliawati *et al*., 2019). Samsudin (2005) and Hapsari and Adie (2010) reported the absence of weaknesses when correlation analysis was used singly to determine the closeness of the relationship between yield and other component traits. Therefore, path analysis, which aims to unravel the correlation among the yield component traits into direct and indirect effects on yield, must be conducted.

Past path analysis for the bambara groundnut genotypes revealed the direct effect values of the traits, i.e., age at germination (−0.05), number of leaves per plant (−0.47), plant height (−0.57), number of flowers (−0.47), age at flowering (−0.78), and the number of pods (0.27) on the seed weight per plant (Oyiga and Uguru, 2011). The direct and indirect effect values of plant vegetative traits on yield have also been found in several other studies on different crops, i.e., corn (Malik *et al*., 2018), rice (Rohaeni and Permadi, 2012), and soybean (Krisnawati and Adie, 2016). Krisnawati and Adie (2016) stated that when a trait has a direct effect that is equal to the correlation of the trait with the yield trait, the trait would be highly effective as a selection criterion. However, Wirnas *et al*. (2006) reported that in addition to being positively correlated with yield, a trait that could effectively used as a selection criterion for yield should also have a high heritability value. Thus, in addition to having a direct effect on yield, the trait would also be passed on to the next generations. This description provides valuable information to plant breeding programs for bambara groundnut and suggests that the traits leaf length, leaf width, and wet stover weight were effective for use as a basis for selection to obtain bambara groundnut with increased wet pod weight.

CONCLUSIONS

The potential line GSG 1.1.1, which was derived from Gresik Regency, and the two other lines BBL 2.1.1 and BBL 6.1.1, which were selected from Lamongan Regency, exhibited high seed productivity during the dry season in Madura Island, Indonesia. Path coefficient analysis revealed that four characters had a positive direct effect on the pod weight yield of bambara groundnut, i.e., the number of internodes, length of the leaves, width of the leaves, and weight of the wet stover. Three morphological traits, i.e., leaf length, leaf width, and wet stover weight, were found to be highly effective and could be used as criteria for the selection of high-yielding bambara groundnut genotypes.

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