RESEARCH

Genotype × Environment Interactions for Oil Content in Peanut and Stable High-Oil-Yielding Sources

P. Janila,* Surendra S. Manohar, Nagesh Patne, Murali T. Variath, and S.N. Nigam

ABSTRACT

Peanut (*Arachis hypogaea* L.) genotypes with superior and stable agronomic performance and high oil content were identified from testing of 160 advanced breeding lines over six seasons. The study revealed significant genotype and genotype × environment (G × E) interaction determining oil and protein content; shelling outturn; and pod, kernel, and oil yield in peanut. The variability among genotypes was high across the environments for pod yield (546–7382 kg ha^{-1}), oil yield (301–2742 kg ha^{-1}), oil content (37–60%), 100-seed weight (21–127 g), and protein content (19–31%). The GGE biplot technique revealed that ICGV 05155 is a stable genotype for oil yield with an average oil yield of 1886 kg ha^{-1}. ICGV 05155 recorded highest average pod yield of 4928 kg ha^{-1}, kernel yield of 3420 kg ha^{-1}, and oil content of 55.1%. ICGV 06049, ICGV 06041, ICGV 06420, and ICGV 03043 were other genotypes with stable oil yield. Simple regression showed significant contributions of oil content (18–54%), and kernel yield (92–99%) to oil yield across the environments. Simultaneous improvement of kernel yield and oil content is feasible in breeding programs, as kernel yield had no negative association with oil content. The high oil content genotypes, ICGV 05155, ICGV 06049, ICGV 06041, ICGV 06420, and ICGV 03043, with stable oil yield were promoted to multilocation adaptive trials required for their release for cultivation and used as parents in breeding programs and development of mapping population to identify quantitative trait loci (QTL) governing oil content.

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Abbreviations: AEC, average environment coordinate; G × E, genotype × environment; NIRS, near-infrared reflectance spectroscopy; NMR, nuclear magnetic resonance; PC, principal component; QTL, quantitative trait loci.

Peanut, or groundnut, is an important food and oil crop. Over 60% of global peanut production is crushed for extraction of oil for edible and industrial uses, while 30% is consumed in food uses. Peanut oil production ranks sixth in the world, second in Africa, and fifth in Asia among various other vegetable oils. On a global basis, it contributes 3.28% to the total vegetable oil basket. In Africa, its contribution is 19.74% and in Asia it is 4.05% (FAOSTAT, 2012). The share of peanut oil in the total vegetable oil basket of the country is high in Nigeria (31.57%), Myanmar (30.5%), India (18.3%), Vietnam (13.91%), and China (9.42%), where the production of peanut is concentrated (FAOSTAT, 2012). Global trading of peanut and its products is low; the exports include 1.65 Tg of shelled peanut, 0.19 Tg of peanut cake, and 0.19 Tg of peanut oil (FAOSTAT, 2011). The value of peanut oil exported is about US$320 million (FAOSTAT, 2011). The major producers of peanuts, like China, India, Vietnam, Myanmar, and Nigeria, are also major consumers of the peanut and its oil.

The cake obtained after extraction of oil is used in animal feed industry, in making enriched easily digestible food for children and aged persons, and as soil amendment. Peanut kernels are nutritious and are a high-energy food, as they contain 48 to 50% of high-quality edible oil and ~25% protein. Higher proportion of unsaturated fatty acid than saturated fatty acid in its oil makes it suitable for food processing industries, and its high smoking

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point makes it an excellent cooking medium. Because of increasing availability of cheaper edible oils, such as palm oil, soybean oil, and others, peanut is losing its place as a major oilseed crop particularly in India. If its position as a premium oilseed crop is to be restored, its oil content needs to be increased to make it economically more competitive and profitable to farmers and oil processors vis-à-vis other edible oil-bearing crops. While in developing countries enhanced oil content is needed to meet the ever increasing demand for high-quality edible oil, in the United States, it is being targeted to produce peanut biodiesel to run farm machinery to reduce the cost of farm operations (USDA–ARS, 2008; Wright, 2012).

Several workers have reported variability and presence of G × E interactions for oil content in cultivated peanut (Bansal et al., 1993; Barrientos-Priego et al., 2002; Isleib et al., 2008; Singkham et al., 2010). Variability for oil content in the range of 45 to 55% was reported in the peanut minicore collection (Upadhyaya et al., 2003) and wild *Arachis* accessions in the ICRISAT gene bank (Upadhyaya et al., 2011), and also in the USDA peanut germplasm repository (Wang et al., 2012). Higher range of variability for oil content was reported in seeds of wild *Arachis* spp. than cultivated types (Cherry 1977; Wang et al., 2010). Raheja et al. (1987) observed that peanut genotypes belonging to Virginia Runner, Virginia Bunch, and Spanish Bunch groups had comparable levels of oil content. In 6840 germplasm accessions, studied in small batches over years at ICRISAT Center, the oil content ranged from 32 to 55% and protein ranged from 16 to 34% (Jambunathan et al., 1985). However, when genotypes with high oil content were systematically evaluated later in another experiment at ICRISAT, the high-oil lines were unable to maintain their high oil content. The same was true for low-oil genotypes (S.N. Nigam, ICRISAT, unpublished data, 2006). Thus, there is a need to identify stable sources of high oil content preferably in high-yielding superior agronomic backgrounds to ensure success of the breeding program.

In this paper, we present the results obtained from studies conducted on 160 peanut genotypes comprised of advanced breeding lines from ICRISAT center and popular varieties released in India that were evaluated in a range of environments at ICRISAT center to identify stable genotypes with high oil content and high pod yield. Such genotypes could serve as parents in breeding programs aimed at improving the oil content, while some of them could be released as cultivars after evaluation trials required for varietal release.

MATERIALS AND METHODS

Genotypes and Testing Environments

One hundred and sixty peanut genotypes comprised of advanced breeding lines developed at ICRISAT and popular cultivars from India were included in the present study. The lines were selected based on their performance. The advanced lines included 113 Spanish and 47 Virginia types. The pedigree of the lines is given in Supplemental Table S1. The growth habit of the lines is given as per the descriptors for groundnut (IBPGR–ICRISAT, 1992). Some of the key traits of the selected lines include resistance to foliar fungal diseases; tolerance to water-deficit stress and *Aspergillus flavus* infection in the field; short-duration type maturing in 90 to 100 d; high-pod-yielding, medium-duration type maturing in 110 to 120 d; and confectionary type with low oil content and large seeds. These elite lines developed at ICRISAT are International Public Goods and are available for sharing for researchers worldwide. In the last 40 yr, 164 ICRISAT-bred groundnut varieties were released for cultivation in over 38 different countries and were used as parents in breeding programs worldwide. The experiment was conducted in six cropping environments in Alfisols (Alfisol-Patancheru Soil Series; Udic Rhodustolf) at ICRISAT Center, Patancheru (17°53′ N, 78°27′ E, and 545 m asl), India, (three rainy-season environments referred to as R08, R09, and R10 and three postrainy season environments referred to as PR08/09, PR09/10 and PR10/11). The rainy season period starts from late part of June and ends in October, while the postrainy season refers to the peanut growing period from the late part of November to April. The rainfall and temperature in the six experimental seasons at ICRISAT are given in Table 1. The total rainfall during the rainy season varied from 841.8 to 1090.6 mm, while during the postrainy season it was from 38.5 to 99 mm. The postrainy season crop was raised with irrigation. The experiment was laid out in an 8 by 20 α-lattice design with two replications. The plot size was 4 m with four rows 30 cm apart grown on broad bed. The plant-to-plant distance within a row was 10 cm. Standard package of practices (60 kg P_2O_5 as basal application, seed treatment with mancozeb at 2 g kg^{-1} of seed and imidachloprid at 2 mL kg^{-1} of seed, pre-emergence application of pendimethalin at 1 kg a.i. ha^{-1}), irrigation soon after planting and subsequently as and when needed, gypsum at 400 kg ha^{-1} at the peak flowering, and protection against insect pests and diseases was followed to raise a healthy crop.

Observations Recorded and Protocols Followed

The weight of well-dried pods from each plot was converted into kilograms (kg ha^{-1}) to estimate pod yield. The shelling outturn (%) was estimated from a sample of 500 g of randomly selected pods. While in the R08, PR08/09, and R09 seasons, it was estimated on the basis of a bulk sample over two replications, in the PR09/10, R10, and PR10/11 seasons, it was done per replication. Oil content (%) was estimated per replication for all the six environments using nuclear magnetic resonance (NMR) spectrometry (Jambunathan et al., 1985). Oil content of the samples was analyzed at the Charles Renard Analytical Laboratory at ICRISAT, Patancheru. Kernel yield was estimated by multiplying shelling outturn and pod yield per replication. Similarly, oil yield was estimated by multiplying kernel yield and oil content. Protein content (%), determined by using Technicon Autoanalyser (Singh and Jambunathan, 1980), and 100-seed weight data were available only for three environments (PR09/10, R10, and PR10/11).

Table 1. Rainfall and temperature during the rainy and postrainy seasons of 2008 to 2010/11 at ICRISAT, Patancheru

	Rainy season								
	Rainy 2008			Rainy 2009			Rainy 2010		
		Temperature			Temperature			Temperature	
Month	Rainfall	Max.	Min.	Rainfall	Max.	Min.	Rainfall	Max.	Min.
	mm	°C		mm	°C		mm	°C	
June	75.6	33.8	23.5	97.6	36.3	24.5	139.8	34.8	24.6
July	114.3	32.6	22.9	59.2	31.9	23.4	274.8	29.3	22.6
August	382.1	29.2	21.8	420.2	31.0	23.1	434.9	29.6	22.4
September	184.4	29.6	21.0	264.6	30.7	22.5	132.2	29.6	22.3
October	85.4	31.0	18.8	60.1	30.8	19.6	108.9	29.9	20.5
Total rainfall and range of max. and min. temperatures	841.8	31.0–33.8	18.8–23.5	901.7	30.7–36.3	19.6–24.5	1090.6	29.3–34.8	20.5–24.6

	Postrainy season								
	Postrainy 2008–2009			Postrainy 2009–2010			Postrainy 2010–2011		
		Temperature			Temperature			Temperature	
Month	Rainfall	Max.	Min.	Rainfall	Max.	Min.	Rainfall	Max.	Min.
	mm	°C		mm	°C		mm	°C	
November	26.6	29.6	16.1	44.2	29.3	18.3	17.9	28.6	19.5
December	0.0	29.6	12.9	7.4	28.0	13.9	12.5	27.3	13.2
January	0.0	29.7	13.1	39.0	27.7	14.3	0.0	28.8	10.9
February	0.0	33.4	16.5	3.0	32.1	16.8	0.4	30.8	15.4
March	5.8	35.4	18.4	0.0	36.6	20.6	0.2	35.1	18.4
April	27.8	38.4	23.0	5.4	39.7	24.2	7.5	36.6	22.7
Total rainfall and range of max. and min. temperatures	60.2	29.6–38.3	12.9–23.0	99.0	27.7–39.7	13.9–24.2	38.5	27.3–36.6	10.9–22.7

Statistical Analysis

Data for each trait were analyzed for analysis of variance (ANOVA) in each environment (either six or three environments depending on the trait) before subjecting them to Bartlett Chi-square test for testing them for homogeneity of variance. The coefficient of variation for each environment was estimated from the RMSE obtained from ANOVA divided by the mean (× 100%). Since heterogeneity among the environmental variances was confirmed for all traits, data were transformed by applying Aitken's transformation, and pooled analysis was performed. Normality test, single-location, and combined ANOVA were performed by SAS PROC GLM (SAS version 9.2; SAS Institute, 2008) considering replications, blocks, and genotypes as fixed. Contrast analysis was done to compare rainy season (R08, R09, and R10) vs. postrainy season (PR08/09, PR09/10, and PR10/11) data.

Since G × E interaction effect was significant, GGE Biplot (Yan and Tinker, 2006) was drawn to study the performance of genotypes for oil yield based on mean value and stability. A GGE biplot graphically depicts the genotype main effect (G) and the G × E effect contained in the multienvironment trials. GGE biplots have been found very useful in understanding G × E and genotype recommendation.

The fixed-effect, two-way model for analyzing multienvironments genotype trials is as follows:

$$E\left(Y_{ij}\right) = \mu + g_i + e_j + \left(\mathrm{ge}\right)_{ij} + \epsilon_{ij}$$

where, μ is the grand mean, g_i and e_j are the genotype and environmental main effects, respectively, $(\mathrm{ge})_{ij}$ is the G × E effect, and ϵ_{ij} is the residual error of the observations. The sites regression model (Yan and Kang, 2003) is defined as follows:

$$E\left(Y_{ij}\right) = \mu + e_j + \sum_{n=1}^{r} \xi_{in}^{*}\eta_{jn}^{*} + \epsilon_{ij}$$

where, r = number of principal components (PCs) required to approximate the original data, ξ_{in}^{*} and η_{jn}^{*} are the ith genotype and the jth environmental scores for PCn, respectively and ϵ_{ij} is the residual error of the observations. Stable genotypes for oil yield in the six sowing seasons were identified by GGE biplot technique as described by Yan (2001, 2002).

Correlation coefficients among different traits in each environments were calculated by Karl Pearson's method using SAS PROC CORR procedure (SAS version 9.2; SAS Institute, 2008). The genotypes were ranked in each season separately for oil, pod and kernel yield, and oil content. Spearman's rank correlation coefficient between seasons was performed to check environmental effect on ranking of genotypes. Simple linear regression was also used to determine the impact of oil content and kernel yield on oil yield of the experimental genotypes for all the environments. Simple and Spearman's rank correlations and simple regressions were estimated using GenStat version 12 (VSN International, 2009). The broad-sense heritability over environments was calculated following Johnson et al. (1955).

Table 2. Variability and heritability of traits included in the study based on the performance of 160 groundnut genotypes evaluated at ICRISAT Center, Patancheru, 2008–2010 cropping environments.

A. Traits evaluated in six seasons.

	Oil yield				Pod yield (kg ha^{-1})				Oil percentage (%)				Kernel yield			
Environment†	Range	Mean	CV	H^2‡	Range	Mean	CV	H^2	Range	Mean	CV	H^2	Range	Mean	CV	H^2
	—— kg ha^{-1} ——				—— kg ha^{-1} ——				—— % ——				—— kg ha^{-1} ——			
R08	301–2181	1133	15.6	0.9	1309–5656	3592	14.0	0.9	37–57	50	4.3	0.9	684–3974	2238	14.2	0.9
R09	377–1742	969	14.0	0.9	1267–4738	2911	14.1	0.9	42–60	53	2.3	1	740–3056	1812	14.1	0.9
R10	90–1598	760	20.1	0.9	546–4486	2303	16.9	0.9	41–53	49	2.0	0.9	203–3105	1553	19.5	0.9
PR08/09	695–2727	1652	14.3	0.8	2248–7206	4551	13.8	0.8	43–60	54	2.9	0.9	1488–4917	3068	13.7	0.8
PR09/10	475–1915	1324	14.2	0.8	1818–4999	3677	12.5	0.8	42–56	50	2.4	0.9	1055–3696	2638	14.3	0.7
PR10/11	1190–2742	1958	11.6	0.8	3210–7382	5370	10.4	0.8	43–56	51	2.3	0.9	2311–5208	3828	11.6	0.7
Mean over three rainy environments	293–1539	954	–	–	1041–4299	2935	–	–	40–56	50	–	–	604–2860	1868	–	–
Mean over three postrainy environments	858–2290	1645	–	–	2744–5982	4532	–	–	43–57	52	–	–	1862–4200	3178	–	–
Mean over six environments	655–1886	1299	–	0.9	1965–5126	3734		0.9	41–57	51		0.9	1372–3420	2523	–	0.9

B. Traits evaluated in three seasons.

	100-seed weight				Shelling outturn				Protein content			
Environment	Range	Mean	CV	H^2	Range	Mean	CV	H^2	Range	Mean	CV	H^2
	—— g ——				—————— % ——————							
PR09/10	33–105	54	9.9	0.9	58–78	72	4.8	0.5	22–30	26	3.6	0.7
R10	21–57	34	9.0	0.9	48–77	67	9.1	0.3	19–31	24	5.8	0.7
PR10/11	33–127	59	10.5	0.9	58–78	71	4.7	0.5	23–30	27	3.4	0.7
Mena over three environments	30–92	49	–	0.9	62–76	70	–	0.6	23–28	25	–	0.7

† Rainy seasons, R08, R09 and R10; Postrainy seasons, PR08/09, PR09/10, and PR10/11.

‡ H^2, broad-sense heritability.

RESULTS AND DISCUSSION

Range of Variability and Heritability of Traits

The range, mean, coefficient of variation, and heritability of various traits under study for each environment and over environments are given in Table 2. The mean pod yield over six environments of peanut genotypes varied between 1965 and 5126 kg ha^{-1}, oil yield between 655 and 1886 kg ha^{-1}, kernel yield between 1372 and 3420 kg ha^{-1}, and oil content between 41 and 57%. The mean shelling outturn of genotypes over three environments ranged between 62 and 76%, 100-seed weight between 30 and 92 g, and protein content between 23 and 28%. Wide variability was observed for all the productivity traits in the study population.

The minimum and maximum temperature in postrainy season were 11 to 24 and 27 to 40°C, respectively. While in the rainy season, the minimum and maximum temperatures were 19 to 25 and 30 to 36°C, respectively. The total rainfall received in rainy seasons varied between 862 and 1091 mm, sufficient to conduct the trials under rainfed conditions. On the contrary, the postrainy season's crop was raised completely on irrigation except for skipping one or two irrigations when rains were received. Higher values were recorded for all the yield traits studied in postrainy seasons than rainy seasons. The maximum and minimum temperatures are favorable in both, rainy and postrainy seasons for growth and development of groundnut crop; however, the regular moisture available through irrigations in postrainy seasons may have contributed to better accumulation and translocation of photosynthates, resulting in higher pod yield in postrainy seasons. The average pod and kernel yields in postrainy seasons were 54 and 70% higher, respectively, than in rainy seasons. The average 100-seed weight in postrainy seasons was higher by 65% than rainy seasons, implying its significant contribution to increased pod and kernel yield in postrainy seasons. Earlier studies have shown that improvement in seed size, seed weight, and number of pods per plant has largely contributed to enhanced pod yield (Rathnakumar et al., 2012). The oil yield was also higher in postrainy seasons by 72% than rainy seasons; both kernel yield and oil content determine oil yield; however, the seasonal difference in oil yield may largely be attributed to kernel yield differences, as the mean oil content between the seasons showed only a small variation of 2%.

High broad-sense heritabilities varying between 0.7 and 0.9 were recorded for pod, kernel, and oil yield in all the six tested environments. Heritability was also high for oil content (>0.9) in all the six environments, suggesting

Table 3. Combined analysis of variance for traits included in the study of 160 groundnut genotypes evaluated at ICRISAT Center, Patancheru, over six seasons.

		Mean sum of squares and their significance†							
		Traits evaluated in six environments‡				Traits evaluated in three environments§			
Source of variation	df	PY	OY	OC	KY	df	HSW	SO	PC
Environment	5	483**	440**	29022**	388**	2	199**	10500**	14244**
Rainy season vs. postrainy season	1	1175**	874**	35**	702**	–	–	–	–
Replication(environment)	6	7**	10**	29**	12**	3	5**	46**	22**
Block(environment × replication)	84	2**	3**	1*	3**	42	1ns¶	5**	2**
Genotype	159	24**	28**	64**	21**	159	33**	3**	6**
Environment × genotype	795	3**	3**	3**	3**	318	2**	1**	3**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† PY, pod yield (kg ha^{-1}); OY, oil yield (kg ha^{-1}); OC, oil content (%); KY, kernel yield (kg ha^{-1}); HSW, 100-seed weight (g); SO, shelling outturn (%); PC, protein content (%).

‡ Rainy seasons, R08, R09, and R10 and postrainy seasons, PR08/09, PR09/10, and PR10/11

§ Rainy season, R10, and postrainy season PR9/10 and PR10/11. * & ** Significant at P = 0.05, 0.01, respectively.

¶ ns, not significant.

possible genetic gains through selection for this trait. Shelling outturn recorded low heritability of 0.3 to 0.5 in the study population, while it was high for 100-seed weight (0.9) and protein content (0.7) in the three environments of testing. Savaliya et al. (2009) also observed high heritability for pod yield, 100-seed weight, and shelling outturn. In contrast to observed high heritability for oil content in the present study, earlier studies reported low (Chiow and Wynne, 1983) and medium (Azharudheen et al., 2013) heritability. For protein content, high heritability was also reported earlier (Azharudheen et al., 2013). High heritability for kernel yield and oil content in this population suggests possible genetic gains for oil yield through selection for kernel yield and oil content. However, poor heritability for shelling outturn, an important component trait for kernel yield, may limit the progress in selection. Robust phenotyping and genotyping tools to select for high shelling outturn in segregating populations may result in enhanced genetic gains for shelling outturn and consequently enhanced oil yield.

Combined Analysis of Variance

The results of combined ANOVA for all recorded traits are presented in Table 3. Genotypes and environments showed significant differences for all the traits included in the study. Genotype × environment interaction, although of smaller magnitude, was also highly significant for all the traits. Environment was the largest contributor to the total variation in all the cases. The rainy season vs. postrainy season contrast for pod yield, kernel yield, oil yield, and oil content showed highly significant differences. In the postrainy season, pod yield was higher by 54.4%, kernel yield by 70.1%, oil yield by 72.4%, and oil content by 2.0% over the rainy season (Table 3A). Absence of moisture stress, low pressure of diseases and insect pests, and bright sunshine in the postrainy season ensures overall better performance by the crop. Shelling outturn, 100-seed weight, and protein content were also higher in the postrainy season (Table 3B).

Best Genotypes in Rainy and Postrainy Environments

ICGV 05155, ICGV 02411, ICGV 06049, ICGV 06041, and ICGV 06420 are the best five genotypes for oil yield with average oil yield of 1752 to 1886 kg ha^{-1} over six seasons. ICGV 05155 and ICGV 02411were among top five for oil yield in both rainy and postrainy season along with three other genotypes, ICGV 07014, ICGV 06038, and ICGV 07016, with an average oil yield of 2207 to 2290 kg ha^{-1}. In general, oil yield in postrainy seasons was higher than in rainy seasons, likewise it was higher in ICGV 05155 (by 18%) and ICGV 02411 (by 22%), the two common best oil yielders of rainy and postrainy seasons. ICGV 07038, ICGV 04093, ICGV 06149, ICGV 05155, and ICGV 05097 (with average pod yield of 4239–4299 kg ha^{-1}) were best in rainy seasons. ICGV 04093 and four other genotypes, ICGV 07108, ICGV 02410, ICGV 07144, and ICGV 07014 (with average pod yield of 5721–5952 kg ha^{-1}), were the top five in postrainy seasons. ICGV 04093, the best pod yielder of rainy and postrainy seasons, recorded 38% higher pod yield in postrainy than rainy seasons. For oil content, ICGV 06420, ICGV 06321, ICGV 06138, ICGV 05155, and GPBD 4 were among the best five in rainy seasons (54–56%), and ICGV 06420, ICGV 07023, ICGV 07249, ICGV 06038, and ICGV 06149 were best (55–57%) in postrainy seasons. ICGV 06420 recorded the highest average oil yield in both rainy (56%) and postrainy (57%) seasons. During postrainy seasons, of the five best oil yielders, ICGV 07014, ICGV 02411, and ICGV 07016 were also the best kernel yielders and ICGV 06038 is one of the five best for oil content, indicating possible contributions of kernel yield and oil content to oil yield. In rainy seasons, ICGV 05155 is one of the five best oil yielding and it was also among the best five for oil content and kernel yield. Thus, enhanced

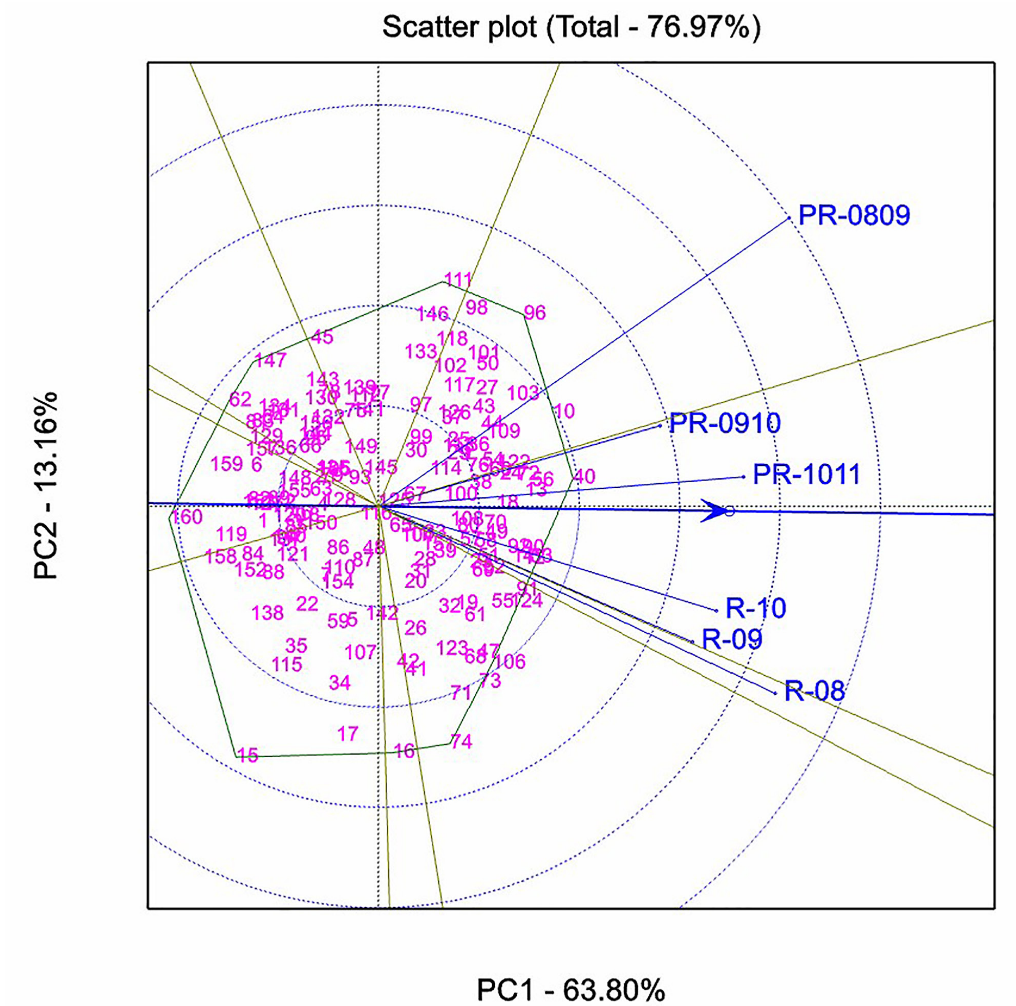

Figure 1. GGE biplots of 160 peanut genotypes for oil yield (kg ha^{-1}) evaluated in six environments at ICRISAT-Patancheru in rainy and postrainy seasons of 2008 to 2010–2011 cropping seasons. The horizontal line with a single arrow head is average environment coordinate (AEC) abscissa. The numbers from 1 to 160 represent the peanut genotypes. PC1 and PC2 are the first and second principal components, respectively. The vertexes represent six environments. Rainy seasons, R08, R09, R10; Postrainy seasons, PR08/09, PR09/10, PR10/11.

oil yield per unit area is possible through increase in both kernel yield and oil content. ICGV 05097 is the highest pod yielding genotype; however, it is not high oil yielding, suggesting significant contribution of oil content to oil yield besides pod yield and that enhancing oil content is important to obtain genetic gain for oil yield.

High Yielding and Stable Genotypes across Environments

Stability of genotypes for oil yield across six seasons was identified by the GGE biplot technique evaluated by average environment coordinate (AEC) method (Yan 2001, 2002). For this, environment centered (centering = 2), genotype–metric (single-value partitioning = 1) biplot for oil yield is presented in Fig. 1. In the GGE biplot figure, the horizontal line with a single arrow head is the AEC abscissa. The AEC abscissa passes through the biplot origin and marker for average environment and points toward higher mean values. The average environment has average PC1 and PC2, the first and second principal components scores over all the environments (Yan 2001; Yan and Tinker 2006). The numbers from 1 to 160 represent the peanut genotypes. The environments are rainy (*R*) and postrainy (PR) with the year given as suffix to the environment as, 2008 = 08, 2009 = 09, 2010 = 10, 2008–2009 = 0809, 2009–2010 = 0910, and 2010–2011 = 1011. The two principal components explained 76.96% (PC1 = 63.80%, PC2 = 13.16%) of total genotype and G × E variation for oil yield. The postrainy 2008–2009 season had higher discrimination ability for oil yield as indicated by the length of the vertex. The closeness of a genotype to AEC indicates the stability of the genotype. The top 10 stable genotypes for oil, pod, and kernel yield and oil content across six seasons are given in Table 4.

The genotype ICGV 05155 is stable across the six seasons for oil, pod and kernel yield, and oil content. It also was highest (among 160 genotypes tested in the present study) for average oil yield (1886 kg ha^{-1}), pod yield (4928 kg ha^{-1}), kernel yield (3420 kg ha^{-1}), and oil content (55.1%). ICGV 06049, ICGV 06041, ICGV 06420, and ICGV 03043 are

Table 4. Selected high-yielding and stable genotypes from 160 groundnut genotypes evaluated at ICRISAT Center, Patancheru, 2008 to 2010–2011 cropping environments.

Sample no.	Genotype no.†	Genotype	R08‡	PR08/09‡	R09‡	PR09/10‡	R10‡	PR10/11‡	Overall	Rainy	Postrainy
High yielding and stable groundnut genotypes for oil yield											
			kg ha^{-1}								
1	40	ICGV 05155	1759	2462	1320	1750	1538	2489	1886	1539	2234
2	56	ICGV 06049	1802	2297	1433	1751	870	2405	1760	1369	2151
3	53	ICGV 06041	1984	2181	1406	1600	1084	2258	1752	1491	2013
4	90	ICGV 06420	1455	2009	1573	1766	1376	2333	1752	1468	2036
5	13	ICGV 03043	1334	2140	1578	1543	1152	2742	1748	1355	2142
6	12	ICGV 03042	1744	2176	1534	1258	1151	2480	1724	1476	1971
7	72	ICGV 06146	1647	2353	1288	1455	1165	2335	1707	1367	2048
8	92	ICGV 06424	1611	1957	1375	1827	1218	2236	1704	1401	2007
9	14	ICGV 03057	1796	2045	1206	1586	1295	2271	1700	1432	1967
10	24	ICGV 04061	1372	2190	1306	1542	1247	2351	1668	1309	2028
High yielding and stable groundnut genotypes for pod yield											
			kg ha^{-1}								
1	36	ICGV 05097	4819	6357	3815	4599	4082	6140	4969	4239	5699
2	40	ICGV 05155	4685	6011	3931	4513	4127	6301	4928	4247	5608
3	72	ICGV 06146	5234	6380	3670	3933	3442	6296	4826	4115	5536
4	56	ICGV 06049	4955	6191	4287	4496	2778	6195	4817	4007	5627
5	53	ICGV 06041	5487	5957	3986	4200	3078	5811	4753	4184	5323
6	44	ICGV 05163	4258	5929	3774	4419	3955	6004	4723	3996	5451
7	92	ICGV 06424	4420	5818	3844	4837	3435	5924	4713	3900	5526
8	13	ICGV 03043	4350	5410	4124	3976	3285	6832	4663	3920	5406
9	57	ICGV 06050	5010	5565	3329	4497	2932	5796	4522	3757	5286
10	18	ICGV 03109	4563	5166	3817	4500	3247	5461	4459	3876	5042
High yielding and stable groundnut genotypes for kernel yield											
			kg ha^{-1}								
1	40	ICGV 05155	3053	4269	2314	3263	3078	4544	3420	2815	4025
2	53	ICGV 06041	3676	4043	2594	3109	2238	4360	3337	2836	3837
3	72	ICGV 06146	3086	4327	2455	2842	2373	4498	3264	2638	3889
4	13	ICGV 03043	2487	3787	2808	2906	2293	5208	3248	2529	3967
5	12	ICGV 03042	3190	3937	2692	2377	2251	4557	3167	2711	3623
6	92	ICGV 06424	2913	3472	2456	3532	2420	4198	3165	2596	3734
7	90	ICGV 06420	2583	3417	2630	3168	2619	4163	3097	2611	3582
8	18	ICGV 03109	2833	3694	2523	3178	2286	3969	3080	2547	3614
9	24	ICGV 04061	2579	3778	2291	2864	2469	4456	3073	2446	3699
10	49	ICGV 06037	2614	3175	1992	3152	2363	5047	3057	2323	3791
Groundnut genotypes with high and stable oil content											
			%								
1	90	ICGV 06420	56.7	58.7	60.0	55.8	52.4	55.8	56.6	56.4	56.8
2	68	ICGV 06138	55.3	57.5	58.6	53.1	51.0	55.0	55.1	55.0	55.2
3	40	ICGV 05155	57.0	57.4	57.6	53.6	50.0	54.9	55.1	54.9	55.3
4	23	ICGV 04060	53.7	57.4	59.1	53.6	51.1	53.5	54.7	54.6	54.8
5	101	ICGV 07019	56.2	59.2	56.6	52.7	50.0	51.7	54.4	54.3	54.5
6	38	ICGV 05141	55.1	58.5	56.6	52.7	51.2	53.7	54.6	54.3	55.0
7	99	ICGV 07017	54.6	58.3	56.8	54.0	51.2	51.8	54.5	54.2	54.7
8	98	ICGV 07016	53.1	56.8	57.5	53.3	52.1	54.3	54.5	54.2	54.8
9	10	ICGV 02411	54.2	57.3	56.9	53.4	51.2	53.8	54.5	54.1	54.8
10	126	ICGV 07249	52.1	58.8	59.0	54.1	50.0	55.0	54.8	53.7	56.0

† Genotype number corresponds to the numbers representing the genotypes in Fig. 1.

‡ Rainy seasons, R08, R09, and R10; Postrainy seasons, PR08/09, PR09/10, and PR10/11.

the genotypes that are stable for oil yield across seasons and also recorded high oil yield of about 1750 kg ha^{-1}. The genotype ICGV 06420 was stable for oil and kernel yield and oil content and was among the 10 best genotypes for oil yield (1752 kg ha^{-1}) and kernel yield (3097 kg ha^{-1}) and had the highest oil content (56.6%). ICGV 06049 was stable for oil and pod yield. It recorded the second highest mean oil yield of 1760 kg ha^{-1}, after ICGV 05155, and was among the top four genotypes for pod yield (4817 kg ha^{-1}). ICGV 06041 was a stable genotype for oil, pod, and kernel yield and recorded an average oil yield of 1752 kg ha^{-1}, pod yield of 4753 kg ha^{-1}, and kernel yield of 3337 kg ha^{-1}. The oil content of ICGV 06049 and ICGV 06041 over seasons was not stable; it varied between 48.4 and 54.1% with a mean of 52.4% for ICGV 06049 and between 48.5 and 54.3% with a mean of 52.3% for ICGV 06041. ICGV 03043 was stable for oil, pod, and kernel yield. It recorded an average oil yield of 1748 kg ha^{-1}, pod yield of 4663 kg ha^{-1}, and kernel yield of 3248 kg ha^{-1}. The oil content of ICGV 03043 ranged between 50.1 and 56.5% over the seasons with an average value of 53.7%.

ICGV 05155, ICGV 06049, ICGV 06041, ICGV 06420, and ICGV 03043 are stable genotypes for oil yield with superior performance that can be promoted for cultivation after conducting adaptive trials and can also be used as parents in breeding programs. The genotypes ICGV 06420, ICGV 06138, ICGV 05155, and ICGV 04060 are stable for oil content across the six season, have high average oil content (54.7–56.65%), and can be used as potential donor for high oil content in breeding programs and to derive mapping populations to identify QTLs for high oil content. On the other hand, TMV 2 was a stable genotype for oil, pod, and kernel yield but was the poorest yielder with an average pod yield of 1965 kg ha^{-1}, kernel yield of 1372 kg ha^{-1}, and oil yield of 655 kg ha^{-1} with 48.1% mean oil content.

Trait Association

Correlations between the traits were analyzed over six environments (Table 5A, 5B); pod yield was significantly positively correlated with kernel yield (0.93 to 0.98) and oil yield (0.90 to 0.97) (Table 5A). Meta and Monpara (2010) observed positive association of pod yield with oil content, while Chiow and Wynne (1983) reported negative association between them. Oil yield had significant positive correlation with oil content (0.43 to 0.74) and kernel yield (0.96 to 1.00), although the correlations were highest with kernel yield. Moreover, pod yield has no negative association with oil content, indicating that both can be improved simultaneously to realize high oil yield per unit area. Significant negative correlation was observed between oil content and 100-seed weight (−0.17 to −0.48) over three environments (Table 5B). The general observation in our breeding program is in agreement with this where the oil content is low in large seeded genotypes that were specifically bred for confectionary purposes. On the contrary, in an earlier study conducted on ungraded seed samples of 64 peanut genotypes, no significant association between oil content and seed mass was observed and positive association between the kernel oil content and seed mass was observed when graded samples of 33 genotypes were studied alone (Dwivedi et al., 1990). Prathiba and Reddy (1994) also did not observe an association of seed mass with oil content. Negative association of oil and protein content was observed in the present study, which is similar to the observation made earlier by Dwivedi et al. (1990). Oil (48–50%), crude protein (21–28%), and carbohydrates (9.5–19%), which include both soluble and insoluble fractions (Jambunathan, 1991; Yaw et al., 2008), are the major constituents of peanut seed, and an increase in any one component is expected to result in decrease of one or more of the other components.

Factors Affecting Oil Yield

A simple regression analysis was performed to quantify the contribution of the factors affecting the oil yield. The percentage variance accounted by oil content to oil yield ranged from 18 to 54%, while the kernel yield accounted for very high percentage, ranging between 92 and 99%. The results imply that oil content and kernel yield, the two major components contributing positively to oil yield, can be targeted for improvement of oil yield per unit area. Moreover, the association between oil content and kernel yield is positive and hence it can be expected that simultaneous improvement of both the components would result in enhanced genetic gains for oil yield. Previous peanut improvement programs could target increase in oil yield only through increased pod yield, and oil content could not be targeted, in part, because of difficulties or inadequate facilities for phenotyping oil content. Oil content is estimated by Soxhlet method, a gravimetric approach that involves laborious process of estimation of solvent extracted oil from a given quantity of ground sample. With the availability of robust tools such as NMR (Jambunathan et al., 1985) and near-infrared reflectance spectroscopy (NIRS) (Misra et al., 2000), it has now become feasible to phenotype a large number of samples for oil content in a short time. A high correlation (r = 0.97) between the estimates of Soxhlet and NMR methods was reported by Jambunathan et al. (1985). For NMR, oven-dried samples are used to determine oil content. Both NMR and NIRS facilitate nondestructive methods of estimation, which becomes crucial in breeding programs. Single, intact kernel (Fox and Cruickshank, 2005); bulk kernel; or pod (Sundaram et al., 2010) can be used for estimating oil content by NIRS.

Table 5. Correlation coefficients of traits based on the performance of 160 groundnut genotypes evaluated at ICRISAT Center, Patancheru, 2008 to 2010–2011 cropping seasons.

A. Correlations between the traits evaluated in six seasons.

Variable, season†	Correlations between the variables					
	Pod yield and kernel yield	Pod yield and oil yield	Pod yield and oil content	Kernel yield and oil yield	Kernel yield and oil content	Oil yield and oil content
R08	0.95**	0.93**	0.59**	0.98**	0.60**	0.74**
PR08/09	0.93**	0.91**	0.23**	0.96**	0.17*	0.43**
R09	0.96**	0.93**	0.41**	0.98**	0.46**	0.61**
PR09/10	0.97**	0.94**	0.33**	0.97**	0.35**	0.57**
R10	0.98**	0.97**	0.48**	0.99**	0.49**	0.55**
PR10/11	0.93**	0.90**	0.46**	0.96**	0.46**	0.69**

B. Correlations between the traits evaluated in three seasons.

Variable	Variable, season†	Shelling outturn (%)	100-seed weight (g)	Protein content (%)
Pod yield (kg ha^{-1})	PR09/10	0.25**	0.25**	−0.16*
	R10	0.19*	0.09ns‡	0.50**
	PR10/11	−0.31**	0.08ns	−0.08ns
Kernel yield (kg ha^{-1})	PR09/10	0.46**	0.22**	−0.18*
	R10	0.36**	0.07ns	0.47**
	PR10/11	0.02ns	0.05ns	−0.04ns
Oil yield (kg ha^{-1})	PR09/10	0.45**	0.06ns	−0.23**
	R10	0.36**	0.05ns	0.47**
	PR10/11	0.00ns	−0.11ns	−0.12ns
Oil content (%)	PR09/10	0.18*	−0.47**	−0.28**
	R10	0.20**	−0.17*	0.18*
	PR10/11	−0.09ns	−0.48**	−0.29**
Shelling outturn (%)	PR09/10	–	−0.01ns	−0.16*
	R10	–	0.02ns	0.07ns
	PR10/11	–	−0.10ns	0.10ns
100-seed weight (g)	PR09/10	–	–	−0.14ns
	R10	–	–	0.24**
	PR10/11	–	–	−0.16*

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† Rainy seasons, R08, R09, and R10; Postrainy seasons, PR08/09, PR09/10, and PR10/11.

‡ ns, not significant.

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