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Diversity and genetic resources of wild *Vigna* species in India

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Abstract

Diversity in morphological characters of 206 accessions of 14 wild *Vigna* species from India was assessed. Of these, 12 species belonged to Asian *Vigna* in the subgenus *Ceratotropis* and two were *V. vexillata* and *V. pilosa* belonging to subgenus *Plectotropis* and *Dolichovigna*, respectively. Data on 71 morphological traits, both qualitative and quantitative, were recorded. Data on 45 qualitative and quantitative traits exhibiting higher variation were subjected to multivariate analysis for establishing species relationships and assessing the pattern of intraspecific variation. Of the three easily distinguishable groups in the subgenus *Ceratotropis*, all the species in *mungo-radiata* group, except *V. khandalensis*, viz. *V. radiata* var. *sublobata*, *V. radiata* var. *setulosa*, *V. mungo* var. *silvestris* and *V. hainiana* showed greater homology in vegetative morphology and growth habit. The species, however, differed in other plant, flower, pod and seed characteristics. Within species variation was higher in *V. mungo* var. *silvestris* populations and three distinct clusters could be identified in multivariate analysis. *V. umbellata* showed more similarity to *V. dalzelliana* than *V. bourneae* and *V. minima* in the *angularis-umbellata* (azuki bean) group. Within species variations was higher in *V. umbellata* than other species in the group. In the *aconitifolia-trilobata* (mothbean), *V. trilobata* populations, were more diverse than *V. aconitifolia*. The cultigens of the conspecific wild species were more robust in growth, with large vegetative parts and often of erect growth with three- to five-fold increase in seed size and seed weight, except *V. aconitifolia*, which has still retained the wild type morphology to a greater extent. More intensive collection, characterisation and conservation of species diversity and intraspecific variations, particularly of the close wild relatives of Asian *Vigna* with valuable characters such as resistance to biotic/abiotic stresses, more number of pod bearing clusters per plant etc. assumes great priority in crop improvement programmes.

Introduction

The genus *Vigna* subgenus *Ceratotropis* consists of 16 (Verdcourt 1970) or 17 (Marechal et al. 1978; Tateishi 1996) recognised species, which are distributed across Asia. Asian *Vigna* species of the subgenus *Ceratotropis* constitute an economically important group of cultivated and wild species, of which a rich diversity occurs in India (Arora 1985; Babu et al. 1985). Taxonomically, cultigen and conspecific wild forms are recognised in all species except *V. aconitifolia* (Marechal et al. 1978; Lukoki et al. 1980). Although this species has apparently responded to selection for larger seed size, there has been no apparent increase in the size of the vegetative parts and it has retained a wild type vegetative morphology. This is in contrast to the situation in *V. radiata* and the other species, where cultigens are much more robust in growth, with large vegetative parts and are often of erect growth.

The Asian *Vigna* are considered to be a morphologically homogenous group which have very specialised and complex floral organs. The works of Maekawa (1955), Baudet (1974) and Tateishi (1996) clearly demonstrated three groups, based on the position of cotyledons on germination and the petiolate or sessile nature of first and second leaves. This was confirmed by several other workers (Jaaska and Jaaska 1990; Kaga et al. 1996; Tomooka et al. 1996, 2000; Konarev et al. 2000). Lawn (1995) also proposed that Asian *Vigna* consists of three more or less isolated genepools, based on cross compatibility studies corresponding with groups based on seedling characteristics proposed by Tateishi (1996) as *angularis-umbellata* (azuki bean group), *radiata-mungo* (mungbean group) and *aconitifoila-trilobata* (mothbean group). Tomooka et al. (2000) proposed a revised list of taxa in the subgenus *Ceratotropis* and suggested three groups, giving them taxonomic rank as Section *Angulares* (azuki bean group), *Radiateae* (mungbean group) and *Aconitifolia*e (mothbean group), and an undetermined section for *V. khandalensis*.

The taxonomic status of the cultivated Asian *Vigna* species has been studied experimentally. They behave as biological species (Smartt 1990). Viable hybrids can be obtained between several species; *V. radiata* is probably the most satisfactory seed parent. It crosses with the wild *V. radiata* var. *sublobata* reciprocally, and with *V. angularis*, *V. umbellata*, *V. mungo* and *V. trilobata* as seed parent only. *V. trilobata* crosses as pollen parent successfully with *V. mungo*, *V. radiata* and *V. aconitifolia*, but reciprocal crosses fail. *V. umbellata* is cross-compatible with *V. angularis* as seed parent only, and with both *V. radiata* and *V. mungo* as pollen parent. *V. angularis* is cross-compatible as pollen parent with *V. umbellata* and *V. radiata*, while *V. mungo* is cross compatible as seed parent only with *V. radiata*. Cross-compatibility of *V. aconitifolia* has not been widely investigated but it has been crossed as a seed parent with *V. trilobata*.

The use of wild relatives as sources of new germplasm is well established in breeding programmes for crop improvement on a world-wide level, but the efficiency with which wild germplasm is utilized for introducing disease resistance and other agronomic characters into elite cultivars varies greatly. Bruchid is a very serious pest of grain legumes during storage. A wild mungbean accession, *Vigna radiata* var. *sublobata* has been reported to be highly resistant to the bruchid *Callosobruchus chinensis* (L.) (Talekar 1994). Mungbean yellow mosaic virus (MYMV) has been a major problem in mungbean. The wild species *Vigna radiata* var. *sublobata* is an important source to incorporate resistance into cultivated varieties (Singh 1994).

In India, the National Bureau of Plant Genetic Resources (NBPGR) has the major responsibility of collecting, maintaining and conserving the crop plant genetic resources including wild related species. More than 200 accessions of wild *Vigna* species collected from various parts of the country are maintained at the NBPGR Regional Station, Thrissur in Kerala (Table 1). A sizable number of these accessions were assembled through systematic explorations and collecting during 1999–2001 (Bisht et al. 2003).

The present study was conducted to describe the diversity in different morphological characters and importance of wild *Vigna* species (mainly in the sub-genus *Ceratotropis*) in evolutionary studies and crop improvement programmes.

Materials and methods

A total of 206 accessions of 14 wild *Vigna* species were included in the study (Table 1). The majority of these species were collected from four main phytogeographical zones, Western Ghats, Eastern Ghats, North-western Himalayas and North-eastern region. Species with a wider range of distribution were *V. radiata* var. *sublobata*, *V. mungo* var. *silvestris*, *V. hainiana* and *V. umbellata* (var. *gracilis*). *V. radiata* var. *setulosa* is endemic to Western Ghats and Eastern Ghats. The distribution range, however, overlapped with other *Vigna* species in the ecotonal zones. *V. khandalensis* is endemic to the Western Ghats and is sparsely distributed around the Pune district of Maharashtra. Only one population was included in the study. Species diversity in the north-western plain zone is very limited. This area has greater diversity in *V. aconitifolia* and *V. trilobata*. *V. bourneae* has

Table 1. Occurrence and characteristics of wild Indian *Vigna* species included in the present study.

Species	Remarks on wild taxa	Accessions included in the study
Subgenus *Ceratotropis*		
Mungo-radiata group		
V. mungo var. *silvestris* Lukoki, Marechal and Otoul	Closest wild relative to cultigen *V. mungo*; widely distributed in Western Ghats and sporadic occurrence in central plateau region (Madhya Pradesh), Melghat (Maharashtra) and parts of Rajasthan (Mt. Abu).	38
V. radiata var. *sublobata* (Roxburgh) Verdcourt	Closest wild relative to cultigen *V. radiata*. Widely distributed in Western Ghats and sporadic distribution in Rajasthan, Madhya Pradesh and Northwestern Himalayas.	33
V. radiata var. *setulosa* (Dalzell) Ohwi and Ohashi	Closely related to *V. radiata*, sporadic occurrence in Western and Eastern Ghats	11
V. hainiana Babu, Gopinathan and Sharma	Widespread distribution in Eastern Ghats (parts of Orissa), Central Plateau region (Chhatisgarh, Madhya Pradesh, Maharashtra), Northwestern Himalayas (parts of Uttaranchal and Himanchal Pradesh).	24
V. khandalensis (Santapau) Raghavan and Wadhwa	Endemic to parts of Western Ghats (Pune district in Maharashtra).	1
Angularis-umbellata group		
V. umbellata var. *gracilis* (Prain) Marechal, Mascherpa and Stainier	Conspecific with the cultigen *V. umbellata*, widespread in Western Ghats, Eastern Ghats and Northwestern Himalayas	39
V. dalzelliana (O. Kunte) Verdcourt	Close to *V. umbellata* wild types, distributed in Western Ghats (Maharashtra) and Eastern Ghats (Orissa).	6
V. bourneae Gamble	Sporadic distribution in Western Ghats (Nilgiris and parts of Kerala).	14
V. minima (Roxburgh) Ohwi and Ohashi	Distributed in parts of Western Ghats.	2
V. glabrescens Marechal, Masherpa and Stainer	Collected from Madhya Pradesh	1
Aconitifolia-trilobata group		
V. aconitifolia (Jacquin) Merechal	Conspecific with the cultigen type, distributed in dry regions of Rajasthan and Madhya Pradesh.	3
V. trilobata (L.) Verdcourt	Semi-domesticated type, distributed in parts of West Bengal, Orissa, Chhatisgarh, Gujarat and Madhya Pradesh.	10
Subgenus *Plactotropis*		
V. vexiliata (L.) A. Rich.	Distributed in Western Ghats, Northwestern Himalayas, Eastern Ghats.	15
Subgenus *Dolichovigna*		
V. pilosa (Willd.) Benth	Distributed in Western Ghats (parts of Kerala and Tamil Nadu).	9

restricted distribution in Nilgiris and parts of Western Ghats (Kerala, in South India). Only two accessions of *V. minima* were included in the study from Western Ghats (Kerala). One accession of *V. glabrescens* was also included, occurring naturally from Madhya Pradesh. *V. vexillata* is widely distributed and collections were made from Western Ghats, Eastern Ghats and North-western Himalayas. *V. pilosa* has a restricted distribution in Western Ghats (parts of Tamil Nadu and Kerala). Accessions of conspecific cultigen types were also included in the study including *V. unguiculata* for comparison. Figure 1A–J depicts the vegetative morphology of 10 wild *Vigna* species in natural stands.

The accessions were grown both under field conditions and in earthern pots at the NBPGR Regional Station in Thrissur (Kerala) and were characterised for various morphological traits, in a phased manner, during 1999–2001. Data were

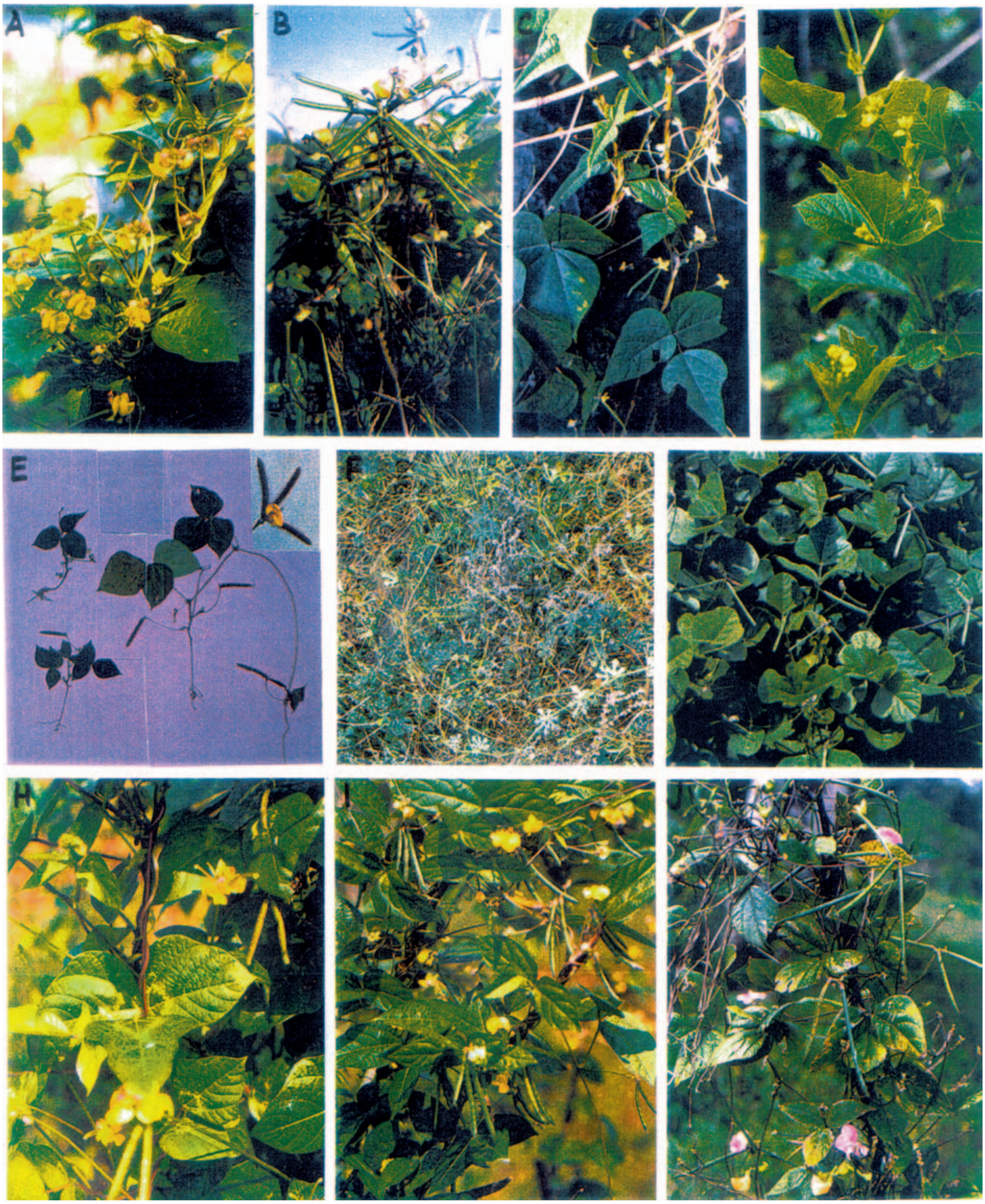

Figure 1. Photographs depicting vegetative morphology of some wild *Vigna* species distributed in India. (A) *V. radiata* var. *sublobata*; (B) *V. radiata* var. *setulosa*; (C) *V. hainiana*; (D) *V. khandalensis*; (E) *V. mungo* var. *silvestris*; (F) *V. aconitifolia*; (G) *V. trilobata*; (H) *V. bourneae*; (I) *V. umbellata*; (J) *V. vexillata*.

recorded for 71 characters, both qualitative and quantitative, using both IPGRI and NBPGR descriptors. Data for quantitative traits were recorded on five randomly selected individuals per accession from one-row field plots of 2 m row length grown in augmented block design in 2001 cropping season. The cultigen types (five accessions each of *V. mungo*, *V. radiata* and *V. umbellata*, and two accessions of *V. aconitifolia*) were used as checks for comparison. These check varieties were replicated throughout the test plot in a block of 50 wild species germplasm accessions (the fourth block comprised 56 accessions). Data for significant characters were subjected to statistical analysis for augmented design (Federer 1956) and the adjusted treatment (accession) means were computed after adjusting them for block effects. The treatment means were standardized to mean 0 and standard deviation 1 for further analysis. Frequency distribution for qualitative characters and range, mean, and variance for quantitative traits were computed using MSTAT-C statistical package developed at Michigan State University, USA.

Data on 45 distinct qualitative and quantitative characters (Table 2) were subjected to multivariate analysis using NTSYS ver. 1.80 statistical package (Rohlf 1992). The multivariate statistics were used for establishing relationships among taxa particularly in the subgenus *Ceratotropis* and the pattern of inter- and intraspecific diversity. The qualitative character states X species accessions data matrix was used to calculate the frequency of occurrence of a particular character state in a species. This frequency matrix was used to construct a cladogram based on Wagner parsimony criteria. The cladogram obtained was rerooted with *Vigna pilosa* as the outgroup. The branches of the cladogram were reordered using the 'Retree' option in 'PHYLIP' ver. 3.60 (Felsenstein 1993). Various alternative positions for each branch were considered, but the cladogram requiring the least number of steps was chosen for discussion here.

The species accessions X qualitative character states data matrix was used to calculate the correlation among various character states scored. The correlation coefficient matrix was subjected to eigenvectors analysis. The eigenvectors derived were used to extract the first three most informative principal components. These three components were plotted in both three dimensional and biplot mode in various combinations. Only the biplots of the first two most informative components were presented.

Similarly, principal components analysis (PCA) was performed for quantitative traits data on individual groups of the subgenus *Ceratotropis*.

Results

The key distinguishing features of wild *Vigna* species under the subgenus *Ceratotropis* and some other subgenera of the genus *Vigna* revealed that epigeal germination and sessile first and second leaves were recorded in all the species accommodated under *mungo-radiata* (mungbean) group. Species in the *angularis-umbellata* (azuki bean) group (*V. bourneae*, *V. dalzelliana*, *V. minima*, *V. umbellata* and *V. glabrescens*) recorded hypogeal germination with petiolate first and second leaves. *Vigna aconitifolia* and *V. trilobata* in the *aconitifolia-trilobata* (mothbean) group recorded epigeal germination with petiolate first and second leaves. All the species in the subgenus *Ceratotropis* have flower colour in various shades of yellow as against purple/violet in *V. vexillata* and pale lilac in *V. pilosa* belonging to the other subgenera. Between-species variation, except for the two characters, number of pods per plant and seed yield, was significantly greater than within-species variation for most of the quantitative characters.

Among all the species in the mungbean group, *V. hainiana*, *V. mungo* var. *silvestris*, *V. radiata* var. *setulosa* and var. *sublobata* showed greater homology in growth habit and other vegetative parts. These species, however, differed in pubescence of various plant parts, and pod and seed characteristics. *V. hainiana* populations had exceptionally small flowers and seeds as compared to the other species in the group. Within-species variation was more prominent in *V. mungo* var. *silvestris* and *V. radiata* var. *sublobata*. *V. khandalensis* was remarkably distinct from other species in its erect plant habit, large foliaceous stipules and broad leaflets, but in flower and pod characteristics it resembled both *V. mungo* and *V. radiata*. In the azuki bean group, *V. umbellata* and *V. dalzelliana* showed more similarity to each other, having slightly curved pods. The *V. umbellata* populations were, however, more diverse. *V. bourneae* resembled

Table 2. Important descriptors for characterisation of wild *Vigna* species germplasm.

No.	Characters/descriptors	Descriptor states
Qualitative descriptors		
1.	Seed germination habit	1. Epigeal, 2. Hypogeal
2.	Attachment of primary leaves (at two leaf stage)	1. Sessile, 2. Sub-sessile, 3. Petiolate
3.	Growth habit (recorded at first pod maturity)	1. Erect, 2. Semi-erect, 3. Spreading, 4. Semi-prostrate, 5. Prostrate, 6. Climbing
4.	Leafiness (at 50% flowering)	1. Sparse, 2. Intermediate, 3. Abundant
5.	Leaf pubescence	1. Glabrous, 2. Very sparsely pubescent, 3. sparsely pubescent, 4. Moderately pubescent, 5. Densely pubescent
6.	Petiole pubescence	1. Glabrous, 2. Pubescent, 3. Moderately pubescent, 4. Densely pubescent
7.	Lobing of terminal leaflet (at first pod maturity)	1. Unlobed, 2. Shallow, 3. Intermediate, 4. Deep 5. Very deep
8.	Terminal leaflet lobe shape	1. Lanceolate, 2. Broadly ovate, 3. Ovate, 4. Rhombic, 5. Others
9.	Stipule size	1. Small, 2. Medium, 3. Large
10.	Stipule shape	1. Ovate; 2. Lanceolate, 3. Others
11.	Stem pubescence	1. Glabrous, 2. Sparsely pubescent, 3. Moderately pubescent, 4. Highly pubescent
12.	Raceme position (at first pod maturity)	1. Mostly above canopy, 2. In upper canopy, 3. Throughout canopy
13.	Calyx colour	1. Green; 2. Purplish green, 3. Greenish purple, 4. Others
14.	Corolla colour	1. Yellow, 2. Greenish yellow, 3. Yellowish green, 4. Green-purplish yellow, 5. Others
15.	Bracteole size	1. Small, 2. Intermediate, 3. Large
16.	Bracteole shape	1. Linear, 2. Lanceolate, 3. Others
17.	Flowering period	1. Asynchronous, 2. Intermediate, 3. Synchronous
18.	Pod attachment to peduncle	1. Erect, 2. Horizontal, 3. Horizontal-pendent 4. Pendent, 5. Others
19.	Pod pubescence	1. Glabrous, 2. Sparsely pubescent, 3. Moderately pubescent, 4. Densely pubescent
20.	Pod curvature	1. Straight, 2. Slightly curved, 3. Curved (sickle shaped)
21.	Pod beak shape	1. Pointed, 2. Blunt, 3. Others
22.	Constriction of pod between seeds	1. Absent, 2. Slight, 3. Pronounced
23.	Pod cross section	1. Semi flat, 2. Round, 3. Others
24.	Seed shape	1. Globose, 2. Ovoid, 3. Narrowly ellipsoid, 4. Cubical to oblong, 5. Kidney shaped, 6. Drum shaped, 7. Others
25.	Seed colour	1. White, 2. Cream, 3. Light brown, 4. Intermediate brown, 5. Dark brown, 6. Grey, 7. Mottled grey, 8. Mottled brown, 9. Mottled cream, 10. Light cream, 11. Green brown, 12. Chocolate, 13. Black
26.	Lusture on seed surface	1. Absent, 2. Present
27.	Mottling on seed surface	1. Absent, 2. Slight, 3. Intermediate, 4. Heavy
28.	Hilum shape	1. Concave, 2. Plain, 3. Convex, 4. Others
Quantitative descriptors		
29.	Terminal leaflet length (cm)	
30.	Terminal leaflet width (cm)	
31.	Petiole length (cm)	
32.	Plant height (m)	
33.	Days to flowering	
34.	Flower bud size (cm)	
35.	No. of flower per raceme	
36.	Peduncle length (cm)	
37.	No. of pods per peduncle	
38.	Days to maturity	
39.	Pod length (cm)	
40.	No. of pods per plant	
41.	No. of seeds per pod	
42.	100-seed weight (g)	
43.	Seed size (mm^2)	
44.	Hilum length (mm)	
45.	Yield per plant (g)	

Table 3. Means of selected quantitative characters[a] of wild *Vigna* species and conspecific cultigen types.

Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
V. mungo (cultigen)	13.28	8.63	13.74	1.27	47.36	0.63	6.63	7.48	4.63	77.09	4.42	63.97	6.54	4.03	16.99	2.15	6.16
V. m. silvestris	9.52	6.64	10.49	1.96	65.40	0.64	3.93	8.72	2.46	94.78	3.77	151.61	7.71	1.60	8.89	2.05	4.65
V. radiata (cultigen)	8.71	6.60	8.52	0.34	44.50	0.81	4.71	7.60	3.57	60.00	6.61	49.79	10.92	2.70	12.07	1.83	1.34
V. r. setulosa	11.11	9.73	10.76	2.04	49.43	0.68	5.85	8.94	2.86	65.43	5.60	25.17	10.43	1.22	6.54	1.22	2.05
V. r. sublobata	7.75	6.60	9.48	1.51	60.13	0.63	5.90	9.47	3.31	78.38	4.80	91.30	10.10	1.16	6.63	1.43	2.13
V. hainiana	10.61	8.97	11.32	2.42	49.83	0.26	6.16	6.63	5.16	74.50	3.93	159.06	9.67	0.68	4.52	1.14	3.26
V. khandalensis	13.43	12.67	10.10	1.98	155.00	0.60	4.00	17.50	5.00	175.00	5.66	15.33	10.00	4.08	15.22	1.52	2.29
V. umbellata (cultigen)	15.63	8.68	18.17	1.92	73.50	0.68	11.50	14.59	7.50	95.00	7.70	51.10	10.00	5.28	18.74	3.35	7.84
V. umbellata var. *gracilis*	7.55	5.43	10.38	2.51	143.93	0.41	4.27	8.86	3.00	165.44	4.22	67.52	10.82	0.85	6.64	1.84	5.76
V. dalzelliana	7.31	5.20	8.00	2.02	99.75	0.41	3.50	7.18	2.00	118.75	4.47	154.68	7.50	0.84	6.11	1.53	1.86
V. bourneae	10.05	8.57	13.05	2.48	135.60	0.75	6.00	17.81	3.80	158.60	6.35	84.00	12.10	1.66	7.78	1.84	3.92
V. minima	7.03	5.50	10.40	1.94	111.50	0.47	4.00	5.83	2.50	135.00	4.63	71.84	7.50	1.07	5.03	1.79	1.42
V. glabrescens	11.63	7.37	17.90	1.60	139.00	0.77	8.00	15.17	5.00	163.00	7.38	3.50	9.00	3.50	12.93	1.97	0.83
V. aconitifolia (cultigen)	4.43	4.03	4.00	0.43	59.00	0.50	5.00	3.50	4.00	83.00	2.50	160.00	5.00	1.89	6.23	0.92	1.93
V. aconitifolia (wild)	4.54	3.96	6.25	1.53	67.00	0.37	4.00	4.72	3.33	92.33	2.19	296.67	4.33	0.48	3.93	0.82	3.51
V. trilobata	4.74	4.80	10.46	0.86	63.00	0.35	4.00	25.99	2.29	85.85	4.96	101.34	9.71	0.89	6.87	1.57	1.12
V. unguiculata (cultigen)	10.83	6.80	11.87	2.45	82.50	1.05	4.00	14.45	1.50	121.50	14.45	52.00	12.50	8.00	28.60	2.72	5.90
V. vexillata	9.14	5.50	7.31	2.29	76.27	1.79	3.64	17.49	2.73	98.54	9.58	61.56	15.45	1.79	8.61	1.81	6.58
V. pilosa	9.98	4.62	5.76	2.04	154.71	0.86	6.28	5.08	4.00	182.57	8.48	59.44	9.71	4.48	19.07	1.81	10.92

[a]1: Terminal leaflet length; 2: Terminal leaflet width; 3: Petiole length; 4: Plant height; 5: Days to flowering; 6: Flower bud size; 7: No. of flowers per raceme; 8: Peduncle length; 9: Pods per peduncle; 10: Days to maturity; 11: Pod length; 12: Pods per plant; 13: Seeds per pod; 14: Seed weight; 15: Seed size; 16: Hilum length; 17: Yield per plant.

V. radiata in pod characteristics. Two populations of *V. minima* showed homology for the majority of the qualitative characters, but they differed for plant height, days to flowering and seed size. In the mothbean group, *V. aconitifolia* populations were more homogeneous among themselves than *V. trilobata* populations. Table 3 lists the mean values for 17 quantitative traits in different *Vigna* species, including the conspecific cultigen types.

Tables 4–6 list the comparative measurement of mean, range and variation of nine quantitative traits of cultigen types and conspecific wild species in three groups of the subgenus *Ceratotropis*. It is evident from these tables that the range of variation, particularly for number of pods per plant and yield per plant, is greater for wild species than the cultigen types. The conspecific cultigen types were however more robust with erect growth habit and recorded three to five-fold increase in seed size and seed weight.

Species relationship through multivariate analysis on qualitative traits was established. The cladogram (Figure 2) revealed that *V. hainiana*, *V. mungo* var. *silvestris*, *V. radiata* var. *sublobata*, *V. radiata* var. *setulosa* and the cultigens *V. mungo* and *V. radiata* were closely associated and formed a distinct group. *V. dalzelliana*, *V. minima* and *V. umbellata* also grouped together. *V. aconitifolia* and *V. umbellata* were closely associated and grouped together in a distinct cluster. Morphologically *V. khandalensis* was quite distinct and formed a distinct group. *V. bourneae* also formed a distinct group and was intermediate between mungbean and azuki bean groups. *V. unguiculata* and *V. vexillata*, though grouped together, are quite distinct taxonomically. *V. pilosa* was also quite distinct and formed a separate group.

The PCA was performed on species in individual groups of the subgenus *Ceratotropis*. The scatterplots for the three groups are presented as

Table 4. Mean, range[a] and variance for important quantitative traits of cultivated and wild *Vigna* species in the *mungo-radiata* group.

Character		*V. mungo*	*V. radiata*	*V. m. silvestris*	*V. r. setulosa*	*V. r. sublobata*	*V. hainiana*	*V. khandalensis*
Plant height	Mean	0.75	0.54	1.96	2.04	1.51	2.42	1.98
	Range	0.44–1.95	0.24–0.83	0.95–3.18	1.37–2.62	0.40–3.01	1.00–6.67	–
	CV (%)	25.90	61.70	29.08	20.00	39.70	57.80	–
Days to flowering	Mean	47.36	44.50	65.40	49.43	60.13	49.83	155.00
	Range	31.00–73.00	34.00–93.00	36.00–139.00	30.00–78.00	34.00–147.00	41.00–64.00	–
	CV (%)	35.30	13.32	32.60	37.00	39.70	15.70	–
Days to maturity	Mean	77.09	68.00	94.78	65.43	78.38	75.50	175.00
	Range	67.00–117.00	58.00–94.00	68.00–158.00	54.00–83.00	51.00–175.00	67.00–90.00	–
	CV (%)	20.10	9.50	23.00	14.60	31.00	10.90	–
Flower bud size	Mean	0.63	0.81	0.64	0.68	0.63	0.26	0.60
	Range	0.50–1.08	0.50–1.04	0.32–0.85	0.40–1.12	0.24–0.96	0.12–0.50	–
	CV (%)	23.80	14.80	29.60	40.20	33.30	77.00	–
No. of pods per plant	Mean	63.97	49.79	151.61	25.17	91.30	159.06	15.33
	Range	18.60–94.00	8.66–111.00	6.00–697.00	10.00–40.57	5.74–289.00	27.00–418.00	–
	CV (%)	19.70	71.20	100.80	44.80	91.00	81.40	–
100-seed weight	Mean	4.03	2.90	1.60	1.22	1.16	0.68	4.80
	Range	2.33–5.10	1.57–4.06	1.20–2.54	10.43–2.22	0.55–2.40	0.53–0.84	–
	CV (%)	11.90	25.50	21.30	47.50	41.70	14.70	–
Seed size	Mean	16.99	12.07	8.89	6.54	6.63	4.52	15.22
	Range	14.09–20.82	8.46–15.99	5.47–14.40	1.02–9.48	1.83–11.53	0.96–5.51	–
	CV (%)	12.60	14.80	25.00	42.80	34.40	25.80	–
Hilum length	Mean	2.15	1.83	2.05	1.22	1.43	1.14	1.52
	Range	1.86–2.46	0.72–8.55	1.47–3.04	0.42–1.91	0.22–2.00	0.59–1.83	–
	CV (%)	7.90	18.00	14.60	36.00	22.30	30.00	–
Yield per plant	Mean	6.16	5.34	4.65	2.05	2.13	3.26	2.29
	Range	1.67–9.88	0.72–8.85	0.34–60.90	0.30–5.61	0.30–4.72	0.81–7.88	–
	CV (%)	41.30	41.79	228.80	77.10	60.00	58.70	–

[a]Range (minimum–maximum), *CV* = Coefficient of Variation.

Figures 3–5. It is evident from Figure 3 that *V. radiata* var. *sublobata* and var. *setulosa* are close in PCA ordination forming a large distinct group. A few weedy races in *V. radiata* var. *sublobata*, however, grouped separately. *V. mungo* var. *silvestris* populations formed three distinct groups and the groups were fairly apart in ordination. *V. hainiana* formed a distinct group and showed more homology among its populations. In the azuki bean group (Figure 4), *V. bourneae* populations were close in ordination and formed a distinct group. *V. umbellata* formed two distinct groups, both overlapping with *V. dalzelliana* populations. In the mothbean group (Figure 5), two *V. aconitifolia* populations were close in ordination. One population overlapped with *V. trilobata*, the latter being more diverse with its populations far apart in PCA ordination.

The PCA performed on the quantitative traits revealed that the first three components accounted for 57.27, 66.57 and 77.07% cumulative variation in the three groups, mungbean, azuki bean and mothbean of the subgenus *Ceratrotropis*, respectively (Table 7). The table also shows the characters with greater weightage in each of the principal components. Important characters with maximum weightage in different PC axes differed in the three groups.

Table 8 summarises the intraspecific morphological variation in wild *Vigna* species populations.

Discussion

The morphological characterisation data of wild *Vigna* species in the subgenus *Ceratotropis* clearly revealed three more or less distinct groups in the present study, as has been described by several earlier workers (Maekawa 1955; Baudet 1974; Jaaska and Jaaska 1990; Lawn 1995; Kaga et al. 1996; Tateishi 1996; Tomooka et al. 1996, 2000, 2003; Konarev et al. 2000).

Table 5. Mean, range[a] and variance for important quantitative traits of cultivated and wild *Vigna* species in the *angularis-umbellata* group.

Character		*V. umbellata*	*V. umbellata* var. *gracilis*	*V. dalzelliana*	*V. bourneae*	*V. minima*
Plant height	Mean	1.92	2.51	2.02	2.48	1.94
	Range	1.92–1.93	1.20–3.00	1.00–2.80	1.50–3.20	1.50–2.38
	CV (%)	28.27	17.53	41.00	20.60	32.20
Days to flowering	Mean	73.50	143.93	99.75	135.60	111.50
	Range	52.00–123.00	59.00–175.00	68.00–127.00	84.00–163.00	76.00–147.00
	CV (%)	28.27	18.72	24.50	135.00	45.00
Days to maturity	Mean	95.00	165.44	118.75	158.6	135.00
	Range	85.00–150.00	75.00–195.00	89.00–156.00	110.00–190.02	102.00–168.00
	CV (%)	16.20	17.28	27.06	15.90	34.50
Flower bud size	Mean	0.68	0.47	0.41	0.75	0.43
	Range	0.60–0.77	0.12–0.85	0.28–0.60	0.45–0.91	0.35–0,50
	CV (%)	17.65	34.15	27.60	21.60	16.10
No. of pods per plant	Mean	51.10	67.52	158.68	84.00	71.84
	Range	38.20–136.00	0.63–376.67	18.29–506.44	4.33–372.00	32.60–111.5
	CV (%)	18.02	120.39	152.00	131.60	71.00
100-seed weight	Mean	5.28	0.85	0.84	1.66	1.07
	Range	4.89–6.68	0.40–1.30	0.36–1.15	1.34–2.16	1.02–1.12
	CV (%)	18.76	32.94	40.09	15.70	6.50
Seed size	Mean	18.74	6.64	6.11	7.78	5.03
	Range	10.48–32.00	5.11–10.46	4.62–8.87	6.68–9.74	3.79–6.26
	CV (%)	15.13	38.70	15.55	11.40	34.60
Hilum length	Mean	3.35	1.53	1.84	1.84	1.79
	Range	3.16–3.55	1.42–2.49	1.24–2.11	1.58–2.34	1.10–1.87
	CV (%)	7.76	10.87	26.10	13.00	6.70
Yield per plant	Mean	7.84	5.76	1.86	3.92	1.42
	Range	6.78–9.90	0.22–27.35	1.00–2.75	0.28–10.90	0.49–2.36
	CV (%)	10.81	280.21	98.27	94.1	92.90

[a]Range (minimum–maximum), *CV* = Coefficient of Variation.

The mungbean group comprised five species. Among the two widely distributed species, *V. mungo* var. *silvestris* and *V. radiata* var. *sublobata*, the former showed greater intraspecific variability. Wide range of variation was recorded for all the important quantitative traits viz. plant height, days to flowering and maturity, number of pods per plant, 100-seed weight and yield per plant (Table 4). Three distinct population types in *V. mungo* var. *silvestris*, were noticed (Figure 3) based on the morphological characterization data. One group belonged to highly twining type populations having more pod bearing clusters with 6–8 hairy sub-erect or ascending pods. The second group belonged to the prostrate type populations with low plant height, had 2–4 hairy pods per peduncle, both deflexed and ascending. These accessions were collected mainly from the drier areas in Central Plateau region and parts of Rajasthan. The third group belonged to weedy races with twining growth habit and relatively bold seeds. These weedy races were collected from parts of Rajasthan and Western Ghats growing in the proximity of cultivated types. *V. radiata* var. *sublobata* populations were comparatively more homogeneous for qualitative traits. However, wide range of variation for quantitative yield related characters was evident (Table 4). A distinct group of weedy races in *V. radiata* var. *sublobata*, collected mainly from parts of Rajasthan, could be distinguished in PCA ordination (Figure 3). *V. radiata* var. *setulosa*, with restricted distribution, is closely related to var. *sublobata* and formed a larger group with the populations of both the species overlapping in PCA ordination (Figure 3). The *setulosa* types, however, possessed comparatively larger and densely hairy pods. The populations collected from parts of Western Ghats were relatively late in maturity and the pods were less pubescent in comparison to the populations collected

Table 6. Mean, range[a] and variance for important quantitative traits of cultivated and wild *Vigna* species in the *aconitifolia-trilobata* group.

Character		*V. aconitifolia* (cultigen)	*V. aconitifolia* wild	*V. trilobata*
Plant height	Mean	0.43	1.53	0.86
	Range	0.11–0.59	0.30–2.28	0.33–1.39
	CV (%)	18.27	69.93	50.00
Days to flowering	Mean	59.00	67.00	63.00
	Range	32.00–84.00	66.00–69.00	40.00–108.00
	CV (%)	16.20	2.58	35.80
Days to maturity	Mean	83.00	92.33	85.85
	Range	57.00–105	92.00–93.00	61.00–137.00
	CV (%)	18.27	0.62	28.90
Flower bud size	Mean	0.50	0.37	0.35
	Range	0.24–0.96	0.03–0.60	0.20–0.50
	CV (%)	28.70	81.08	41.00
No. of pods per plant	Mean	160.00	296.67	101.34
	Range	11.00–270.30	256.83–360.00	9.14–344.00
	CV (%)	18.02	18.69	121.60
100-seed weight	Mean	1.89	0.48	0.89
	Range	1.20–3.80	0.37–0.62	0.74–1.11
	CV (%)	18.76	25.00	14.70
Seed size	Mean	6.23	3.99	6.87
	Range	5.47–9.48	3.84–4.09	5.20–10.22
	CV (%)	16.13	3.31	23.40
Hilum length	Mean	0.92	0.82	1.57
	Range	0.75–1.50	0.75–0.95	1.21–2.20
	CV (%)	10.76	13.41	20.30
Yield per plant	Mean	1.93	3.51	1.12
	Range	0.32–3.45	0.93–6.39	0.63–1.82
	CV (%)	41.30	78.06	49.50

[a]Range (minimum–maximum), *CV* = Coefficient of Variation.

from Eastern Ghats of India. *V. hainiana,* another widely distributed species in the mungbean group, showed similarity to both *V. mungo* and *V. radiata* wild types. In pod characteristics *V. hainiana* resembles *V. radiata* var. *sublobata*, but differed from the latter in having flexuous stems, large peltate stipules, long greyish or greyish brown hairs on stem and petioles (like *V. mungo* var. *silvestris*). Morphologically this species is more primitive than *V. mungo* var. *silvestris* and *V. radiata* var. *sublobata*, with comparatively small flowers and very small seeds. In PCA ordination, all the accessions formed one distinct group. Wide range of variation for most of the yield related quantitative traits was recorded. The populations from north-western India were less viny pigmy types with relatively small pods and seeds. *V. khandalensis*, endemic to India, was quite distinct from other Asian *Vigna* species. It was tall, erect, thick-stemmed and shrub like with large foliaceous stipules. However, it shows morphological similarity to both *V. mungo* (close raceme) and *V. radiata* (sub-erect, glabrous/minutely strigose medium thick pods).

In the azuki bean group, *V. umbellata* wild types (var. *gracilis*) are distributed more widely than the other closely related species, *V. dalzelliana*. The *umbellata* types were more robust with comparatively longer and bold pods. The population from the north-western Himalayas were less robust with thinner leaflets and shorter pods and are adaptive to abiotic stress situations (mainly drought). Morphologically, *V. dalzelliana* was similar to *V. umbellata,* with glabrous or minutely hairy, slightly sickle shaped pods with a characteristic long linear hilum. *V. umbellata* and *V. dalzelliana* populations formed two distinct overlapping groups (Figure 4). *V. bourneae*, accommodated in this subgroup exhibits a narrow range of distribution and is endemic to parts of South India (Nilgiris and Kerala), the populations were comparatively more homogeneous and distinct, as is evident in PCA ordination (Figure 4). With the exception of the

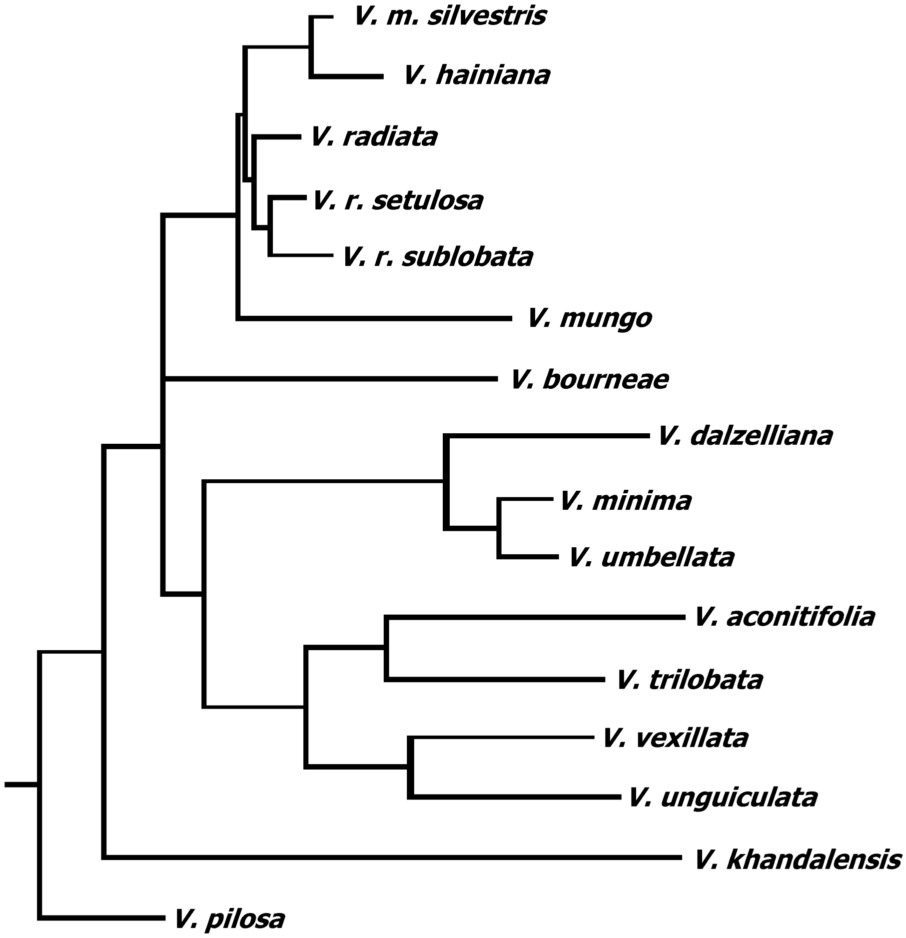

Figure 2. Cladogram of wild *Vigna* species and conspecific cultigen types.

major species-distinguishing characteristics (hypogeal germination and petiolate first and second leaves), this species shows resemblance to *V. radiata* in other vegetative and pod characteristics. Only two populations of *V. minima* were studied in the present work. These types are less robust, less leafy, and have comparatively smaller flowers, thinner and smaller pods and smaller seeds. The species *V. glabrescens* is probably an amphidiploid reported to be combining the genomes of *V. radiata* and *V. umbellata* (Dana 1964). However, based on rDNA sequence variation studies (Goel et al. 2001), *V. glabrescens* has been shown to be a derivative from *V. umbellata* and *V. angularis.* It is an annual herb, with erect growth habit. It is apparently the only natural amphiploid in the subtribe Phaseolinae (Marechal et al. 1978) and few populations are reported to occur in India. Only one population was studied in the present investigation.

In the mothbean group, wild *V. aconitifolia* types were morphologically very similar to cultivated types, except for their more spreading habit, more dissected leaflets, rough hard-shelled pods with roundish dull seeds. Two populations from the western plains and parts of Rajasthan were comparatively pigmy types and were close in PCA ordination (Figure 5). The cultigens were, however, erect or decumbent-ascending with variously dissected leaves and non-shattering pods. *V. trilobata* types are more widespread in distribution possessing more roundish, black seeds with slightly raised hilum, unlike those of *V. aconitifolia*, *V. trilobata* populations were more diverse in PCA ordination

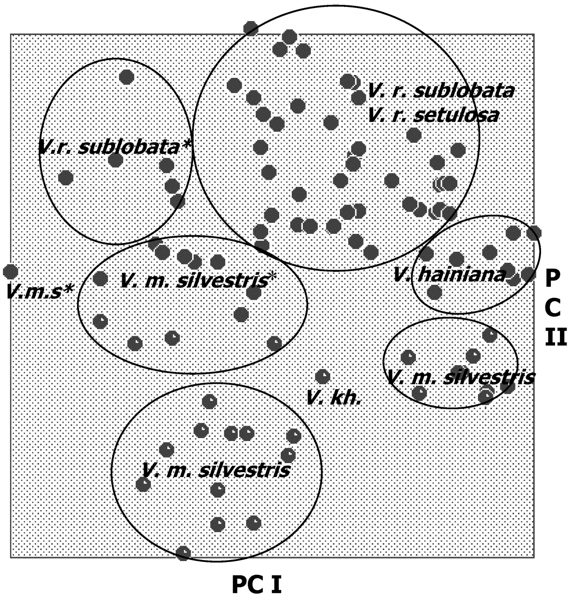

Figure 3. Principal components analysis ordination of wild Asian *Vigna* species in the *radiata-mungo* (mungbean) group of subgenus *Ceratotropis V. m.s.* (*V. mungo* var. *silvestris*), *V. kh.* (*V. khandalensis*); *weedy races.

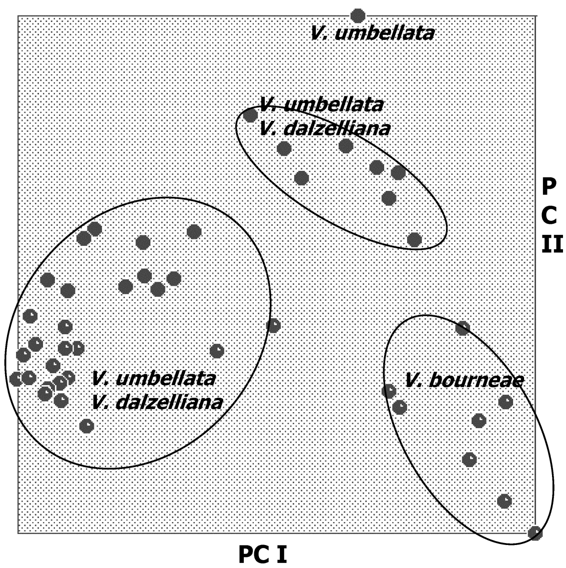

Figure 4. Principal components analysis ordination of wild Asian *Vigna* species in the *angularis-umbellata* (azukibean) group of subgenus *Ceratotropis.*

as the populations were collected from diverse agro-ecologies. Three populations from Eastern Ghat regions were distinct from other populations with more dissected bigger leaves and high

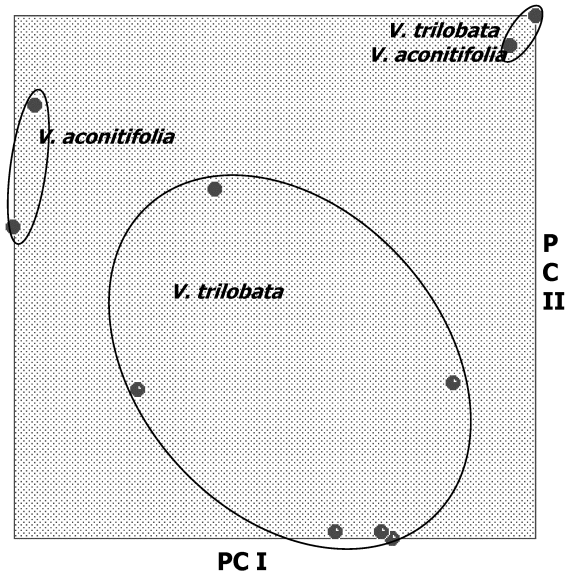

Figure 5. Principal components analysis ordination of wild Asian *Vigna* species in the *aconitifolia-trilobata* (mothbean) group of subgenus *Ceratotropis.*

leafiness. These populations were close in PCA ordination (Figure 5).

Among the *Vigna* species, other than subgenus *Ceratotropis*, *V. vexillata* is more widespread in distribution. Morphologically it is distinct from all other species because of its larger pods (up to 20 cm) and pea-like flowers. The populations from the Western Ghats region of Maharashtra were more robust than the pigmy thin leaved types from the northwestern Himalayas. *V. pilosa* populations were comparatively more homogeneous.

The Asian *Vigna* are considered to be recently evolved and morphological differentiation between taxa are limited (Baudoin and Marechal 1988). As a consequence, distinguishing characters between taxa are few and the sub-specific classification of some Asian *Vigna* is complex. The cultivated Asian *Vigna* species have a number of common characteristics. Typically they have flowers of similar size and relatively much larger than those of *V. aconitifolia* (and *V. trilobata*), *V. hainiana*, *V. dalzelliana* and *V. minima*. Pods in cultivated forms are less dehiscent at maturity than those of the conspecific wild relatives. Relative to the size of the wild forms (e.g. *V. radiata* var. *sublobata*, *V. mungo* var. *silvestris*, *V. umbellata* var. *gracilis*), the seed of cultigen types does exhibit gigantism and a

Table 7. Variation explained by each Eigenroot and important characters with maximum weightage in Principal Components Analysis.

PC axes	Total variation explained %	Cumulative	Important characters with maximum weightage
Mungo-radiata group			
I	28.41	28.41	Terminal leaflet width, terminal leaflet length, petiole length
II	16.94	45.35	Seed size, seed weight, days to maturity, days to flowering
III	11.92	57.27	Seed yield, peduncle length, no. of pods per plant, plant height
Angularis-umbellata group			
I	38.83	38.83	Seed weight, no. of flowers per raceme, petiole length, no. of pods per peduncle
II	17.49	56.32	Days to maturity, plant height, no. of seeds per pod, hilum length, no. of pods per plant
III	10.25	66.57	Yield per plant, peduncle length, no. of seeds/pod, days to maturity, days to flowering
Aconitifolia-trilobata group			
I	37.60	37.60	No. of pods per plant, pod length, no. of seeds per pod, peduncle length, petiole length
II	27.34	64.94	No. of pods per peduncle, plant height, seed size, seed yield per plant
III	12.13	77.07	Days to flowering, days to maturity, no. of pods per peduncle, seed yield per plant, seed size

three- to five-fold size increase has been recorded (Tables 4–7). In *V. trilobata* (a semi-domesticated species often confused with *V. aconitifolia*) no increase in seed size is apparent, a good distinction from the five fully domesticated species (Smartt 1990).

The wild species have a great potential for use in crop improvement programmes (AVRDC 1990; Srinives et al. 1999). The weedy type landraces particularly in *V. mungo* var. *silvestris* and *V. radiata* var. *sublobata* assembled from parts of Rajasthan, Western Ghats and other parts of the Central Plateau region in proximity of cultivated fields and studied in the present work need extensive survey and collecting. These weedy races are competitive with cultivated races but retain some important characters of the wild races. Consequent occasional crossing between the two leads to setting up of differential-hybridization cycle and release of more potential variability. This is one remarkably elegant evolutionary process wherein barriers to geneflow maintain identity of the two types and, at the same time, limited exchange of genes releases variability. Deliberate selection practices by man from the released variability provide a new order of selection pressure making the population an array of deliberately chosen components. In the present study, a few of the weedy races in *V. mungo* var. *silvestris* and *V. radiata* var. *sublobata* possessed many valuable characters such as greater number of pod-bearing clusters and pods per cluster besides resistance/tolerance to biotic/abiotic stresses particularly yellow mosaic virus and drought. These accessions have great agronomic potential for use in crop improvement programmes and are currently being used in genetic enhancement studies in greengram at the NBPGR (Bisht et al. 2002). The *V. trilobata* populations from Eastern Ghats also has a great potential as a cover and forage crop. The use of wild *Vigna* species assembled by the NBPGR in biosystematics and evolutionary studies, and in establishing species relationships, etc. (Arora et al. 1973; Dana 1966; Jain and Mehra 1980; Miyazaki 1982) or their utility in breeding for disease resistance (Ahuja and Singh 1977; Ignacimuthu and Babu 1984, 1987) and the paucity of such collections in genebanks, point towards the need for more concerted efforts to enrich such genetic resources.

The above account highlights the extent of diversity among wild *Vigna* species in India. Pockets of diversity exhibiting both sympatric and disjunct

Table 8. Summary of intraspecific variation for important characters of wild *Vigna* species in the subgenus *Ceratotropis*.

Species	Intraspecific variations
Mungbean (*mungo-radiata*) group	
V. radiata var. *sublobata*	Between population variations observed for leafiness, leaf pubescence, lobing of terminal leaflets, leaflet shape, days to flowering, raceme position, seed shape and size. Wide range of variation was also recorded for various quantitative traits viz., plant height, days to flowering/maturity, number of pods per plant, 100-seed weight and yield per plant. A few weedy races with twining habit and relatively bold pods and seeds could be distinguished.
V. radiata var. *setulosa*	Populations varied for seed shape and mottling of seeds. Variation was also observed for flower bud size, peduncle length and seed size. A few populations with highly pubescent bold pods and relatively bold seeds but low number of pods per plant were distinguished. Wide range of variation was also recorded for quantitative traits viz., plant height, days to flowering/maturity, number of pods per plant, 100-seed weight and yield per plant.
V. mungo var. *silvestris*	Three distinct types of populations were noticed: (a) Highly twining/climbing types with low branching potential with sub-capitate clumps of 6–8 hairy pods, sub-erect or ascending, each 3–5 cm long, thick slightly beaked, 3–6 seeded; seeds dull black with rough surface; hilum much raised, cracked or split; some population have very high yield potential. (b) More prostrate types; low plant height; plants being comparatively less hairy with 2–4 hairy pods/peduncle, both deflexed and ascending, each 6–8 seeded; seeds blackish dull, smaller to above type, with less split/raised hilum. (c) Weedy races with early flowering twining type, relatively bold pods and seed size.
V. hainiana	The population revealed greater homology for floral organs. Variation between populations observed for terminal leaflet size, plant height, days to flowering/maturity, flower bud size, pubescence of various plant parts, number of pods per plant, seed shape, mottling of seed surface and seed yield. A few pigmy type populations could also be distinguished.
Azuki bean (*angularis-umbellata*) group	
V. umbellata var. *gracilis*	Between population variation observed for pubescence of various plant parts, flower bud size, no. of flowers per raceme, pods per peduncle, seed size and seed weight. Variations in quantitative traits as days to flowering and maturity, number of pod bearing clusters and pods per plant, seed size and yield were also recorded.
V. dalzelliana	Populations varied for stem pubescence, lobing of terminal leaflets, plant height, days to flowering/maturity, peduncle length, pods/peduncle and seed size.
V. bourneae	Populations were more homogeneous. Between population variations were, however, observed for days to flowering and pods per peduncle.
V. minima	Populations were more homogeneous for most of the qualitative traits. Variations, however, were observed for plant height, days to flowering and seed size.
Mothbean (*aconitifolia-trilobata*) group	
V. aconitifolia	Populations varied for terminal leaflet shape, no. of pods/peduncle and seed shape.
V. trilobata	Populations varied for leaflet shape, size and lobation; stipule size; seed shape and mottling of seed surface. Variations also recorded for plant height and yield related traits.

distribution are important from an exploration standpoint, as is also their collection from ecologically variable sites within their range of distribution. About nine species are concentrated in the northern part of Western Ghats, of which *V. mungo* var. *silvestris* and *V. radiata* var. *sublobata* are better represented, from natural stands, in the present study. Collection of more weedy races in both the above mentioned species stands a priority as these races are important from both crop improvement and evolutionary standpoint. *V. radiata* var. *setulosa* populations are of sporadic occurrence in certain pockets and needs extensive collection as very few populations were represented in the present study. The *setulosa* types are more robust in pod and seed characteristics and their potential use in improvement of cultigen types is yet to be explored. About 5–6 *Vigna* species have been reported exhibiting overlapping distribution in Eastern Ghats (Arora 1985; Bisht et al. 2003). *V. hainiana* is the most widely distributed species in the *mungo-radiata* complex and fairly represented in the presented study. *V. hainiana* populations showed closeness to both *V. mungo* var. *silvestris* and *V. radiata* var. *sublobata* (considered to be the progenitor of cultivated *V. mungo* and *V. radiata*, respectively; Arora et al. 1973; Chandel et al. 1984) but all the populations in the present study had very small flowers with much thinner pods as compared to the other two closely related species. This species can play a greater role in phylogeny and evolutionary studies particularly in the *mungo-radiata* complex. *V. radiata* var. *setulosa*, has sporadic distribution in higher elevations (more than 800 m) around Koraput district in Orissa in Eastern Ghats. These populations were distinct from those collected from the Western Ghats in more densely hairy bold and relatively smaller pods and bigger seed size. These populations also displayed resistance to YMV in the present study. More *setulosa* populations from the Eastern Ghats therefore need to be collected and their breeding potential particularly for resistance to YMV needs to be explored. Very few populations of *Vigna* species from north-western Himalaya are represented in the present study. More populations of *V. radiata* var. *sublobata* from lower elevations of the Western Himalaya need to be collected as these populations are reported to possess yellow mosaic resistance (Singh 1994). Collection of *V. radiata* var. *sublobata* populations from southern parts of the Western Ghats (disjunct distribution occurs) is also needed. Equal emphasis needs to be given to closely-related species exhibiting sympatric distribution i.e. *V. umbellata* and *V. dalzelliana*, *V. mungo* var. *silvestris*, *V. radiata* var. *sublobata* and *setulosa* in Western Ghats. Paucity of species diversity was observed in the north-western plain zones extending eastwards to the Indo-Gangetic belt and few populations of *V. aconitifolia* and *V. trilobata* were represented in the present study and more populations need to be collected and studied. Apart from species diversity, to sample intraspecific variation fully, particularly in the *V. mungo–V. radiata* complex, fine grid sampling needs to be done in areas where such diverse populations overlap. By selective sampling, one is likely to collect here taxonomically/genetically more variable populations.

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