

# Photoperiod Responses of Extra-Short-Duration Pigeonpea Lines Developed at Different Latitudes

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## ABSTRACT

There is interest in growing pigeonpea [*Cajanus cajan* (L.) Millsp.], a tropical grain legume crop, in temperate regions. A few extra-short-duration lines were developed in Minnesota (~45° N), USA, to improve the crop's adaptation to temperate regions. We investigated whether photoperiod responses of the Minnesota lines (MN #) differed with lines (ICPL #) bred in the tropics. Five ICPL lines and three MN lines were grown under artificially extended daylength (ED) simulating 45° N and normal daylength (ND) at Patancheru, India, (17° N) during the 1995 and 1996 rainy seasons. Six ICPL and two MN lines were also tested at Suwon (37° N), Korea, in 1998. At Patancheru, the line × photoperiod interactions were highly significant for grain yield, total dry matter (TDM), harvest index (HI), days to flowering (DF), and maturity (DM). Under ND, yield was significantly more for ICPL lines and correlated with TDM ( $r = 0.892$  and  $0.902$ ,  $n = 8$ ), DF, and DM, but not with HI. Under ED, yield was more for MN lines and correlated positively with HI and negatively with DF and DM (in 1996), but not with TDM. The additive main effects and multiplicative interaction (AMMI) analysis suggested a distinct interaction pattern for MN lines. Yield was correlated negatively with DF and DM in Korea also where a MN line gave the highest yield. The results suggest that there has been a selection for a high HI potential and early flowering in MN lines for better adaptation to longer days and a high TDM production potential in ICPL lines to shorter days.

PIGEONPEA is a tropical grain legume crop that is well adapted to subsistence agriculture in the tropical and subtropical regions. However, in recent years there has been interest in developing shorter duration cultivars with wider adaptation to a range of environments and intensive production systems because of rising demand for its grain, green leaves for grazing, as well as a need for diversification of important production systems. There is also interest in cultivation of this crop in nontraditional areas because of its beneficial effects on soil fertility and organic matter (Whitbread et al., 1999).

Through empirical selection for earliness, a number of extra-short-duration (ESD) lines have been bred at ICRISAT-Patancheru and elsewhere (Singh, 1996), which has increased cropping options for pigeonpea. These lines can be grown as a catch crop (Nam et al., 1993; Chauhan et al., 1993) and in rice (*Oryza sativa* L.) fallows in the short-rainy season in Sri Lanka (Chauhan et al., 1999). Feasibility of their intensive cultivation

in rotation with wheat (*Triticum aestivum* L.) has also been shown for the Indo-Gangetic Plain (Dahiya et al., 2002).

Appreciable reduction in the life cycle duration of ESD cultivars has made it not only possible to grow pigeonpea as an intensively managed commercial crop (Wallis et al., 1981), but also to grow it over a wider range of latitudes. However, ESD cultivars showed a significant line × environment interaction when grown at diverse latitudes (Chauhan et al., 1998; Wallace and Yan, 1998). To achieve a targeted improvement in this crop, factors that contribute to line × environment interactions need to be understood.

Photoperiod and temperature are two major environmental factors that influence global adaptation of crops through their effects on days to flowering (DF). Additionally, photoperiod can affect photosynthate partitioning. In some peanut (*Arachis hypogaea* L.) genotypes, long photoperiod has been shown to reduce partitioning of dry matter to pods (Witzenberger et al., 1988). Decreased partitioning to grain competitively favors partitioning toward organs that continue vegetative growth, thereby increasing dry matter production and leaf area (Wallace and Yan, 1998). Cultivars that are bred for higher latitudes not only should mature before the winter sets in but their partitioning to seed should also be less sensitive to long photoperiod and thus produce high seed yield.

Recently, a few ESD lines based on lines derived from ICRISAT lines have been developed at the University of Minnesota, USA (Davis et al., 1995). Even though the lines developed at ICRISAT-Patancheru and Minnesota are grouped together in the extra-short-duration maturity group, it is not known if they differ in response to photoperiod. A comparison of these lines could provide better understanding of the basis of adaptation of the crop to different environments. This study was, therefore, conducted to examine whether lines developed at Patancheru and Minnesota differed in their responsiveness to photoperiod.

## MATERIALS AND METHODS

Nine ESD lines (ICPL 4, ICPL 84023, ICPL85010, ICPL 85012, ICPL 88015, MN 1, MN 5, and MN 8, and ICPL 88039) were selected for the study. Of these, all ICPL lines were bred at ICRISAT-Patancheru (17° N). The MN lines were reselections made in the Minnesota (45° N) environment (Davis et al., 1995) from the ICPL 85010 and ICPL 88015

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**Abbreviations:** AMMI, additive main effects multiplicative interaction; DF, days to flowering; DM, days to maturity; ED, extended day length; ESD, extra-short-duration; GEI, genotype × environment interaction; HI, harvest index; L × P, line × photoperiod environment; ND, normal day length; REML, residual maximum likelihood; TDM, total dry matter.

populations supplied by ICRISAT. Lines ICPL 84023, ICPL 85012, and ICPL 88039 are promising ESD lines developed through pedigree selection method at ICRISAT. ICPL 4 is a determinate pure line selection made at ICRISAT from an ESD cultivar Prabhat, which was released in the 1960s for cultivation in India (Asthana et al., 1996).

Eight of these lines (ICPL 4, ICPL 84023, ICPL 85010, ICPL 85012, ICPL 88015, MN 1, MN 5, and MN 8) were grown in Alfisol (clayey-skeletal, mixed, isohyperthermic family of Udic Rhodustalf) fields at ICRISAT-Patancheru near Hyderabad, India (17° N, 78° E; 550 m elevation). They were grown under normal (tropical) daylength (ND) and extended (temperate) daylength (ED), which was adjusted weekly to simulate 45° N latitude up to the September equinox during the rainy seasons of 1995 and 1996. The experiment consisted of planting in two adjacent plots in a precision field, one for ND and another for ED, and within each the lines were arranged in a randomized complete block design. There were three replications within each. The plot size for each was 4 × 3 m. Prior to sowing, the field was surface tilled to incorporate 100 kg ha<sup>-1</sup> diammonium phosphate containing 18% N and 20% P. Ridges were then established that were 60 cm wide. Seeds were sown on 24 June of both 1995 and 1996 on the ridges. Plant-to-plant spacing within rows was 10 cm. Two seeds per hill were sown and seedlings thinned to one per hill at about three weeks after sowing. The gross plot size comprised 10 rows of 4-m length spaced 30 cm apart.

After planting, the fields were sprayed with a mixture of preemergence herbicides, fluchlorolin [*N*-(2-chloroethyl)-2,6-dinitro-*N*-propyl-4-(trifluoromethyl) alanine] (450 g kg<sup>-1</sup>) at 1.5 kg ha<sup>-1</sup> and prometryn [*N,N'*-bis (1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine] (500 g kg<sup>-1</sup>) at 1.5 kg ha<sup>-1</sup> and a post emergence herbicide paraquat (1,1'-dimethyl-4,4'-bipyridyldium ion) (2.5 g kg<sup>-1</sup>) at 4.0 kg ha<sup>-1</sup>. Two hand weedings were done. Insect pests during the reproductive phase of the crop were intensively controlled with insecticide sprays. The trials were grown rainfed, but because of adequate rainfall, plants at no time suffered from drought stress.

The photoperiod treatments were imposed from sowing onward. A thick black cotton curtain was raised every night to separate photoperiod treatments. The ND treatment consisted of exposing lines to prevailing natural daylength, whereas the daylength extension in the ED treatment was with 100-W incandescent bulbs in a grid of 2.5 × 3 m. Bulb height was maintained about one meter above the canopy. The bulbs were switched on from the time day light intensity fell to ~600 J m<sup>-2</sup>. The extended daylength simulated temperate daylength of 45° N latitude (included natural daylength plus civil twilight). These bulbs provided only about 25 to 53 μmol m<sup>-2</sup> s<sup>-1</sup> of photosynthetically active radiation at the canopy height within the ED treatment during the extended period. The bulbs were attached to an automatic timer and programmed to switch on and off at specified times.

Days to 50% flowering (when at least 50% plants had one open flower from the first flush) and maturity (when 75% pods had turned brown from the first flush of pods) were recorded. In 1996, samples of five contiguous plants were also taken for growth analysis at 23, 40, 57, and 78 d after sowing. The number of leaves, leaf area, and oven dry (80°C for 48 h) weight of vegetative and reproductive structures were recorded. At maturity, total (above ground) dry matter (leaves + stems + pods) and grain yield per unit area were recorded. Yield and total dry matter (TDM) were recorded from a 9-m<sup>2</sup> area. Harvest index (HI) was calculated as grain yield as percentage of total above ground dry matter.

The data of days to flowering and maturity (DM), yield, TDM, and HI were analyzed by the analysis of variance proce-

dures of GENSTAT software (Genstat Manual, 1983). As the error variances for the two photoperiod treatments were homogeneous for yield, their data were pooled and reanalyzed as a single trial with four environments (ND95, ED95, ND96, and ED96) resulting from two seasons and two photoperiod treatments. To compare two groups of genotypes, the residual maximum likelihood (REML) component analysis, which is useful for the analysis of an unbalanced design as in the present case with unequal number of lines in different groups, was performed. In this analysis, constant + environment + group + environment × group were treated as a fixed model and environment.replication as a random model. The pattern of interaction was determined by the additive main-effects and multiplicative interaction (AMMI) model analysis (Zobel et al., 1988). The AMMI analysis uses analysis of variance (AN-OVA) followed by a principal component analysis applied to the sums of squares allocated by the ANOVA to the line × environment interaction.

Another experiment was conducted at the National Crop Experiment Station (NCES), Suwon (37° N), Korea, in 1998. The trial was sown on 16 June 1998. There were eight lines; seven of the lines used in Patancheru experiment (ICPL 4, ICPL 84023, ICPL 85010, ICPL 85012, ICPL 88015, MN 5, and MN 8) were grown, and MN 1 was replaced with ICPL 88039. The trial was laid out in a randomized complete block design with three replications. Row-to-row spacing was 60 cm with 5 cm plant-to-plant spacing. One seed per hill was sown. The experiment was grown under rainfed conditions, but it suffered no drought stress. The DF, DM, and grain yield were recorded. As the effects of insect pests and diseases were negligible, these were not accounted for.

## RESULTS

### Weather

The weather parameters for Patancheru indicated that 1995 received slightly more rainfall and had higher solar radiation (Table 1). However, the mean maximum and minimum temperatures were similar for the two seasons. At Suwon, Korea, the mean maximum and minimum temperatures, although less than those at Patancheru, were conducive for pigeonpea growth until October, by which time all the lines had matured. The photoperiod including civil twilight was longer at Suwon until September.

### Phenology and Crop Growth

There were significant line × photoperiod environment (L × P) interactions for DF and DM (Table 2). The MN lines were generally earliest to flower and mature in both ND and ED. There was a 4- to 17-d delay in flowering and maturity of lines under ED.

Growth analysis of two contrasting lines, MN 5 and ICPL 85012, revealed slower accumulation of TDM in MN 5 under ND than under ED from the early stages (Fig. 1). Initially, accumulation of dry matter in the reproductive structures was greater in MN 5. MN 5 developed fewer leaves, which were also smaller under ND. In contrast the differences in TDM accumulation between ND and ED were small for ICPL 85012. In both lines there was a reduction in number of leaves after about 60 d from sowing because of senescence, but the decline was less steep in ICPL 85012 under ED.

**Table 1. Mean monthly rainfall, solar radiation, maximum and minimum temperatures, and photoperiod (including civil twilight) during the 1995 and 1996 growing seasons at ICRISAT Patancheru, India, and during the 1998 growing season at Suwon, Korea.**

| Season             | Parameter   | Unit               | June | July | August | September | October |
|--------------------|-------------|--------------------|------|------|--------|-----------|---------|
| Patancheru (17° N) |             |                    |      |      |        |           |         |
| 1995               | Rainfall    | mm                 | 136  | 252  | 246    | 113       | 361     |
|                    | SR†         | MJ m <sup>-2</sup> | 603  | 470  | 552    | 530       | 436     |
|                    | MaxT‡       | °C                 | 36.5 | 30.1 | 30.2   | 30.2      | 29.1    |
|                    | MinT§       | °C                 | 25.0 | 22.8 | 22.8   | 22.1      | 20.4    |
|                    | Photoperiod | h                  | 13.9 | 13.8 | 13.4   | 12.9      | 12.5    |
| 1996               | Rainfall    | mm                 | 87   | 211  | 451    | 161       | 84      |
|                    | SR          | MJ m <sup>-2</sup> | 571  | 542  | 414    | 521       | 478     |
|                    | MaxT        | °C                 | 35.2 | 32.8 | 29.9   | 29.9      | 30.1    |
|                    | MinT        | °C                 | 24.1 | 23.8 | 22.9   | 22.0      | 20.7    |
| Suwon (37° N)      |             |                    |      |      |        |           |         |
| 1998               | Rainfall    | mm                 | 214  | 306  | 592    | 141       | 25      |
|                    | MaxT        | °C                 | 25.9 | 28.8 | 29.4   | 27.8      | 22.1    |
|                    | MinT        | °C                 | 17.7 | 22.3 | 22.5   | 18.6      | 12.0    |
|                    | Photoperiod | h                  | 15.7 | 15.4 | 14.5   | 13.3      | 12.1    |

† SR, solar radiation.  
 ‡ MaxT, maximum temperature.  
 § MinT, minimum temperature.

At maturity, the L × P environment interactions were highly significant for yield, TDM production, and harvest index (Table 3). In 1995, there was general increase in yield under ED, whereas in 1996 there was a decline in some lines (Table 3). MN 5 had lowest of all yields under ND, but had highest or one of the highest yields under ED in both seasons. In 1995, ICPL 84023 responded to ED with comparatively higher yield like that of MN 5, but its yield was significantly less than MN 5 in 1996. In 1995, ED caused MN 5 to have largest (300%) increase in yield. In 1996, ED significantly decreased yield of ICPL 4 and ICPL 85012, but increased yield of ICPL 88015 by 27%, of MN 1 by 29%, of MN 5 by 248% and MN 8 by 209%. Total dry matter production was lowest for MN lines than for ICPL lines, but increased under ED. Among the MN lines, the largest increase in TDM was for MN 5 (Table 3). There was a decline in harvest index under ED in both years. MN 5 attained the maximum HI under ED (Table 3).

The REML analysis indicated a significant origin of line × photoperiod environment interaction for yield and DM but not for DF, TDM, and HI (Table 4). The lines developed in the tropics gave higher mean yield in the ND environment whereas the lines developed in

temperate regions gave higher yield in the ED environment.

The AMMI biplot of mean grain yield across lines, environments and the interaction principal component axis 1 (IPCA 1) accounted for the largest (79%) proportion of genotype × environment interaction (GEI) sums of squares (Fig. 2). This biplot showed magnitude of differences in GEI because of each line and because of each photoperiod environment. The largest IPCA 1 scores were those of MN 5 and MN 8 and equally high, but opposite scores were for ICPL 4, ICPL 85012, and ICPL 84023. The interaction scores were close to zero for MN 1, and for ICPL 88015 and ICPL 85010, from which MN lines were derived, which makes a biological sense. The ED and ND environments had opposite IPCA1 scores. The ED environments of both 1995 and 1996 had IPCA 1 scores of similar sign as that of MN 5 and MN 8. The multiplicative effect of IPCA scores of similar positive or negative signs is positive and that of opposite signs negative and added to the mean value of environments + mean value of lines – grand mean, it increases or decreases the predictive performance of a line in a given environment.

The correlation of yield with TDM was significant

**Table 2. Line × photoperiod environment interaction means (L × P) for days to flowering and maturity of five ICPL lines and three MN lines grown in different day length environments, Alfisols, 1995, 1996 rainy seasons, ICRISAT-Patancheru, India.**

| Line                     | Flowering |      |      |      | Maturity |      |      |      |
|--------------------------|-----------|------|------|------|----------|------|------|------|
|                          | ND95†     | ED95 | ND96 | ED96 | ND95     | ED95 | ND96 | ED96 |
| d                        |           |      |      |      |          |      |      |      |
| ICPL 4                   | 61        | 74   | 60   | 69   | 97       | 107  | 111  | 123  |
| ICPL 84023               | 58        | 70   | 53   | 60   | 95       | 112  | 111  | 121  |
| ICPL 85010               | 63        | 80   | 55   | 62   | 101      | 116  | 106  | 119  |
| ICPL 85012               | 54        | 69   | 59   | 63   | 91       | 105  | 116  | 122  |
| ICPL 88015               | 60        | 72   | 52   | 62   | 100      | 125  | 107  | 120  |
| MN 1                     | 55        | 64   | 50   | 59   | 97       | 108  | 94   | 118  |
| MN 5                     | 44        | 53   | 47   | 56   | 82       | 105  | 82   | 117  |
| MN 8                     | 49        | 66   | 49   | 61   | 85       | 106  | 83   | 115  |
| SE (L × P)<br>(within P) |           | 1.9  |      |      |          | 2.4  |      |      |
| CV%                      |           | 1.8  |      |      |          | 2.5  |      |      |
| Significance             |           | 5.2  |      |      |          | 4.1  |      |      |
|                          |           | ***  |      |      |          | ***  |      |      |

\*\*\* Significant at 0.001 probability level.

† ND95, ED95, ND96, and ED96 are normal (17° N) and extended daylength (simulating 45° N until September equinox) environments in 1995 and 1996.

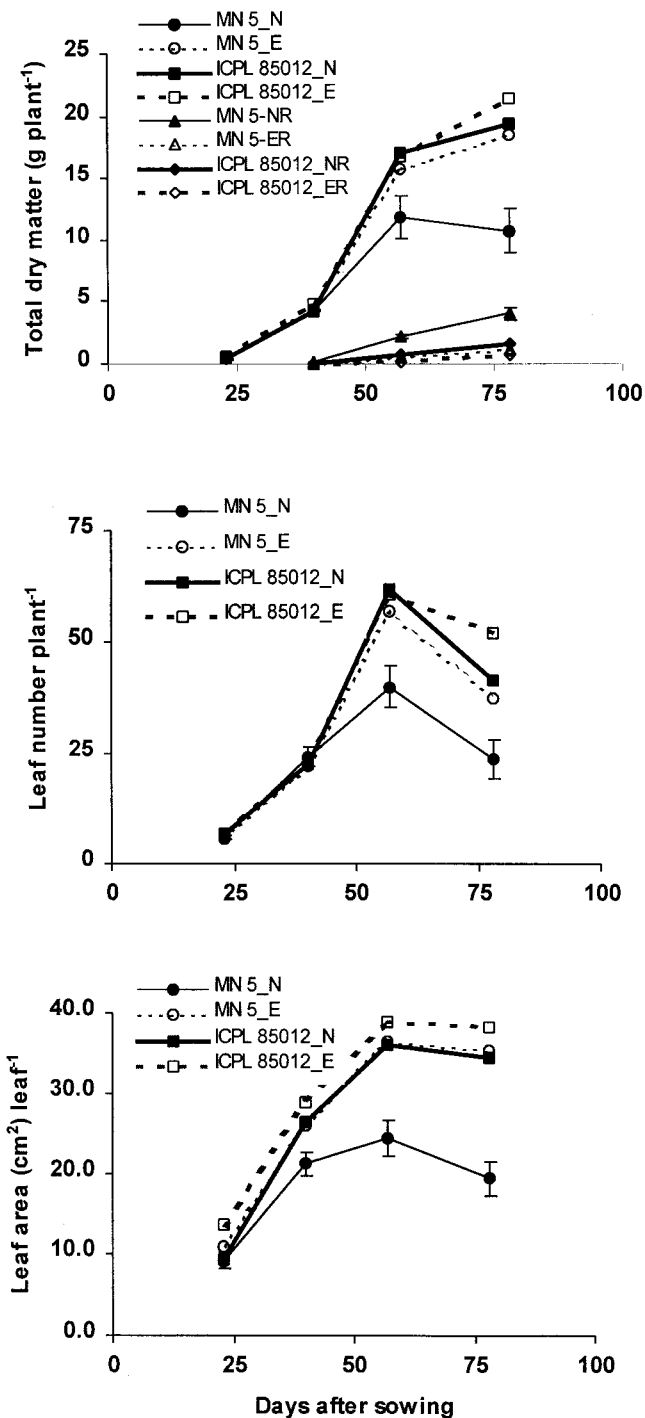


Fig. 1. Total dry matter accumulation, leaf number per plant and leaf area per leaf of MN 5 and ICPL 85012 under extended (E) and normal (N) day lengths, Alfisol, 1996 rainy season at ICRISAT-Patancheru. Suffix R with E and N represent reproductive structures. Vertical bars are standard errors of means for comparing total dry matter and reproductive structures of both lines under E or N.

and positive under ND, but not under ED in any of the years (Table 5). The correlation of HI with yield was significant positive under ED in 1996, whereas it had no correlation under ND in any of the years. The yield was correlated positively with DF and DM under ND, but correlated negatively under ED, the relationships

with both being significant in 1996. The reproductive period correlated significantly with yield under ND in 1996.

### Performance of Lines in Suwon, Korea

The lines varied considerably in yield from a very low for ICPL 88039 to up to 2.78 Mg ha<sup>-1</sup> for MN 5 (Table 6). Earliest flowering and maturity accompanied the higher yield of MN 5. ICPL 84023 also gave 1.7 Mg ha<sup>-1</sup> yield, whereas others had lower yields. Grain yield was correlated negatively with DF ( $r = -0.928, n = 8$ ). The correlation of yield was also significant and negative with DM ( $r = -0.779, n = 8$ ), but positive with the duration of reproductive period ( $r = 0.721, n = 8$ ). Each day delay in flowering reduced yield by 112 kg ha<sup>-1</sup> (Fig. 3). Hundred-seed mass of different lines grown in Korea was 2 to 28% higher than that at Patancheru, the largest difference being for MN 5 (data not presented).

### DISCUSSION

In this study, the magnitude of responses to photoperiod environments in yield, total dry matter accumulation, harvest index, and times to flowering and maturity varied significantly among different lines. The major finding of this study is that as a group, the MN lines developed in the temperate region gave lower yield in the ND environment of Patancheru than the ICPL lines developed in the tropics, whereas, they produced higher yield in the ED environment. The AMMI biplot of yield also indicated that at least MN 5 and MN 8 had distinctly different interaction patterns for yield than the ICPL lines, whereas MN 1 and ICPL 85010 and ICPL 88015 parents had a similar, but distinct pattern than the other ICPL lines. Among all eight lines, the lowest yield of all eight lines grown at Patancheru occurred for MN 5 under ND in both 1995 and 1996. In contrast, under ED, MN 5 was on par with the highest yielding line ICPL 84023 in 1995, and was highest yielding in 1996.

Photoperiod responses of different crops including pigeonpea have been generally studied in terms of changes in phenology (Vince-Prue, 1975; Lawn and Troedson, 1990). In the present study, ED caused significant delays in flowering of all lines. The differences among lines in DF in response to photoperiod observed in this study could have arisen due to differences in photoperiod sensitivity of lines, in either base photoperiod (above which flowering is delayed) and critical photoperiod (above which no floral initiation occurs) (Carberry et al., 2001). A combination of these parameters could result in earliest flowering in some lines, such as MN 5 and MN 8, under varied daylength.

The use of an extended photoperiod that decreased with the progress of the season, as would naturally happen, permitted investigation of the effect of this on flowering as well as on partitioning (i.e., harvest index). This could not be recorded in the previously published photoperiod studies on pigeonpea probably because of the use of constant extended daylength (McPherson et al., 1985; Turnbull, 1986). An increase in TDM in this study under ED was observed in all lines, which was



**Table 3. Line × photoperiod environment interaction (L × P) means for grain yield, total dry matter (stem + leaves + pods) and harvest index at maturity of five ICPL lines and three MN lines grown in different day length environments, Alfisols, 1995, 1996 rainy seasons, ICRISAT-Patancheru, India.**

| Line         | Yield               |       |      |      | Total dry matter    |       |      |      | Harvest index |      |      |      |
|--------------|---------------------|-------|------|------|---------------------|-------|------|------|---------------|------|------|------|
|              | ND95†               | ED95  | ND96 | ED96 | ND95                | ED95  | ND96 | ED96 | ND95          | ED95 | ND96 | ED96 |
|              | Mg ha <sup>-1</sup> |       |      |      | Mg ha <sup>-1</sup> |       |      |      | %             |      |      |      |
| ICPL 4       | 0.68                | 0.90  | 1.75 | 1.46 | 2.12                | 3.77  | 7.02 | 7.70 | 34.0          | 23.7 | 24.9 | 19.0 |
| ICPL 84023   | 1.05                | 1.53  | 1.94 | 1.77 | 2.91                | 5.93  | 5.67 | 7.00 | 35.9          | 25.7 | 34.3 | 25.4 |
| ICPL 85010   | 0.76                | 1.43  | 1.85 | 2.08 | 2.72                | 7.33  | 5.85 | 8.13 | 28.9          | 20.9 | 31.9 | 25.5 |
| ICPL 85012   | 0.94                | 1.39  | 2.22 | 1.80 | 2.70                | 4.25  | 7.31 | 8.00 | 35.2          | 32.8 | 30.6 | 22.5 |
| ICPL 88015   | 0.92                | 0.95  | 1.62 | 2.06 | 3.05                | 3.52  | 4.47 | 7.66 | 29.7          | 27.4 | 36.1 | 26.6 |
| MN 1         | 0.84                | 0.96  | 1.47 | 1.90 | 2.85                | 4.64  | 4.27 | 7.36 | 29.3          | 20.6 | 34.8 | 26.0 |
| MN 5         | 0.50                | 1.50  | 0.89 | 2.21 | 1.18                | 4.48  | 3.24 | 6.79 | 42.3          | 33.7 | 27.5 | 32.6 |
| MN 8         | 0.70                | 1.01  | 1.02 | 2.14 | 2.24                | 4.19  | 3.35 | 7.14 | 31.0          | 24.0 | 30.9 | 30.1 |
| SE (L × P)   |                     | 0.141 |      |      |                     | 0.472 |      |      |               | 2.10 |      |      |
| (within P)   |                     | 0.118 |      |      |                     | 0.417 |      |      |               | 2.09 |      |      |
| CV%          |                     | 14.7  |      |      |                     | 14.6  |      |      |               | 12.4 |      |      |
| Significance |                     | ***   |      |      |                     | ***   |      |      |               | ***  |      |      |

\*\*\* Significant at 0.001 probability level.

† ND95, ED95, ND96 and ED96 are normal (17° N) and extended daylength (simulating 45° N until September equinox) environments in 1995 and 1996.

attributable to increase in their duration as well as to increase in both number of leaves and individual leaf area and consequently increased leaf area duration. This was accompanied by a decreased HI in most lines. On the basis of research with bean (*Phaseolus vulgaris* L.), Wallace et al. (1993) and Wallace and Yan (1998) suggested that long photoperiods caused inhibition of allocation of assimilate to seeds and increased allocation to vegetative organs. In peanut, greater partitioning to pods was reported under short photoperiods (Witzenberger et al., 1988; Harris et al., 1988) and significant L × P interactions for pod yield attributable to such response have been reported (Nigam et al., 1998). Lawn (1989) suggested that in tropical legumes, relative partitioning of photoassimilates into reproductive organs or vegetative organs after the start of flowering depends on the degree of determinateness (preference for partitioning to seed) and that photothermal regimes have a direct influence on the expression of determinateness. Long photoperiods, either independently or in conjunction with high temperatures, seem to promote indeterminateness even in early flowering types through variously extending flowering period, reducing synchrony of flowering and pod set, and delaying pod ripening. In the ED environments, selection for determinateness could be more effective and hence more adaptation in those

environments. Although information on frequency of flower opening in the compared photoperiod environments was not collected, flowering appeared more synchronous in MN lines. Lawn (1989) also suggested that greater synchrony of flowering would be needed in legumes because this provides flexibility for use in intensive production systems and enables matching phenology to the environment to avoid terminal drought stress. Synchronous maturity also reduces the window of vulnerability to insect pests, in addition to facilitating mechanized production (Wallis et al. 1981). This aspect requires further attention in future studies even from the point of raising yield potential in pigeonpea, as unequal competition for assimilates among reproductive sinks of different ages could be one of the reasons for its lower yield potential.

Grain yield, as the product of TDM and HI, can be affected by a change in either or both. Some insight as to why the MN lines may have yielded better than ICPL lines under ED environment and not under ND was provided by the correlation of measured traits with yield. Under ND, yield was correlated significantly with TDM, indicating a source limitation for yield. Under ED, it was correlated with HI (significant in 1996), which could be due to yield being limited by the lower potential for one or more yield components such as number of

**Table 4. Effect of photoperiod on mean days to flowering, maturity, grain yield, total dry matter, and harvest index of a group five ICPL lines and another group of three MN lines on Alfisols, 1995–1996 growing seasons at Patancheru.**

| Trait            | Unit                | Environment | Group |      | SE Mean (G × P)‡ | Significance |
|------------------|---------------------|-------------|-------|------|------------------|--------------|
|                  |                     |             | ICPL† | MN   |                  |              |
| Flowering        | d                   | ND§         | 57    | 49   | 1.0              |              |
|                  |                     | ED          | 68    | 60   |                  |              |
| Maturity         | d                   | ND          | 103   | 87   | 1.4              | ***          |
|                  |                     | ED          | 117   | 111  |                  |              |
| Yield            | Mg ha <sup>-1</sup> | ND          | 1.37  | 0.90 | 0.092            | **           |
|                  |                     | ED          | 1.54  | 1.62 |                  |              |
| Total dry matter | Mg ha <sup>-1</sup> | ND          | 4.38  | 2.85 | 0.325            |              |
|                  |                     | ED          | 6.33  | 5.77 |                  |              |
| Harvest index    | %                   | ND          | 32.2  | 32.6 | 0.94             |              |
|                  |                     | ED          | 24.9  | 27.9 |                  |              |

\*\* Indicates significance at P = 0.01.

\*\*\* Indicates significance at P = 0.001.

† ICPL = ICPL lines bred at Patancheru; MN = MN lines reselected at Minnesota, USA.

‡ G × P = Group (ICPL and MN) × photoperiod environment interaction.

§ ND = Natural day length and ED = extended daylength.

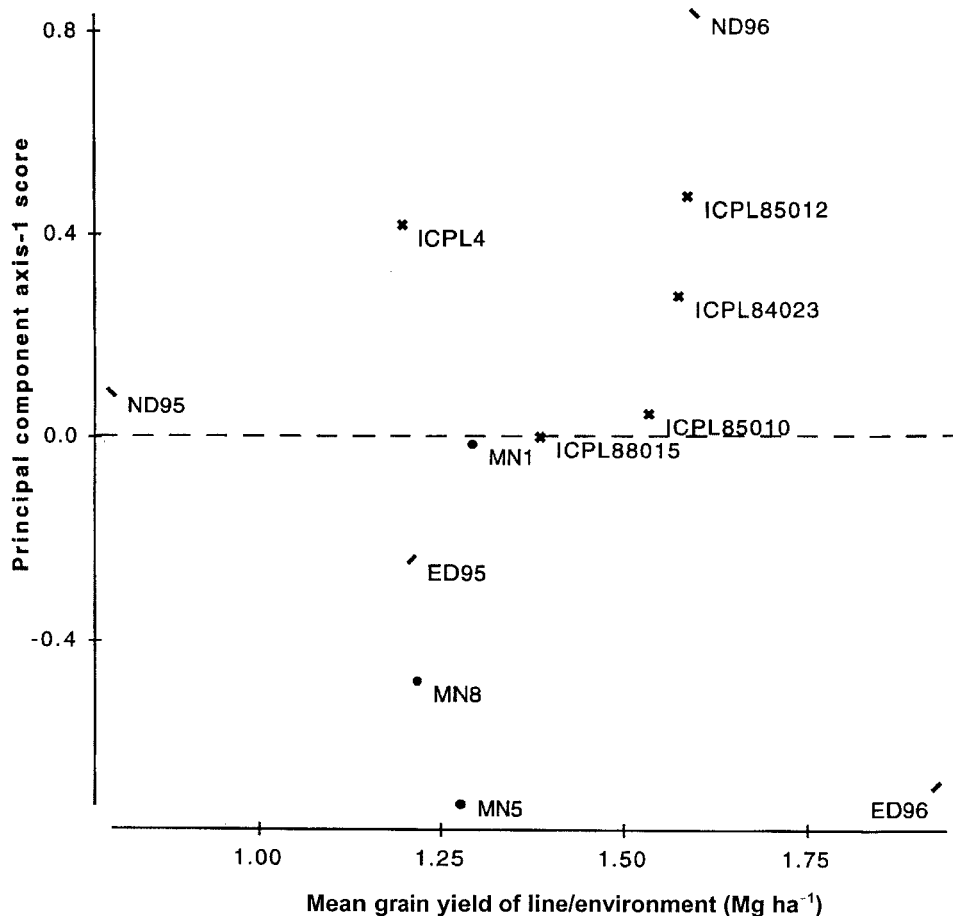


Fig. 2. Biplot of interaction principal component axis 1 against mean yield of five lines (ICPL 4, ICPL 84023, ICPL 85010, ICPL 85012, ICPL 88015) developed at Patancheru and three (MN 1, MN 5 and MN 8) developed in Minnesota, USA, in two natural day environments, ND95, ND96 (in 1995 and 1996) and two extended day environments, ED95 and ED96 (in 1995 and 1996). The dashed line separates negative and positive scores. Each environment is shown by a separate symbol.

Pods, seeds per pod, and seed mass. In the ND environment, because of early flowering, yield of MN lines may be limited by TDM production. In contrast, in the ED treatment, greater TDM due to an increase in the leaf area arising from more leaves that were also bigger, it was nonlimiting. In the ED environment in 1996, DF was correlated negatively with yield, which could be due to a larger decrease in harvest index of later flowering lines arising out of their greater photoperiod sensitivity. Under ED, MN 5 and MN 8 lines had early flowering with higher harvest index than the ICPL lines. It

Table 5. Correlation coefficients of relationship of seed yield with days to flowering, maturity, and reproductive period, harvest index and total dry matter in different photoperiod environments.

| Trait               | 1995-Season |              | 1996-Season |              |
|---------------------|-------------|--------------|-------------|--------------|
|                     | Natural-day | Extended-day | Natural-day | Extended-day |
| Flowering           | 0.517       | -0.155       | 0.829**     | -0.760*      |
| Maturity            | 0.534       | -0.152       | 0.964**     | -0.829*      |
| Reproductive period | 0.178       | -0.023       | 0.936**     | 0.229        |
| Harvest index       | -0.368      | 0.453        | 0.195       | 0.907**      |
| Total dry matter    | 0.892**     | 0.631        | 0.902**     | -0.283       |

\* Indicates significance at  $P = 0.05$ .  
 \*\* Indicates significance at  $P = 0.01$ .  
 \*\*\* Indicates significance at  $P = 0.001$ .

appears that the harvest index of lines, which flowered early, was adversely affected less under ED. These observations may also help explain how the relative importance of TDM and HI in determining yield in different lines may vary across different photoperiod environments.

In multilocation or sowing-date experiments, photoperiod effects are usually confounded by temperature effects, which control also plant development. Lawn and Troedson (1990) reported that in pigeonpea the

Table 6. Days to flowering and maturity, and yield of eight extra-short-duration lines shown on 16 June 1998 during the summer season, Suwon, Korea.

| Line         | Flowering | Maturity | Yield<br>Mg ha <sup>-1</sup> |
|--------------|-----------|----------|------------------------------|
|              | d         |          |                              |
| ICPL 4       | 77        | 125      | 0.52                         |
| ICPL 84023   | 70        | 121      | 1.68                         |
| ICPL 85010   | 72        | 123      | 0.88                         |
| ICPL 85012   | 78        | 128      | 0.55                         |
| ICPL 88015   | 75        | 128      | 0.58                         |
| ICPL 88039   | 87        | 130      | 0.03                         |
| MN 5         | 62        | 118      | 2.78                         |
| MN 8         | 75        | 119      | 0.75                         |
| SE mean (±)  |           |          | 0.370                        |
| CV%          |           |          | 66                           |
| Significance |           |          | *                            |

\* Significant at 0.05 probability level.

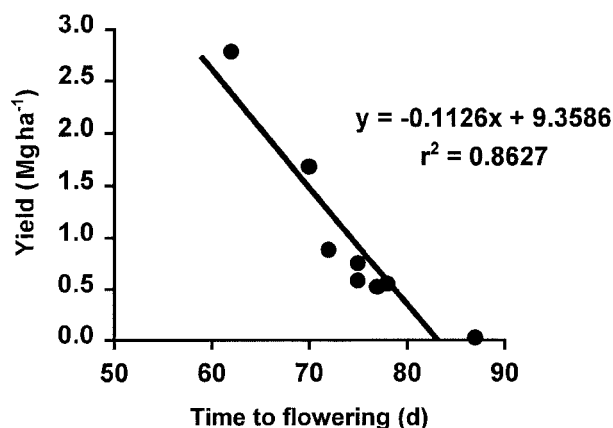


Fig. 3. Relationship between days to flowering and yield at Suwon, Korea, 1998.

magnitude of photoperiod and temperature effects on flowering could be similar over a range of photothermal regimes, whereas Wallace and Yan (1998) reported a modulation of photoperiod response for flowering by temperatures  $>24^{\circ}\text{C}$ . In the present study, the difference in mean temperatures experienced by the crop in the two photoperiod environments was within a  $0.3^{\circ}\text{C}$  range until 50% flowering. Therefore, the differential effect of temperature was not expected to have been very large. The simulation of a temperate environment was feasible only until the September equinox. However, the photoperiod sensitive phase for flowering of all lines ended by that time (Carberry et al., 2001). The differences in temperatures after flowering could also have a major influence on dry matter partitioning into yield. The climatic conditions of temperate regions, especially lower temperatures, could contribute to bigger seed size. For example, the 100-seed mass of MN 5 was 24% higher (8.8 g at Suwon compared with 7.1 g 100 seeds<sup>-1</sup> at Patancheru) in the temperate environment of Korea.

At Suwon, MN 5 yielded  $2.8 \text{ Mg ha}^{-1}$ , which was the highest yield of all eight lines. This could have resulted from its positive interaction with the extended photoperiod and also an increase in its seed mass. Line ICPL 88039 appeared to be so photoperiod sensitive that it produced very little yield when grown at Suwon. It flowered late but the few pods it set matured before the end of October and hence may not have been affected by frost. ICPL 88039, however, was reported to out yield ICPL 85010, used in this study, when grown in the subtropics (Dahiya et al., 2002). This suggests that there could be an optimum level of photoperiod insensitivity for the best performance of a line at given latitude, provided moisture and nutrients are not limiting. Interestingly, the relationship of DF and DM with yield in the temperate environments of Korea was highly negative, suggesting that later flowering lines were more sensitive to long photoperiod. There was a negative relationship between time to flowering and yield similar to that observed in the ED environment at Patancheru. This suggests that for better adaptation under long photoperiod regimes, selection for earliness may be desirable not only to ensure escape from frost but also to reduce

negative impact of extended photoperiod on grain yield. In contrast, for shorter daylength environments, there could be emphasis on selection for higher dry matter production.

It appears that all the ESD lines bred in tropical conditions in India are more photoperiod sensitive and produce more dry matter and yield in shorter day environments, whereas some MN lines are less photoperiod sensitive and produce more yield through higher HI in the extended daylength environment. Since this information could be gained by daylength extension, which simulates photoperiods at higher latitudes, the methodology employed could provide a cost-effective solution for identifying lines better adapted to different latitudes.

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