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Growth Traits and Sink Capacity in Late Sown Soybean Cultivars with Different Stem Lengths

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Soybeans (*Glycine max* L. Merr.) late planted are sown as a double cropping, which causes a short growing period. Because of the short season, growers employ high plant density (PD) of cultivars developed primarily for a full–season's growth to compensate a potential loss of seed yield. The objective of this study was to examine the effects of two plant densities and soybean cultivars having various stem lengths as growth characteristics and to determine some casual relationships of the growth characteristics and seed yield for the development of breeding strategies. All cultivars in high PD significantly ($P<0.05$) reduced in leaf area (48.0–70.7%), dry weights of leaves (1.8–44.2%) and stems (14.0–54.0%). Short stem cultivars (Camp and HS 287) significantly ($P<0.05$) increased in the number of pods at the upper nodes (3.1–15.6%) and in number of pods carried on the main stem (70.0–86.4%) as PD increased. Larger decline in sink capacity (seed g plant^{-1}) was observed in long stem (38.9–75.8%) than in short stem (30.0–38.2%) cultivars, but dry biomass apparently increased in all cultivars, ranging from 8.2 to 53.1%. Biomass of short stem cultivar Camp significantly increased from 7,240 to11,082 kg ha^{-1} (53.1% increased) in high PD. Harvest index (HI) increased in most short stem cultivars in high PD. Seed yield (kg ha^{-1}) of all cultivars increased (3.9–14.8%) in high PD, particularly short stem cultivars, Camp and HS 287. The major components for increased seed yield in high PD were an increase in the number of pods per unit area and the number of pods of the main stem in late planted soybeans.

INTRODUCTION

Planting soybeans (*Glycine max* L. Merr.) as a double crop following small grain crops such as winter wheat and barley has been a conventional practice in parts of the U.S and Northeast Asia. Double cropped soybeans are often planted later than what would be considered the optimal planting season, resulting in a short growing period. Late planting reduces the seed yield of soybean because of shorter vegetative growth compared to conventional planted soybean for optimal seed yield. Thus, lower seed yield in late planted soybean may be compensated with plant density (PD), fertilizer, planting pattern, and plant type (Board *et al.*, 1992; Cho *et al.*, 2004; Ikeda, 1992; Ikeda and Sato, 1990). High population density of the conventional soybean cultivars has caused productivity decline (Jones *et al.*, 2003). Reductions in seed yields may be resultant from a lower number of seeds per plant, smaller size of seed, lodging, or a combination of these with other yield components. The previous results suggest that a high plant population affects growth characteristics and ultimately limited seed yield due to insufficient development of the canopy of leaves which prevented full use of photosynthetically active radiation (Ball *et al.*, 2000; Cho *et al.*, 2004; Cho *et al.*, 2005; Jones *et al.*, 2003). Soybean yield and biomass as being related to interception of photosynthetically active radiation (PAR) from the emergence of seed development stage to the complete establishment of the canopy prior to the early reproductive stage might be very crucial to consider in order to ensure high seed yields (Edwards *et al.*, 2005).

Soybean seed yields increased as row spacing reduced from 100 to 75 and to 50 cm compared to low PD rows (Board *et al.*, 1992). High population density significantly increased plant dry biomass per unit area, but decreased both in the number of branches and the accumulation of dry matter per plant (Ball *et al.*, 2000; Jones *et al.*, 2003; López–Bellido and Fuentes, 1990). The influence of the diverse effect of plant densities on seed yield varied and depended upon environmental conditions, but a high seed yield was the most suitable choice under growth–restricting conditions such as late planting (López–Bellido *et al.*, 2000). The increase in seed yield per unit area increased grain yield (Norsworthy and Frederick, 2002; Shield *et al.*, 1996).

Harvest index (HI), the ratio of grain dry weight to total above ground dry matter, expresses the economically relevant contribution to the total increase in dry biomass (Spaeth *et al.*, 1984). HI is closely related to sink capacity and the stability of HI reflects the important effect of the shoot dry matter on pod development during reproductive stages in soybeans (Kakiuchi and Kobata, 2004).

A constant demand for the development of superior cultivars and cultural practice under high PD has been a major concern in many investigations (Scheiner *et al.*,

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2000). One of the ultimate purposes of soybean breeders is to develop stable, high yielding cultivars that are agronomically superior (Scott and Kephart, 1997). But, little work has been accomplished in regards to aiding our understanding of the effects of PD in different main stems of soybeans on growth characteristics. Understanding of growth responses and patterns of soybean to different plant densities helps the development of superior cultivars which perform well over various growth conditions. The objective of this study was to examine the effects of plant densities and diverse stem growths, and to determine the interaction among the growth characteristics with seed yield to develop strategies that can be used for breeding programs.

MATERIALS AND METHODS

Plant materials

Two groups of main stem growth type with a total of five soybean cultivars (Camp, Eunhakong, HS 287, Iksannamulkong, and Pureunkong) were used in this study: one group having a long main stem included Iksannamulkong and Pureunkong which ranged from 76±4 to101±8 cm in plant height (Table 1). Another group having short main stems was Camp and HS 287 which ranged from 50±5 to 45±6 cm in plant height. Eunhakong was used as an intermediate stem, 63±5 cm in plant height. The long and short stem cultivars divided into two subclasses: highly and few branched types. Iksannamulkong possessed 4.2±0.4 branches which was more than that of Pureunkong which had 1.2±0.3 branches. Camp and HS 287 had 4.1±0.4 and 2.3±0.3 concerning the number of branches, respectively. Eunhakong had 3.2±0.4 regarding number of branches. Other growth characteristics, including maturity and 100–seed weight, of cultivars are shown in Table 1.

Field experiments

Field experiments were conducted over a period of three years in Iksan (126.97° E, 36.00° N), Korea. Seeds were planted in fields during the first week of June in a randomized complete block design with three replicates at the Honam Agricultural Research Institute farms. Each plot consisted of four rows spaced 0.60 m apart, 4 m in length, in which seeds were sown following a harvest of winter crop (barley). The seedlings were thinned to achieve a designated plant population density (i.e., 33 and 66 plants m^{-2} as low and high plant densities, respectively). The amount of applied fertilizer was N; 1.0 kg, P; 1.7 kg, and K; 1.5 kg per a^{-1} as basal fertilizations. No irrigation was provided during the crop growth period. Border rows were planted to eliminate edge effects.

At least three samples were randomly taken from each of the two central rows in each plot for growth characteristics, including number of mature pods per plant, seeds per pod, number of nodes, 100–seed weight, and plant dry biomass. Leaf area was measured on a LI–3100 electronic area meter (Li–Co, Lincoln, NE). Total dry biomass was determined after mature plants were dried in an oven for 3 days at 80 °C and pods were separately collected from each plant.

Lodging was based on a 1 (no lodging) to 9 (completely lodged) scale (Bertram and Pedersen, 2004). Sink capacity indicating the capacity of the plant to form yield was estimated by total seed weight (g) per plant. HI, the ratio of seed mass to total plant biomass, was calculated as total dry seed weight divided by total above ground dry biomass per plant (Denier van der Gon *et al.*, 2002).

Statistical analysis

The data were subjected to analysis of variance (ANOVA) using a randomized complete block design over three years. Mean values from three replicates and a pooled standard error of the mean were calculated by PROC GLM (SAS Institute Inc., 1999) and used for calculating the least significant differences (LSD) at the 0.05 level of probability comparison of means among treatments.

Table 1. Major vegetative and reproductive characteristics of cultivars with different stem growth habits and lateral branch types used in this study

Cultivar	Main stem	Branch [a] (no.)	Growth type	Plant height (cm)	R1 [b] (d)	Maturity (d)	100-seed weight (g)
Eunhakong	Intermediate, with highly branched type	3.2±0.4	DT	63±5	31 Jul. (56)	9 Oct. (126)	11.6±0.4
Iksannamulkong	Long, with highly branched type	4.2±0.4	DT	76±4	4 Aug. (60)	9 Oct. (126)	12.6±0.2
Pureunkong	Long, with few branched type	1.2±0.3	IT	101±8	13 Jul. (38)	27 Sep. (114)	13.5±0.9
Camp	Short, with highly branched type	4.1±0.4	DT	50±5	2 Aug. (58)	10 Oct. (127)	8.0±0.2
HS 287	Short, with few branched type	2.3±0.3	DT	45±6	26 Jul. (51)	29 Sep. (116)	15.4±0.3

DT: determinate type; IT: indeterminate type. [a] Includes primary branches except for subbranches. [b] At least one flower is located at any node on the main stem.

RESULTS

Responses of vegetative characteristics to plant density

Plant height increased in plots of high PD (66 plants m^{-2}) from 4 to 18% as compared to low PD (33 plants m^{-2}) (Table 2). Increase in plant height was seen more ofen in short stem cultivars (Camp and HS 287) (up to 18%) than in long stem ones, but the diameter of the main stem in all cultivars declined from 11 to 21% in high PD.

Lateral branches in high PD decreased by 31–75% in all cultivars. A decrease in the number of lateral branches was observed more often in cultivars with few branches (Purenukong and HS 287) than in the highly branched ones (Iksannamulkong and Camp). All cultivars showed delayed maturity of 1–3 days as the number of plants increased per unit area. Internode length significantly ($P<0.05$) increased at mid–vegetative stages (V7–12) in long stem cultivars with highly branched cyme in high PD (60×10 cm) (Fig. 1). Short stem genotype (i.e., Camp) with highly branched cyme in high PD significantly increased in internode length at the upper nodes (V13–15).

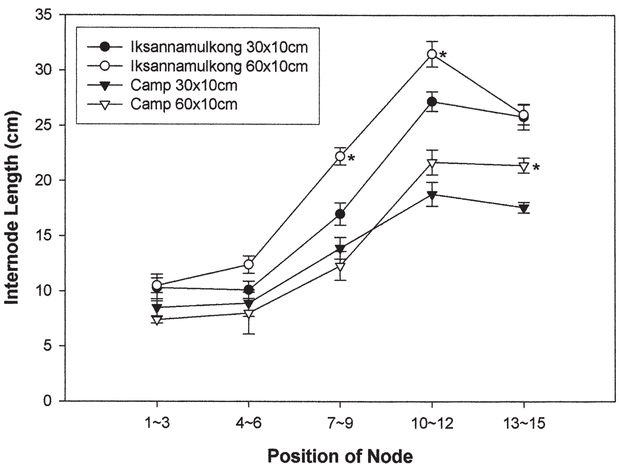

Fig. 1. Three–year mean of the position of nodes and internode length in two cultivars with long stem Iksannamulkong and with short stem Camp grown under different plant densities.
*: Significantly different at the 0.05 probability level as compared to low PD (30×10 cm). n=18.

Lodging scare for short stem cultivars was 2.3 in low and 3.7 in high PD, respectively (Table 2). Lodging resistance apparently decreased from 22 to 61% as PD increased particularly in cultivars with long stems rather than in those with short stems.

Reproductive traits of the different stem growth types

ANOVA (Table 3) indicates that significant ($P<0.05$) effects of cultivar and PD were found in relation to the number of pods per plant, and pods on the main stem and at lower nodes (Table 3). Interaction of cultivars with plant densities significantly affected the number of pods per plant and pods on the main stem. The mean number of pods per plant in all cultivars ranged from 33.7 to 63.0 in low PD, whereas it ranged from 23.0 to 48.3 in high PD (Table 3). Long stem cultivars showed more reduction (25.6% in Iksannamulkong and 41.3% in Purenkong) in the number of pods per plant than short stem cultivars (23.3% in Camp and 19.3% in HS 287).

The percentage of number of pods carried on the main stem to the total pods per plant ranged from 42.9 to 93.9% in all cultivars in high PD (Table 3). Short stem cultivars significantly increased in the percentages

Table 2. Vegetative growth characteristics in five soybean cultivars with different stem growth habits in two plant densities for three–year trials

Cultivar	Plant density (no. m^{-2})	Plant height (cm)	Lodging 1–9	Stem diameter (cm)	Branch (no.)	Maturity (d)
Eunhakong	33	81	6.3	7.4	3.2	3 Oct. (116)
	66	85	7.7	6.6	2.0	6 Oct. (119)
		5% up	22% up	11% down	38% down	3 days late
Iksannamulkong	33	92	6.3	7.2	4.2	8 Oct. (121)
	66	101	8.3	5.9	2.9	9 Oct. (122)
		10% up	32% up	18% down	31% down	1 day late
Pureunkong	33	114	3.0	8.3	1.2	3 Oct. (116)
	66	119	4.3	7.2	0.3	4 Oct. (117)
		4% up	43% up	13% down	75% down	1 day late
Camp	33	71	2.3	7.8	4.1	10 Oct. (123)
	66	78	3.7	6.2	2.2	12 Oct. (125)
		10% up	61% up	21% down	46% down	2 days late
HS 287	33	45	2.3	6.2	2.3	1 Oct. (114)
	66	53	3.7	5.2	1.1	2 Oct. (115)
		18% up	61% up	16% down	52% down	1 day late
	Cultivar (G)	9.2**	1.3**	1.1*	0.7**	0.6**
	Density (D)	4.9*	1.0**	0.7*	0.5**	0.4**
	G×D	NS	NS	NS	NS	0.8**

*, **: Significant at the 0.05 and 0.01 probability levels, respectively. NS: Not significant at the 0.05 probability level. n=18.

Table 3. Mean numbers of pod and distribution of pods carried on main stems and on different nodes in each soybean plant grown in different plant population density for three years

Cultivar	Plant density (no. m^{-2})	Pod no. (plant^{-1})	Pod on main stem no. (%) [a]	Distribution of pods at node		
				lower (1–6)	middle (7–10)	upper (11–)
Eunhakong	33	48.0	22.4 (46.7)	18.9	23.9	5.2
	66	27.4	19.6 (71.9)	8.2	11.6	7.6
Iksannamulkong	33	51.1	19.7 (38.6)	15.8	27.5	7.8
	66	38.0	16.3 (42.9)	7.5	24.1	6.4
Pureunkong	33	39.2	28.2 (71.9)	16.4	15.0	7.8
	66	23.0	21.6 (93.9)	5.4	10.0	7.6
Camp	33	63.0	24.0 (38.0)	32.1	19.3	11.6
	66	48.3	33.8 (70.0)	8.2	24.5	15.6
HS 287	33	33.7	21.8 (64.5)	15.3	16.7	1.8
	66	27.2	23.5 (86.4)	8.3	15.8	3.1
	Cultivar (G)	5.0**	13.3*	4.4**	NS	NS
	Density (D)	2.5**	4.5*	3.8**	NS	NS
	G×D	5.6**	10.0*	NS	NS	NS

*, **: Significantly different at the 0.05 and 0.01 levels of probability, respectively. NS: Not significant at the 0.05 probability level. n=18.
[a]: Indicates the percentage of number of pods on a peduncle against a total number of pods in a plant.

Table 4. Effects of plant density on yield components and seed yield in soybean cultivars with long and short stem lengths, and lateral branch types

Cultivar	Plant density (no. m^{-2})	Seed per plant (no. plant^{-1})	Seed per pod (no. pod^{-1})	100-seed weight (g)	Yield (kg ha^{-1})
Eunhakong	33	94.1	2.0	14.4	2,210
	66	55.6	2.0	14.3	2,300
Iksannamulkong	33	92.6	1.9	14.6	2,420
	66	68.8	1.8	14.1	2,620
Pureunkong	33	75.7	1.9	14.9	1,700
	66	45.7	2.0	14.5	1,790
Camp	33	108.1	1.7	12.0	2,470
	66	92.3	1.9	11.4	2,900
HS 287	33	64.8	1.9	15.4	2,530
	66	55.6	2.1	14.7	2,740
	Cultivar (G)	16.4**	0.4*	0.7**	169.5**
	Density (D)	6.2**	NS	0.3**	101.9**
	G×D	14.0**	NS	NS	NS

*, **: Significantly different at the 0.05 and 0.01 levels of probability, respectively. NS: Not significant at the 0.05 probability level. n=18.

of number of pods on the main stem to the total pods per plant from 70.0% in Camp (highly branched type) to 86.4% in HS 287 (few branched type) as PD increased. The number of pods at both lower and middle nodes of almost all cultivars declined in high PD. However, short stem cultivars significantly increased in the number of pods at the upper nodes in high PD (Table 3).

Yield components and seed yield by sink capacity and harvest index

Cultivars were seen as significant ($P<0.05$) regarding the number of seeds, seed yield, leaf area, dry biomass, and sink capacity (Table 4 and 5). Interaction of cultivar with PD significantly ($P<0.05$) influenced the number of seeds per plant, sink capacity and plant dry biomass. Seeds per plant in all cultivars decreased in high PD, however decreased relatively less (16.5–17.1%) in short stem cultivars (Camp and HS 287) than in long stem cultivar. The number of seeds in all cultivars remained the same in both plant densities. One hundred–seed weight declined (1 to 9%) in high PD as compared to low PD (Table 4). The seed yield (kg ha^{-1}) of all cultivars increased (3.9–14.8%) in high PD. In particular, short stem cultivars, Camp and HS 287, grown in high PD produced a higher seed yield than the long stem type of plants and showed an efficiently improved seed yield from 14.8% and 7.7%, respectively.

Leaf area (48.0–70.7%), and dry weights of leaves (1.8–44.2%) and stems (14.0–54.0%) reduced in all cultivars in high PD (Table 5). Similarly, sink capacity (seed g plant^{-1}) declined more in long stem cultivars (38.9–75.8%) than in short stem (30.0–38.2%) soybean cultivars, but plant dry biomass (kg ha^{-1}) increased 8.2 to 53.1% in high PD. In particular, the dry biomass of Camp significantly increased from 7,240 to11,082 kg ha^{-1} (53.1% increased) in high PD (Table 5). For HI, the

Table 5. Yield components and seed yield in relation to sink capacity and harvest index in various soybean cultivars grown in different plant densities for three years

Cultivar	Plant density (no. m^{-2})	Leaf area (cm^2 $plant^{-1}$)	Dry weight (g $plant^{-1}$)		Sink Capacity [a] (seed g $plant^{-1}$)	Plant dry biomass (kg ha^{-1})	Harvest index [b] (HI)
			Leaves	Stems			
Eunhakong	33	1,705	6.9	16.9	6.9	7,220	0.31
	66	999	5.6	12.5	3.9 (76.9 % ↓)	8,210	0.28
Iksannamulkong	33	1,979	7.5	17.4	7.5	7,610	0.32
	66	1,267	5.2	11.3	5.4 (38.9 % ↓)	9,400	0.28
Pureunkong	33	1,912	6.3	18.8	5.8	6,700	0.25
	66	1,292	5.7	15.2	3.3 (75.8 % ↓)	7,250	0.25
Camp	33	2,109	9.0	21.0	7.6	7,240	0.32
	66	1,308	6.7	14.1	5.5 (38.2 % ↓)	11,082	0.35
HS 287	33	1,700	5.6	10.6	5.2	6,620	0.38
	66	1,094	5.5	9.3	4.0 (30.0 % ↓)	6,540	0.42
$LSD_{0.05}$	Cultivar (G)	69.2*	0.5**	1.2**	0.4**	35.0**	0.01*
	Density (D)	51.7**	0.3*	0.7**	0.2**	31.8**	NS
	G×D	NS	0.7*	1.5*	0.5*	71.1**	NS

*, **: Significantly different at the 0.05 and 0.01 levels of probability, respectively. [a]: Sink capacity (capacity of the plant to form seed yield) was estimated by seed grain weight (g) per plant. [b]: Harvest index, the ratio of seed mass to total plant biomass, was calculated as total dry seed weight divided by total aboveground dry biomass per plant, that is estimated by a formula of (economic yield/production yield) ×100.

values ranged from 0.25 to 0.28, which either slightly decreased or were sustained in long main stem soybean cultivars (Iksannamulkong and Pureunkong), but increased in short stem cultivars (0.35 in Camp and 0.42 in HS 287, respectively).

DISCUSSION

Growth characteristics to plant density

All cultivars grown in high PD apparently decreased in stem diameter, number of branches, number of pods, number of seeds per plant, seed weight, but increased in plant height, lodging, and number of pods on the main stem (Table 2, 3 and 4). The previous studies reported a decrease in lateral branches and pods per plant as the number of plants per unit area increased (Lopez–Bellido *et al.*, 2000; Herbert, 1977).

Number of pods per plant in cultivars with short main stems decreased less than those with long stem (Table 3). In particular, the number of pods per plant at the lower nodes significantly decreased in all cultivars in high PD, but the number of pods on the main stem of each plant significantly increased, ranging from 42.9 to 93.9%. This indicates that the increased number of pods on the primary main stem rather than on the lateral branches in high PD is likely to be an important component for high seed yield. The number of pods on the main stem would contribute to a higher seed yield in high PD (Board *et al.*, 2003; Cho *et al.*, 2005; Egli and Bruening 2002). The number of pods per plant and the number of seeds per pod are known to be important components for an increase in seed yield (Cho *et al.*, 2002; Suh *et al.*, 2000). In relation to the effect of PD on seed yield, one study (Norsworthy and Frederick, 2002) reported that the total seed yield of highly branched cultivars was significantly correlated with total seed yield at a low PD (r=0.67).

In terms of internode, short stem genotype Camp with highly branched cyme showed not much change in the length of internode at the early vegetative stages (V1–12) in high PD, whereas long stem genotype Iksannamulkong showed a significant ($P<0.05$) increase in the length of the internode during the mid–vegetative stage (V7–12) in high PD (Fig. 1). Length of internode and stem diameter in short stem cultivars were likely to be less sensitive to high PD than those with long stem. Studies (Cober *et al.*, 2005; Lee *et al.*, 1991; Park *et al.*, 1990; Cooper, 1981) reported that growth traits such as length of internode and primary main stem diameter had a very close relation to the increased extent of lodging from 10 to 66% and decreased seed yield in various high PD trials.

All cultivars improved in seed yield up to 14.8% in high PD even though yield components such as the number of seeds per plant, number of pods per plant and seed weight had decreased. However, a higher yield of all cultivars in high PD was clearly due to a larger number of plants per unit area.

Growth characteristics and yield components by sink capacity

Leaf area and dry biomass per plant decreased in all cultivars with high PD. Sink capacity has been known to be affected by sink size (e.g., weight of the sink tissue, including seeds) and sink activity (e.g., uptake of photosynthates per unit weight of sink tissue) (Borrás *et al.*, 2003). Under the conditions of increased PD, much of the source leaves could be shaded during vegetative and early reproductive growth stages. Shade provided by neighboring plants with accompanied by resource competition due to the large number of plants in close proximity decreased leaf area and negatively influenced sink capacity, which determines yield components and seed yield (Jones *et al*., 2003). Because of high PD, photosynthesis could be inhibited, resulting in a change of photosynthate translocation and partitioning along with sink capacity. This study reveals that metabolic activities of source tissues (e.g., photosynthesis, assimilate loading in source tissues) could decline with resources competition (interception of light, nutrients, moisture, etc.) and influence sink capacity under the field conditions of high PD.

Although sink capacity per plant decreased in high PD, plant dry biomass per unit area was significantly improved (Table 4 and 5), resulting in a high seed yield for almost all cultivars, particularly cultivars with short stems (Camp and HS 287). Cultivars with short stems were likely to be well adapted to high PD cropping practices. The lower effect of PD on number of pods against seed yield per unit area was apparently observed in high PD, because of compensation afforded by the increased number of pods per plant in low PD. A similar study (Board *et al*., 2003; López–Bellido *et al*., 2000) showed that the number of pods per unit area had the most important direct and indirect effects on soybean seed yield.

Values of traits and harvest index (HI) to breeding programs

The possible causal factor behind the declined HI in cultivars with long stems in high PD was probably due to low light interception, negatively affecting the number of seeds per plant, pods on the lower nodes, 100–seed weight, and plant dry weight (Edwards *et al*., 2005; Denier van der Gon *et al*., 2002). Nevertheless, short stem cultivars showed a better performance as presented by higher HI (Table 5) in high PD. Comparatively higher HI in Camp and HS 287 suggests that cultivars with short stems were genetically stable in reference to their crop performance in an agricultural practice having heavy competition among plants. The stability of higher HI shown in cultivars with short stems reflects the important effect of the plant dry biomass increase on pod setting during the reproductive growth period (Kakiuchi and Kobata, 2004). Plant types of short stems are likely to be a potential germplasm with favorable genetic components, which could be used for breeding programs to improve seed yield under the condition of high PD (Table 5).

The major factors responsible for increased yield in high PD practice were an increase in the number of pods per unit area and the number of pods on the main stem (fertile node production) (Table 3). In a breeding strategy, short stem type cultivars may have some limited capacity to possess more numbers of pods on the main stem rather than lateral branches particularly in cases of high PD and late planting practices. Therefore, the number of seeds and pods per unit area could be used as indirect selection criteria for high seed yielding cultivars planted at a later date and having a high plant density.

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