RESEARCH

Breeding for Earliness in Pigeonpea: Development of New Determinate and Nondeterminate Lines

M. I. Vales,* R. K. Srivastava, R. Sultana, S. Singh, I. Singh, G. Singh, S. B. Patil, and K. B. Saxena

ABSTRACT

Considering the increasing demand for pigeonpea [*Cajanus cajan* (L.) Millsp.], especially in India, breeders have realized the need to develop high-yielding, super-early maturing (<90 d) lines that could be planted in a wider range of latitudes and/or altitudes to enhance the crop adaptation and to diversify the legume-based cropping systems. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) initiated a breeding program in 2006 to develop "super-early" (flowering in <50 d) determinate (DT) and nondeterminate (NDT) pigeonpea lines. Eleven parental lines with days to 50% flowering ranging from 49 d (MN 5) to 103 d (ICP 6974) were crossed using a full diallel mating design. A pedigree-based approach was followed to select for early flowering. The selection gain was larger initially (reduction of 7 d) but there was less reduction (2 d) from F_3 to F_4. Determinate and NDT lines that flowered in 45 to 56 d at ICRISAT-Patancheru reached advanced (F_5 and F_6) generations. The newly developed lines flowered and matured at a higher latitudes (tested at 30° N vs. 17° N) and altitudes (tested at 1250, 545, and 247 m asl). These lines could be used in new cropping systems (i.e., pigeonpea–wheat [*Triticum aestivum* L.]) that would allow expanding pigeonpea production to nontraditional planting areas (i.e., wider latitudes and higher altitudes) and could even offer wider planting time flexibility to farmers.

M.I. Vales, Dept. of Crop and Soil Science, Oregon State University, 109 Crop Science Bldg. Corvallis, OR 97331-3002; R.K. Srivastava, R. Sultana, S. B. Patil, and K.B. Saxena, ICRISAT, Patancheru, 502 324, A.P., India; S. Singh and I. Singh, Punjab Agricultural Univ. (PAU), Ludhiana 141 004 Punjab, India; G. Singh, Vivekananda Parvathiya Krishi Anusandhan Sansthan (VPKAS), Almora, 263 601, Uttarakhand. Received 25 Aug. 2012. *Corresponding author (isabel.vales@oregonstate.edu).

Abbreviations: DT, determinate; NDT, nondeterminate.

Pigeonpea is an important legume crop of the semiarid tropics of Asia, Africa, and Latin America. It is a perennial (3–5 yr) bush but typically cultivated as an annual crop. Being high in protein (21–25%) (Saxena et al., 2010), it complements cereals for a balanced diet. In addition to food (dry split and fresh grains), pigeonpea has multiple uses, making it an ideal crop for sustainable agriculture: fodder, feed, fuel, functional utility (for making baskets, huts, and fences), fertilizer (fixes atmospheric nitrogen and facilitates the release of phosphorus in soil), pharmaceutical, reforestation, lac (insect-secreted resin) production, improvement of soil structure, and reduction of erosion, especially on slopes (Mula and Saxena, 2010).

India is the largest producer of pigeonpea in the world (70–80%). In 2010, pigeonpea was planted in 3.53 10^{-6} ha in India, generating 2.46 10^{-6} t (FAOSTAT, 2010). Although several pigeonpea varieties have been released, productivity of pigeonpea has been difficult to increase (around 700 kg ha^{-1} in the last decade) (FAOSTAT, 2010). Despite being the largest producer of pigeonpea, the annual production in India does not meet domestic

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Table 1. Major pigeonpea maturity groups based on days to 50% flowering of genotypes planted by mid June at ICRISAT-Patancheru, Andhra Pradesh, India (17°30′ N, 78°16′ E, and 545 m asl). Table based on Green et al. (1979). The reference cultivars were updated and the new super-early group added.

ICRISAT maturity group	Maturity group	Days to 50% flowering (DAP)[†]	Reference cultivars
00	Super-early	<50	MN5
0	Extra-short	51–60	ICPL 88039
I	Extra-short	61–70	Prabhat
II	Short	71–80	UPAS 120 and ICPL 87
III	Short	81–90	Pusa Ageti and T 21
IV	Short	91–100	ICP 6
V	Short-medium	101–110	BDN 1 and Maruti
VI	Medium	111–130	Asha
VII	Medium	131–140	ICP 7035
VIII	Medium-long	141–160	ICP 7065 and Bahar
IX	Long	>160	NP (WR) 15 and MAL 13

[†] DAP, days after planting.

Table 2. Flowering pattern and days to 50% flowering of pigeonpea parental lines based on 3 yr (2008, 2009, and 2010) of evaluations at ICRISAT-Patancheru, Andhra Pradesh, India.

Genotype[†]	Flowering pattern[‡]	50% flowering (DAP)[§]	Maturity group
MN 5	DT	49	Super-early
MN 1	DT	53	Extra-short or super-early
ICPL 85010	DT	55	Extra-short
MN 8	DT	56	Extra-short
Mean (DT)		*53*	
AL 1518	NDT	58	Extra-short
AL 1621	NDT	59	Extra-short
ICPL 88039	NDT	61	Extra-short
UPAS 120	NDT	77	Short
ICP 6973	NDT	84	Short
ICP 6972	NDT	89	Short
ICP 6974[¶]	NDT	103	Short-medium
Mean (NDT)		*76*	
Mean across years[#]		68	
CV (%)		5.3	
LSD (0.05)		6.0	

[†] The seed coat was brown for all genotypes except those underlined, which were cream color.

[‡] DT, determinate; NDT, nondeterminate.

[§] DAP, days after planting.

[¶] The genebank source was heterogeneous and listed as DT. We used a NDT selection.

[#] Mean of 2008 was 67, mean of 2009 was 67, mean of 2010 was 70, and LSD (0.05) between years was 3.2.

demand; therefore, India needs to import pigeonpea every year, mainly from Myanmar, Kenya, Malawi, and Tanzania. The domestic demand in India is expected to rise even further due to population growth (1.39% natural growth rate estimated for 2016) (Ramachandran, 2006). Therefore, there is an urgent need to increase pigeonpea production and productivity. The recent development and expansion of medium duration cytoplasmic-nuclear male-sterility system hybrids in pigeonpea represents a breakthrough to increase yield (up to 4 t ha^{-1}) (Saxena and Nadarajan, 2010). However, more efforts are required to expand hybrids and the current hybrids may not be suitable for all areas and/or cropping systems.

There is large variation for days to 50% flowering in pigeonpea, ranging from less than 50 d to more than 160 d (Table 1). Most of the traditionally grown pigeonpea cultivars and landraces are represented by varieties from the medium and long duration maturity groups that mature in 150 to 280 d. These pigeonpea cultivars do not allow using the same field for planting other crops within the same year and are quite sensitive to photoperiod variation (Silim et al., 2006; Carberry et al., 2001; Turnbull and Ellis, 1987) requiring short days for flower induction. This has restricted pigeonpea adoption beyond 30° north and south latitudes (Saxena, 2008). Both photoperiod and low temperature sensitivity of most of the available cultivars (Turnbull et al., 1981) has limited the expansion of pigeonpea to higher latitudes and altitudes and also has limited its use in alternative cropping systems.

Therefore, the development of short duration lines that are less photoperiod and temperature sensitive could be a breakthrough for pigeonpea expansion to wider latitudes and altitudes and to provide alternative cropping system options (including shorter rotations, i.e., wheat–pigeonpea) and would also play a key role to move toward market-based agriculture. Super-early maturing pigeonpea cultivars could be ready to harvest in less than 3 mo, thus allowing farmers to plant and harvest more than one crop per year (i.e., pigeonpea and wheat); this would result in increased income for the farmers and diversification of the cropping systems, thus contributing to reduced poverty and hunger and improved nutrition in nontraditional pigeonpea growing areas, and at the same time contribute to reduced environmental degradation.

A breeding program was initiated at ICRISAT in 2006 to develop super-early duration pigeonpea lines. The number of days to 50% flowering in pigeonpea has been shown to have high heritability and additive gene action with partial dominance of earliness (Gupta et al., 1981; Githiri et al., 1991); therefore, progress from selection is expected. This article describes the achievements in breeding super-early determinate (DT) and nondeterminate (NDT) pigeonpea lines and discusses the potential new niches that these materials could target.

MATERIALS AND METHODS

The pigeonpea parental lines used to initiate the super-early breeding program were MN 5, MN 1, ICPL 85010, MN 8, AL 1518, AL 1621, ICPL 88039, UPAS 120, ICP 6973, ICP 6972, and ICP 6974 (Table 2). The first four lines have DT flowering pattern and the rest are NDT. MN 1, MN 5, and MN 8 were developed by pedigree selection in Minnesota (45° N) (Davis et al., 1995) based on materials received from ICRISAT (Patancheru, Andhra Pradesh, India). "ICP" refers to germplasm accessions maintained at the ICRISAT genebank and "ICPL" refers to breeding material (pure lines) developed by the ICRISAT pigeonpea breeding program. ICPL 88039 was recently released as an extra-short duration variety (Saxena et al., 2011) in India, "AL" lines were developed at Punjab Agricultural University (PAU) (Ludhiana, Punjab, India), and UPAS 120 (short duration variety) was developed at G. B. Pant University of Agriculture and Technology (Pantnagar, Uttarakhand, India).

The parental lines were planted under field conditions at ICRISAT-Patancheru in June 2006 and crossed following a full diallel scheme to produce 110 hybrids. A pedigree-based selection program was practiced to improve earliness (based on days to flowering and maturity). In June 2007, 109 hybrids (one cross, ICP 6973 × AL 1621, was unsuccessful) were planted in single rows of 4 m length (14 seeds per hybrid) in the field. The plots were covered with nylon nets to prevent cross-pollination by insects. The F_1 hybrids were selfed to generate the F_2 generation. Single plant selections were performed in the F_2 generation based on earliness (up to 50 and 63 d to first flower for DT and NDT segregants, respectively) and were advanced to F_3 and subsequently to F_4 by performing similar selection criteria. A substantial proportion of the plant population was lost due to Phytophthora blight (*Phytophthora drechsleri* f. sp. *cajani*) attack and waterlogging in F_2 and F_3 generations. Hence a relatively weak selection intensity of 0.35 was exercised for earliness and maturity in these generations (Srivastava et al., 2010). During the 2009 rainy season, remnants seed of the F_3 generation along with the single plant selected seeds of F_4 generations were grown under insect-proof cages in the field. In these generations, selection was exercised for days to flower and maturity but also for higher number of pods per plant, seeds per pod, more number of primary and secondary branches, longer fruit bearing branches, and bolder seeds. Plants with earlier or equal days to flower than the respective checks (MN5 [DT] and ICPL 88039 [NDT]) were selected. Among such lines, we identified a single F_4 DT line that flowered in 34 d and matured in 65 d (compared to MN 5 with 50 d to flower and 82 d to maturity) and a NDT line that flowered in 45 d and matured in 78 d (compared to ICPL 88039, which flowered in 65 d and matured in 104 d) (Srivastava et al., 2010). During the 2010 rainy season, the F_4 and F_5 generations were evaluated using a subjective visual selection score (1 indicating best and 5 indicating worst) at the flowering stage that combined the following characteristics: days to flowering (early flowering desired), plant vigor (high vigor desired), lateral branches (lateral productive branches desired), and distribution of flowers (profuse and evenly distributed flowers preferred); MN 5 (DT) and ICPL 88039 (NDT) were used as reference checks and given a visual scores of 3. Families with selection scores 4 and 5 were not selected. After harvesting, further visual selection was performed based on seed appearance (seeds per plant, seed color uniformity, and seed size) of individual plant and additional genotypes were discarded.

The parental lines were planted in 2008, 2009, and 2010 at ICRISAT-Patancheru in the month of June in nonrandomized trials. Each plot consisted of three rows (17 seeds per row) of 4 m length with a distance between the rows of 75 cm and plant-to-plant distance of 25 cm. The main data collected on a plot basis included days to 50% flowering, flowering pattern, and seed coat color.

Generation advancement under greenhouse conditions allowed multiplying seed for conducting preliminary field trials. Selected F_5 families were planted in June 2010 using a randomized complete block design with two replications (Tables 3 and 4). Each experimental plot consisted of three rows of 4 m length with a distance between the rows of 75 cm and plant-to-plant distance of 25 cm. The following data were collected: flowering pattern (DT vs. NDT), days to 50% flowering, days to 75% maturity, plant height at maturity, number of seeds per pod, number of pods per plant, 100-seed weight, grain yield, and seed coat color. Data on most of the traits were collected on a plot basis, except number of seeds per pod, pods per plant, 100-seed weight, and seed coat color, which were based on the average of five competitive plants per plot.

Some of the most promising DT and NDT lines (six DT and eleven NDT) were assigned ICPL (ICRISAT pigeonpea line) numbers (Table 5 and 6) and tested at ICRISAT-Patancheru (Andhra Pradesh, India, 17°30′ N, 78°16′ E, and altitude 545 m asl), at PAU-Ludhiana (Punjab, India, 30°56′ N, 75°52′ E, and altitude 247 m asl), and at the Almora location of Vivekananda Parvathiya Krishi Anusandhan Sansthan (VPKAS) (Uttarakhand, India, 29°56′ N, 79°40′ E, and altitude 1250 m asl) using randomized complete block design with two replications. The trials (separate trials for NDT and DT lines) were planted on 17, 11, and 6 June 2011 at Patancheru, Ludhiana, and Almora, respectively. Each plot consisted of two rows of 4 m each, and the spacing was 25 cm plant-to-plant and 50 to 75 cm row-to-row (75 cm at Patancheru and 50 cm at Ludhiana and Almora). The data collected were days to 50% flowering, days to 75% maturity, plant height, 100-seed weight, seeds per pod, and grain yield at all locations (Note: 100-seed weight and seeds per pod were not collected at Almora). At ICRISAT-Patancheru, the agronomic practices included basal application of 100 kg ha^{-1} of diammonium phosphate, preemergence herbicide application using pendimethalin and paraquat dichloride at 2 and 4 L ha^{-1}, respectively, two hand weedings, two irrigations (one each at early vegetative and pod filling stage), and three sprays of pesticides (acephate and spinosad at 1 kg ha^{-1} and 0.2 L ha^{-1}, respectively) at 10 d intervals to control pod borers (*Maruca vitrata* Fab. and *Helicoverpa armigera* Hub.) between flowering and podding stages. At PAU-Ludhiana, the agronomic practices included basal application of 87.5 kg ha^{-1} of diammonium phosphate, and weeds were controlled using pendimethalin at 1.5 L ha^{-1} (preemergence) and one hand weeding after 6 wk and two irrigations, at vegetative and flowering stage, were applied. For the control of pod borers (*Maruca vitrata* and *Helicoverpa armigera*), two sprays of indoxacarb at 0.5 L ha^{-1} and two sprays of spinosad at 0.15 L ha^{-1} (two sprays) were done at 10 d intervals. At VPKAS-Almora, no irrigation or chemical fertilizer was applied to the crop; the crop was grown in a certified "organic" experimental field. Among insects only blister beetles (*Mylabris pustulata* Thunberg) were prominent at Almora and these were controlled by hand picking.

Phenotypic distributions for days to flowering and mean, range, minimum, and maximum values were obtained for the segregating populations using Microsoft Excel (Microsoft, 2010). Data from the replicated trials were analyzed using the Proc GLM

Table 3. Performance for various morphological traits and yield attributes of F_5 determinate (DT) selected lines and checks evaluated in replicated trials at ICRISAT-Patancheru, Andhra Pradesh, India in 2010.

Entry name†	Female	Male	50% flowering	75% maturity	Plant height	100-seed weight	Seeds per pod	Pods per plant	Grain yield
			DAP‡	DAP	cm	g	no.	no.	kg ha^{-1}
DT lines:									
ICPX 060033-8-8-9-2	MN 8	MN 5	46	80	70.0	7.9	3.6	33.8	519.8
ICPX 060033-8-8-9-11	MN 8	MN 5	46	80	65.0	7.7	3.6	29.3	368.5
ICPX 060033-8-1-3-10	MN 8	MN 5	47	73	62.5	8.4	3.8	23.6	432.7
ICPX 060033-1-3-9-12	MN 8	MN 5	47	81	65.0	8.3	3.9	26.8	440.7
ICPX 060024-9-8-8-5	MN 5	ICPL 85010	47	75	77.5	8.5	3.5	30.4	508.6
ICPX 060033-15-3-3-3	MN 8	MN 5	48	81	62.5	8.5	3.7	24.2	355.6
ICPX 060033-15-3-1-3	MN 8	MN 5	48	81	60.0	8.6	4.1	23.3	408.0
ICPX 060033-1-3-9-7	MN 8	MN 5	48	78	65.0	7.6	3.7	29.6	437.7
ICPX 060024-9-8-9-16	MN 5	ICPL 85010	48	79	75.0	9.7	3.3	33.6	445.1
ICPX 060033-6-10-5-4	MN 8	MN 5	48	80	65.0	8.0	4.3	24.0	454.3
ICPX 060024-7-6-4-9	MN 5	ICPL 85010	48	78	62.5	8.5	3.7	37.6	461.1
ICPX 060033-15-3-1-1	MN 8	MN 5	48	79	65.0	8.5	3.6	32.2	465.4
ICPX 060033-8-8-9-12	MN 8	MN 5	49	82	67.5	7.5	4.1	19.7	274.7
ICPX 060033-15-1-1-3	MN 8	MN 5	49	83	60.0	8.9	3.2	28.4	308.6
ICPX 060033-5-7-15-8	MN 8	MN 5	49	83	65.0	8.1	3.9	24.0	406.2
ICPX 060033-8-1-2-5	MN 8	MN 5	49	83	65.0	8.6	4.3	22.4	274.7
ICPX 060033-1-3-9-14	MN 8	MN 5	49	79	65.0	8.6	3.3	28.5	379.0
ICPX 060033-4-1-4-5	MN 8	MN 5	49	79	57.5	8.2	3.9	28.2	458.0
ICPX 060027-12-5-5-1	MN 5	AL 1621	50	88	90.0	7.8	3.8	40.0	620.4
ICPX 060033-6-7-1-4	MN 8	MN 5	50	78	60.0	7.6	3.5	24.7	321.0
ICPX 060033-6-7-1-5	MN 8	MN 5	51	79	57.5	8.0	3.9	19.2	189.5
ICPX 060033-5-3-2-6	MN 8	MN 5	51	82	65.0	8.8	4.1	22.5	266.7
Mean DT			*48*	*80*	*65.8*	*8.2*	*3.8*	*27.5*	*399.8*
MN 1 (check)			52	83	60.0	8.1	3.8	50.2	702.5
MN 5 (check)			50	83	80.5	7.8	3.7	34.4	567.3
CV (%)			3.8	3.7	5.9	6.3	4.6	24.6	26.2
LSD (0.05)			3.9	6.5	9.8	1.0	0.3	21.0	291.9

†Entry names underlined had cream seed color; the rest had brown seed color.

‡DAP, days after planting.

statement of SAS (SAS, 2008). Correlations between the evaluated traits were performed using Pearson's correlation on SAS.

RESULTS

Parental Lines

Based on 3 yr evaluation (2008, 2009, and 2010) at Patancheru, the 11 parental lines used as sources of earliness showed significant differences for days to 50% flowering (Table 2). The average days to 50% flowering ranged from 49 d (for MN 5, SE = 1.5) to 103 d (for ICP 6974, SE = 3.9) (Table 2). MN 5 and MN 1 were the only two parental lines that fall in the super-early category as previously defined in Table 1 (<50 d to 50% flowering at the ICRISAT-Patancheru location); the other parental lines can be classified in the extra-short to short-medium maturity categories (Table 2). As a group, the seven NDT parental lines flowered significantly later (76 d) than the four parental lines with DT flowering pattern (53 d).

F_1 Generation

The average days to 50% flowering of the 109 F_1 hybrids was 71 and the average maturity was 107 (data not shown) in 2007. None of the F_1 hybrids flowered earlier than the earliest parent MN 5 (49 d to 50% flowering). However, there were hybrids (i.e., ICP 6973 × ICP 6974 and ICP 6972 × ICP 6974) flowering significantly later, that is, 121 and 123 d to 50% flowering, respectively (data not shown), than the latest parental line used ICP 6974 (103 d after planting; Table 2). Reciprocal crosses showed similar days to 50% flowering and 75% maturity (data not shown). The average days to 50% flowering of the F_1 hybrids was similar to the mean of the parental lines involved. In eight hybrids the heterosis for days to 50% flowering was less than −10% and in four hybrids it was greater than +10% (data not shown).

Generation Advancement

The combined F_2 segregating populations tested in 2008 (a total of 4699 lines) had average days to flowering of 58. The mean of days to flowering was reduced to 51 in the next generation (F_3, 1626 lines) tested in 2009 and further reduced to 49 in the next generation (F_4, 3498 lines) tested in 2010 (Fig. 1). The gain for selection was larger initially (−7 d) but there was less reduction (−2 d) from F_3 to F_4; this could indicate that the genetic variation available to make further progress from selection is getting exhausted and that we are likely reaching the maximum earliness.

Table 4. Performance for various morphological and yield attributes of F_5 nondeterminate (NDT) selected lines and check evaluated in replicated trials at ICRISAT-Patancheru, Andhra Pradesh, India, in 2010.

Entry name[†]	50% flowering	75% maturity	Plant height	100-seed weight	Seeds per pod	Pods per plant	Grain yield
	DAP[‡]	DAP	cm	g	no.	no.	kg ha^{-1}
NDT lines:							
ICPX 060027-6-4-2-3	51	89	95.0	7.4	3.6	50.8	740.7
ICPX 060027-7-10-3-7	52	87	90.0	7.2	3.5	42.7	516.7
ICPX 060027-6-4-5-2	52	88	97.5	7.5	3.6	57.4	819.8
ICPX 060027-6-4-4-1	52	91	90.0	7.9	3.6	51.3	887.7
ICPX 060027-4-1-1-1	52	97	112.5	7.9	3.5	77.0	1221.6
ICPX 060027-9-2-3-1	52	94	95.0	8.0	3.4	50.7	649.4
ICPX 060027-9-3-8-7	53	94	105.0	7.4	3.3	48.5	510.5
ICPX 060027-6-4-5-4	53	89	102.5	7.6	3.7	50.0	723.5
ICPX 060027-1-3-9-15[§]	53	96	107.5	7.4	3.5	69.6	461.7
ICPX 060027-6-4-5-1[§]	53	92	92.5	7.7	3.6	55.3	622.2
ICPX 060027-6-4-4-5	53	94	97.5	7.7	3.6	41.5	664.8
ICPX 060027-6-4-5-5	53	95	97.5	7.3	3.5	57.4	702.5
ICPX 060027-6-4-4-6	53	94	95.0	7.4	3.7	54.6	828.4
ICPX 060027-4-1-1-6	53	101	107.5	7.9	3.8	65.9	928.4
ICPX 060027-6-4-4-3	54	95	95.0	6.8	3.6	71.6	526.5
ICPX 060027-1-5-7-12	54	96	107.5	7.5	3.4	71.8	788.9
ICPX 060027-4-1-1-2	54	97	102.5	7.5	3.5	73.8	955.6
ICPX 060027-4-1-1-4	54	97	120.0	7.3	3.7	73.1	1017.9
ICPX 060027-6-6-1-6	54	90	92.5	7.1	3.4	52.1	500.6
ICPX 060027-12-5-5-2	55	94	100.0	7.5	3.6	50.1	609.3
ICPX 060027-3-11-1-5[§]	56	94	105.0	8.7	3.9	40.6	245.1
ICPX 060027-6-6-1-1	56	97	110.0	7.6	3.7	55.8	659.3
Mean NDT lines	*53*	*94*	*100.8*	*7.6*	*3.6*	*57.3*	*708.2*
ICPL 88039 (check)	58	105	112.5	9.7	4.1	61.8	1104.9
CV (%)	3.8	3.7	5.9	6.3	4.6	24.6	26.2
LSD (0.05)	3.9	6.5	9.8	1.0	0.3	21.0	291.9

[†] All entries had brown seed coat color. All entries were derived from the cross of MN 5 (female) with AL 1621 (male).

[‡] DAP, days after planting.

[§] Mainly NDT but residual segregation for determinate.

Evaluation of F_5 Lines in Agronomic Trials at ICRISAT-Patancheru

Within the F_5 families, there was more uniformity for flowering pattern; only three out of the 44 families evaluated showed residual segregation for DT and NDT. Since the main selection criterion was days to 50% flowering, all F_5 families were combined for the analysis; however, the results are presented based on plant type (DT vs. NDT) (Tables 3 and 4).

Flowering was significantly earlier in DT F_5 lines (48 d to 50% flowering) compared with NDT lines (53 d to 50% flowering) (Tables 3 and 4). All the selected F_5 NDT lines evaluated were derived from the cross MN 5 × AL 1621 whereas the selected F_5 DT lines were derived from crosses involving MN 5, MN 8, ICPL 85010, and AL 1621. Most of the DT F_5 lines had similar flowering time to MN 5 (the earliest parent) and also had similar yield (except four lines that had lower yield). MN 1 and MN 5 flowered at similar time. Twelve F_5 lines (the top 12 from Table 3) flowered significantly earlier than MN 1, and the yield of these lines was similar (except ICPX 060033-8-8-9-11, ICPX 0600-15-3-3-3, and ICPX 060033-15-3-1-3, which that had significantly lower yield than MN 1). The yield of these lines could be potentially higher, but high precipitation in 2010 (~950 mm precipitation during the rainy season) caused waterlogging and Phytophthora blight damage resulting in significant plant stand reduction. Most of the NDT F_5 lines had significantly earlier flowering than the check ICPL 88039 (a popular variety within the extra-short maturity group) and there were several F_5 lines that had equivalent yield to ICPL 88039 (i.e., ICPX 060027-4-1-1-1 and ICPX 060027-4-1-1-4).

Significant positive correlations were found between yield and a number of traits (days to 50% flowering, days to 75% maturity, plant height, and number of pods per plant). Days to 50% flowering was significantly negatively correlated with 100-seed weight (data not shown); however, yield was not significantly negatively correlated with 100-seed weight. Since earliness could result in smaller seeds it is important to select for earliness in combination with seed size and overall grain yield to combine earliness with good agronomic characteristics.

Multilocation Trials

Eleven advanced NDT lines and six advanced DT lines were evaluated for days to 50% flowering at ICRISAT-Patancheru (Andhra Pradesh), PAU-Ludhiana (Punjab),

Table 5. Flowering, maturity, and plant height of nondeterminate (NDT) and determinate (DT) lines evaluated at ICRISAT-Patancheru (PA) (Andhra Pradesh, India), at Punjab Agricultural University-Ludhiana (LU) (Punjab, India), and at Vivekananda Parvathiya Krishi Anusandhan Sansthan-Almora (AL) (Uttarakhand, India) in 2011.

	50% flowering (DAP)‡			75% maturity (DAP)			Plant height (cm)		
	Location								
Line name†	PA	LU	AL	PA	LU	AL	PA	LU	AL
NDT Lines:									
ICPL 20325	56	84	82	96	133	137	117.5	193.5	152.0
ICPL 20326	56	81	80	96	132	137	122.5	187.5	167.0
ICPL 20327	56	82	81	95	129	135	125.0	200.0	167.0
ICPL 20328	55	76	80	96	118	134	122.5	162.5	162.0
ICPL 20329 (F_5)	56	75	83	95	128	138	105.0	193.0	162.0
ICPL 20330 (F_5)	52	75	82	94	118	135	100.0	135.0	165.0
ICPL 20331	56	72	78	96	118	134	107.5	145.0	156.0
ICPL 20332	54	75	79	93	116	135	97.5	134.0	163.0
ICPL 20333	55	75	79	93	117	132	100.0	127.5	150.0
ICPL 20334	54	77	74	95	117	131	107.5	131.5	146.0
ICPL 20335	53	74	79	93	111	129	100.0	112.5	158.0
Mean NDT lines	55	77	80	95	122	134	109.5	156.5	158.9
ICPL 88039 (check)	58	92	87	100	154	137	115.0	190.0	198.5
PAU 881 (check)	–	86	–	–	129	–	–	202.5	–
AL 201 (check)	–	90	–	–	133	–	–	208.5	–
CV (%)	1.3	0.9	1.1	1.5	1.0	3.3	7.3	3.1	4.3
LSD (0.05)	1.6	1.5	2.0	3.2	2.8	NS§	17.8	11.0	15.4
DT Lines:									
ICPL 20336	49	62	71	88	127	71	67.5	95.5	86.0
ICPL 20337	49	59	70	88	129	70	60.0	100.0	93.0
ICPL 20338	49	55	69	85	118	69	67.5	91.0	95.0
ICPL 20339	50	55	67	88	129	67	65.0	100.5	88.0
ICPL 20340	49	56	68	86	129	68	65.0	93.5	94.0
ICPL 20341	49	58	68	86	119	68	60.0	90.0	92.0
Mean DT lines	49	58	69	87	125	69	64.2	95.1	91.3
MN 1 (check)	56	81	82	98	147	82	87.5	131.5	126.0
MN 5 (check)	49	58	71	95	129	71	80.0	100.5	104.0
AL 15 (check)	–	77		–	137	–	–	175.0	–
CV (%)	2.1	1.0	3.2	1.9	0.4	3.2	9.6	2.3	6.8
LSD (0.05)	2.5	1.5	3.9	4.1	1.3	3.9	15.7	6.1	11.6

† ICPL 20325, ICPX 060027-4-1-1-1-B; ICPL 20326, ICPX 060027-4-1-1-4-B; ICPL 20327, ICPX 060027-4-1-1-6-B; ICPL 20328, ICPX 060027-4-1-1-2-B; ICPL 20329, ICPX 060017-6-14-1-B; ICPL 20330, ICPX 060077-7-4-6-B; ICPL 20331, ICPX 060027-1-3-9-15-B; ICPL 20332, ICPX 060027-6-4-4-1-B; ICPL 20333, ICPX 060027-6-4-5-2-B; ICPL 20334, ICPX 060027-6-4-5-4-B; ICPL 20335, ICPX 060027-6-4-2-3-B; ICPL 20336, ICPX 060033-4-1-4-5-B; ICPL 20337, ICPX 060033-5-7-15-8-B; ICPL 20338, ICPX 060024-9-8-8-5-B; ICPL 20339, ICPX 060033-8-8-9-2-B; ICPL 20340, ICPX 060024-7-6-4-9-B; ICPL 20341, ICPX 060033-6-10-5-4-B). See Tables 3 and 4 to link with female and male parents. All lines are at F_6 generation, except two NDT lines. Entry names underlined had cream seed coat color; the rest had brown seed color.

‡ DAP, days after planting.

§ NS, not significant.

and VPKAS-Almora (Uttarakhand) in India. The locations represent different latitudes (17° N at Patancheru to around 30°N at Ludhiana and at Almora) that would mainly illustrate the photoperiod effect (extended daylength at 30° N latitude given the June planting date) and also different altitudes (Patancheru at 545 m asl, Ludhiana at 247 m asl, and Almora at 1250 m asl) that would mainly account for the temperature differences. There was a highly significant genotype × location interaction for days to 50% flowering; therefore, the results are shown for each location (Table 5 and 6). The DT types flowered significantly earlier than the NDT types at all three locations. In general, the advanced F_6 generation DT lines flowered at similar time as the DT check MN 5 (Table 5); only a few DT lines were considered earlier than MN 5 at Ludhiana and Almora. On the other hand, all the advanced NDT lines (mainly F_6 generation) flowered significantly earlier than the NDT check ICPL 88039 at all locations (Table 5). In terms of yield (Table 6), several the lines produced more than 1000 kg ha^{-1} and in a few instances (i.e., NDT line ICPL 20329) produced more than 2000 kg ha^{-1} (Tables 6) at both Ludhiana and Almora.

Days to 50% flowering in DT lines appear to be less affected by photoperiod (comparing Ludhiana vs. Patancheru at 30° N and 17° N, respectively) than the NDT lines; the flowering difference between Ludhiana and Patancheru was 9 d for the DT lines and 22 d for the NDT lines (Table 5). This could be explained by the fact that extended daylength (Ludhiana) promotes continuation of vegetative growth and thus delays flowering in NDT types; on the other hand, the end of vegetative growth is determined and stops at flowering time in DT types. A

Table 6. Seed weight, seeds per pod, and grain yield of nondeterminate (NDT) and determinate (DT) lines evaluated at ICRISAT-Patancheru (PA) (Andhra Pradesh, India), at Punjab Agricultural University-Ludhiana (LU) (Punjab, India), and at Vivekananda Parvathiya Krishi Anusandhan Sansthan-Almora (AL) (Uttarakhand, India) in 2011.

	100-seed weight (g)		Seeds per pod (no.)		Grain yield (kg ha^{-1})		
	Location						
Line name[†]	PA	LU	PA	LU	PA	LU	AL
NDT Lines:							
ICPL 20325	6.8	7.6	3.8	3.5	1692.9	1712.5	541.7
ICPL 20326	6.6	7.2	3.9	3.5	1706.7	1356.3	1166.7
ICPL 20327	6.5	7.1	3.9	3.4	1638.1	1737.5	1395.8
ICPL 20328	7.4	8.1	3.8	3.9	1227.6	1481.3	1145.8
ICPL 20329 (F_5)	6.6	7.3	3.9	3.4	1126.9	2212.5	2083.3
ICPL 20330 (F_5)	7.1	7.4	3.7	3.5	1198.3	1687.5	1291.7
ICPL 20331	6.7	7.4	4.3	3.2	858.1	1550.0	1541.7
ICPL 20332	6.6	7.1	4.2	3.7	1239.0	1012.5	1375.0
ICPL 20333	6.4	7.4	3.8	3.5	1174.3	912.5	1379.2
ICPL 20334	6.5	7.5	4.0	2.4	1393.3	875.0	1333.3
ICPL 20335	6.4	7.1	3.5	3.0	1240.0	875.0	1645.8
Mean NDT lines	6.7	7.4	3.9	3.4	1317.7	1401.1	1354.5
ICPL 88039 (check)	8.6	7.1	4.3	3.6	1612.4	2306.3	1645.8
PAU 881 (check)	–	6.7	–	3.6	–	1768.8	–
AL 201 (check)	–	7.7	–	4.0	–	1600.0	–
CV (%)	7.5	1.2	6.2	2.6	21.7	7.4	8.5
LSD (0.05)	NS[‡]	0.1	NS	0.1	NS	243.2	258.2
DT Lines:							
ICPL 20336	8.3	7.2	4.2	3.5	674.2	1062.5	333.3
ICPL 20337	8.3	8.2	4.1	4.2	787.7	1031.3	643.5
ICPL 20338	9.2	7.7	3.8	3.6	675.8	1000.0	754.6
ICPL 20339	7.6	6.5	4.3	3.6	628.9	1250.0	631.9
ICPL 20340	10.3	8.4	3.8	2.9	1033.4	1937.5	831.0
ICPL 20341	8.0	7.4	4.1	3.2	675.0	1125.0	988.4
Mean DT lines	8.6	7.6	4.1	3.5	745.8	1234.4	697.1
MN 1 (check)	7.5	8.3	4.6	4.3	1170.9	1562.5	956.0
MN 5 (check)	8.5	7.4	3.9	3.4	1198.2	1181.3	863.4
AL 15 (check)	–	8.1	–	4.0	–	1250.0	–
CV (%)	4.3	1.7	3.1	4.7	13.1	16.7	6.1
LSD (0.05)	0.8	0.30	NS	0.3	265.9	510.2	80.2

[†] ICPL 20325, ICPX 060027-4-1-1-1-B; ICPL 20326, ICPX 060027-4-1-1-4-B; ICPL 20327, ICPX 060027-4-1-1-6-B; ICPL 20328, ICPX 060027-4-1-1-2-B; ICPL 20329, ICPX 060017-6-14-1-B; ICPL 20330, ICPX 060077-7-4-6-B; ICPL 20331, ICPX 060027-1-3-9-15-B; ICPL 20332, ICPX 060027-6-4-4-1-B; ICPL 20333, ICPX 060027-6-4-5-2-B; ICPL 20334, ICPX 060027-6-4-5-4-B; ICPL 20335, ICPX 060027-6-4-2-3-B; ICPL 20336, ICPX 060033-4-1-4-5-B; ICPL 20337, ICPX 060033-5-7-15-8-B; ICPL 20338, ICPX 060024-9-8-8-5-B; ICPL 20339, ICPX 060033-8-8-9-2-B; ICPL 20340, ICPX 060024-7-6-4-9-B; ICPL 20341, ICPX 060033-6-10-5-4-B). See Tables 3 and 4 to link with female and male parents. All lines are at F_6 generation except two NDT lines. Entry names underlined had cream seed coat color; the rest had brown seed color.

[‡] NS, not significant.

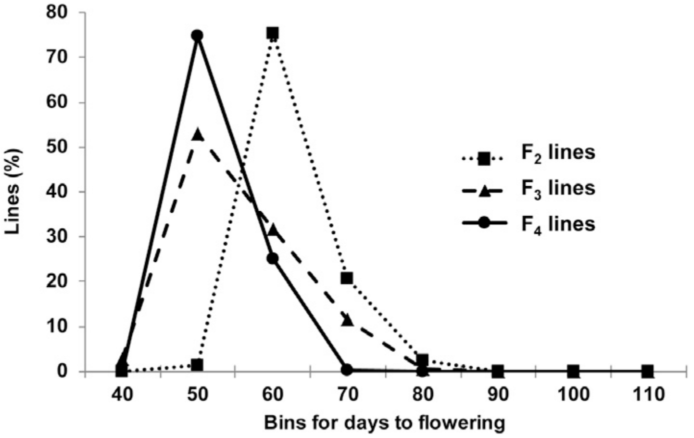

Figure 1. Distribution of days to flowering of pedigree-based selection F_2, F_3, and F_4 families evaluated at Patancheru, Andhra Pradesh, India, in 2008, 2009, and 2010, respectively, during the rainy season (June planting). Days flowering mean and range: for F_2, mean = 58 (range = 48–95), for F_3, mean = 51 (range = 37–108), and for F_4, mean = 49 (range = 40–70). The mean days to flowering of the 11 parental lines over the 3 yr period was 68; the mean of the earliest parent, MN 5, was 49 d to 50% flowering.

similar trend was found when comparing DT and NDT lines at Almora vs. Patancheru (latitude 30° N vs. 17° N and altitude 1250 m asl vs. and 545 m asl for Almora and Patancheru, respectively), but the difference between the DT and NDT lines was not as large (20 d in the case of DT types and 25 d in the case of NDT types) (Table 5). The comparison between Almora and Ludhiana (similar latitude—around 30° N—but different altitude—1250 vs. 247 m asl for Almora and Ludhiana, respectively) indicated that there was a delay in flowering at Almora, possibly due to the effect of lower temperatures at Almora in comparison with Ludhiana. However, flowering of the NDT lines was less affected by altitude than in DT lines (Table 5). Overall, pigeonpea genotypes flowered later at higher latitudes and also at higher altitudes, suggesting that both photoperiod and temperature affect flowering time. Days to flowering in DT types was less delayed by latitude than in NDT types. On the other hand, days to flowering in NDT types were more delayed by latitude than by altitude.

DISCUSSION

Within the pigeonpea germplasm available for breeding purposes at ICRISAT, there is variation for flowering, but materials flowering in less than 50 d are not frequent. MN 1, MN 5, and MN 8 flowered in 49 to 56 d at ICRISAT-Patancheru (17° N); MN 5 and MN 1 flowered in 58 and 81 d, respectively, at PAU-Ludhiana (30° N) and in 71 (MN 5) and 82 (MN 1) days at VPKAS-Almora (30° N) (all three locations in India in this study). The parental lines MN 1, MN 5, and MN 8 flowered in less than 60 d at 45° N in Minnesota (Davis et al., 1995); MN 5 flowered in 62 d and MN 8 flowered in 75 days in Suwon, Korea (37° N) (Chauhan et al., 2002).

The average days to 50% flowering of advanced DT breeding lines used in this study was 49, 58, and 69 d (at Patancheru, Ludhiana, and Almora, respectively) whereas it was 55, 77, and 80 d for NDT types at the three locations, respectively. During the selection process we identified individual plants in F_3 and F_4 generations that flowered significantly earlier than the earliest parent (MN 5) and that could be considered as transgressive segregants due to the accumulation of genes contributing to earliness.

However, once the evaluations were conducted at F_5 and F_6 generations in replicated trials and data for 50% flowering collected on a plot basis, the values for days to flowering were, in general, significantly similar to those obtained in MN 5, indicating that MN 5 has already a genetic composition that makes it one of the earliest options available to date in pigeonpea.

In the case of NDT types, it was possible to develop new lines that were significantly earlier than the earliest short duration cultivar ICPL 88039; this likely happened because of the pyramiding of genes contributing to earliness. Combining earliness with NDT flowering pattern seems to be challenging, as none of the advanced NDT lines flowered as early as MN 5. Nondeterminate lines are preferred in many areas because of the reduced pod borer damage (in comparison to the DT types) due to the distribution of the pods (dispersed in NDT types vs. clustered in DT types). In any case, control of pod borer damage should be easier in super-early lines (both DT and NDT) than in medium duration due to the shorter stature (Table 5), which makes insecticide control (manual or mechanical) easier to handle. Considering that ICPL 88039 is one of the earliest (extra-short) varieties (flowering in 58, 92, and 87 d at Patancheru, Ludhiana, and Almora, respectively) we can say that the main breakthrough of the ICRISAT breeding program was to develop NDT types that were significantly earlier than ICPL 88039 and had similar yield (Tables 5 and 6). Further studies are warranted to evaluate earliness per se, photoperiod, and temperature sensitivity of the newly generated lines and also to elucidate the nature of the linkages between flowering patterns (DT and NDT) and earliness. Selection for earliness and selection for photoperiod and temperature sensitivity should be undertaking in parallel. Selecting for earliness alone does not necessarily provide daylength insensitivity; this was pointed out by Wallis et al. (1981) based on evaluations of early maturing lines developed in Australia and Haryana Agricultural University under two different photoperiods.

In other legume crops (i.e., chickpea [*Cicer arietinum* L.] and soybean [*Glycine max* (L.) Merr.]) earliness has been achieved and is providing farmers with options for their cropping systems. Pigeonpea fixes around 40 kg N ha^{-1} in the soil and helps maintaining soil fertility and texture. Extra-short duration pigeonpea (ICPL 88039, ICPL 85010, and AL 201) have already been shown to contribute to higher productivity of the pigeonpea–wheat rotation system and farmers have indicated that extra-short duration pigeonpea was preferred in crop rotation because of their early maturity and also because of large seed size and increased yield of the following wheat crop (Dahiya et al., 2001, 2002). Pigeonpea–wheat rotations using short duration pigeonpea have shown high net benefits to the farmers (Bantilan and Parthasarathy, 1999). To include pigeonpea in wheat cropping systems, farmers need varieties that mature in 80 to 130 d and are less photoperiod sensitive. Super-early pigeonpea could fit the pigeonpea–wheat cropping system; they will mature sufficiently ahead of the time to prepare the land for the following wheat crop. In addition to offering wider spatial adaptation, super-early pigeonpea varieties could also offer farmers temporal flexibility by allowing them to widen the pigeonpea planting window without affecting much the crops' productivity. Super-early pigeonpea may also escape diseases, drought, and pod borer attacks if planted early in June and harvested before those stresses occur. This is also the case for short duration pigeonpea planted in June and harvested before *Helicoverpa armigera* become active (October through December in Gulbarga District, Karnataka, India) (Patil et al., 1997). However, we have observed that waterlogging and *Maruca vitrata* attacks (this stress is particularly problematic in DT types) could be problems for super-early pigeonpea. Therefore, proper drainage of the fields and appropriate pest management will be essential. Farmers could also get an economic incentive by introducing pigeonpea grain in the market earlier than the regular time.

Super-early pigeonpea also open options for replacing rice (*Oryza sativa* L.) from the rice–wheat rotation (there is interest in reducing rice area in parts of India) and/or offer alternative rotations. In latitudes ranging from 15 to 20° N where rice is a very important crop, the majority of fields are left fallow for 5 to 6 mo (early November to early June) after harvesting due to unavailability of irrigation water, inadequate rainfall, and nonavailability of suitable crop varieties to be included in the rotation. Among the different maturing pigeonpea cultivars tested for introduction into this system, extra-short and super-early pigeonpea could be an attractive option to grow the crop on stored soil moisture (in soils with good water-holding capacity) after harvesting rice. Super-early and extra-short pigeonpea genotypes could also be used in other countries where rice is an important crop, for example, in Sri Lanka (Chauhan et al., 1999). Introduction of super-early pigeonpea in rice fallows will likely increase farmers' income but also improve soil health and productivity, save irrigation water, promote long-term sustainability of agriculture, and improve human nutrition.

It is difficult to predict if super-early genotypes will find acceptance among the farmers, but it is very likely that niches for these materials will be available. Yield was positively correlated with flowering, maturity, plant height, and number of pods per plant (Patel et al., 1988); we have also observed similar correlations (data not shown) and therefore lower yields per plant in super-early when compared with medium maturity groups are expected. Negative correlation were observed (data not shown) between flowering, maturity, height, and seed size; this could be due to physiological reasons since the reproductive period in early maturing genotypes is short and this affects the seed size adversely; due to short reproductive period there is also less accumulation of photosynthates from source to sink (seed). If yield and duration of the crop season are considered together, super-early pigeonpea could be an attractive investment (yield per time invested). In addition, planting super-early pigeonpea materials would not put in peril the following cash crop (i.e., wheat), which is a very important consideration for the many farmers. The yield of DT and NDT lines under adverse conditions (waterlogging and Phythopthora damage in 2010; Tables 3 and 4) was half of the yield obtained under more favorable conditions (2011; Table 6). The yield potential of the NDT seems to be, in general, higher than in the DT types. Despite the lower yields, DT types have a very good attribute, synchronization of maturity. Total yield in super-early types (both DT and NDT types) could be increased by increasing plant population density; hence agronomic studies are warranted to give spacing recommendations to maximize gain yield. Increasing yield by adjusting plant density together with mechanical insecticide applications and mechanical harvesting (due to the shorter stature of the plants) could make the super-early genotypes more attractive to the farmers. Chauhan et al. (1984) tested extra-short pigeonpea lines under different population densities (160,000, 260,000, 420,000, and 670,000 plants ha^{-1}) and indicated that 160,000 and 260,000 plants ha^{-1} gave better yield; however, genotype × density interaction was observed. Suggested plant distance ranges from 15 to 30 cm and row-to-row distance ranges from 40 to 75 cm for short duration pigeonpea. Further spacing trials for super-early pigeonpea lines are needed to identify optimum spacing to maximize production.

The outputs described in this paper are new super-early genotypes that could be used by national programs as sources of earliness in their breeding programs or even promoted directly— after multilocation evaluations—as new varieties in locations representing a wider array of latitudes and altitudes. Other advantages of having super-early materials for breeding and genetic analysis purposes include faster generation turnover (up to four generations per year) such as suggested by Saxena (1996), which could assist in faster introgression of traits of interest. Mapping populations suitable to study the genetics of biotic and abiotic stresses could also be developed faster (~ 2 yr to get recombinant inbred lines); however, a prerequisite would be to have contrasting parents for the traits of interest in the super-early maturity group.

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