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Yield and Seed Quality as Affected by Water Deficit at Different Reproductive Growth Stages in Soybean

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ABSTRACT

The effect of water deficits on soybean [*Glycine max* (L.) Merr.] could appear on seed quality through changes of morphological plant characteristics. Two Korean genotypes, Hwangkeum (determinate growth habit) and Muhan (indeterminate growth habit), were used to examine the influences of treatment stage and method of water deficit during reproductive growth period on yield and seed quality of soybean. Water deficit at R5 or R6 stages was as damaging to seed quality as double water-deficit treatments at R2+R5 or R2+R6. However, seed from double water-deficit treatment tended to have lower oxidation-reduction potential compare to the corresponding single water-deficit treatment. In comparison with Muhan, Hwangkeum had significantly greater oxidation-reduction potential value.

Seed yield per plant in both genotypes depended greatly on seed yield of branches. However, the proportion of number of branch seed to total seed number in Hwangkeum was increased as the water deficit was applied during later reproductive stage, whereas, in Muhan the proportion was lower. Water-deficit treatments including the single and double water-deficit treatments and non-stressed treatment were able to be classified into five groups for Hwangkeum and four groups for Muhan based on the influences on yield components, number of pod, number of seed, and single seed weight, using principal component analysis. In both genotypes, R2+R5 water-deficit treatment decreased number of pod and seed, but increased single seed weight. On the contrary, R6 or R2+R6 stress increased the pod and seed number, but decreased single seed weight.

Keywords : soybean, water deficit, yield, seed quality, oxidation-reduction potential, protein content, oil content, principal component analysis.

Water is a primary limiting factor to successful soybean [*Glycine max* (L.) Merr.] production, and water deficit often occurs in soybean production areas during critical periods of seed formation and filling. The magnitude of the seed yield reduction that occurs when soybeans experience a water stress is dependent upon the phenologic timing of that stress (Kim and Koh, 1997). The sensitivity of soybeans to water stress, when measured in terms of seed yield reduction, tends to increase as the crop advances through its natural sequence of growth and development, with minimal sensitivity during vegetative growth period but maximal sensitivity during pod and seed development (Doss et al., 1974; Ashley and Ethridge, 1978; Hill et al., 1979; Korte et al., 1983). This phenologic differential in soybean sensitivity to water stress appeared to be inversely related to the degree of compensation that may occur among the components of seed yield (Shaw and Laing, 1966). Such yield component compensation tends to minimize the adverse effect of the stress on ultimate seed yield (Shaw and Laing, 1966). However, the degree of compensation that can occur upon relief from a given water stress is governed by the yield components that can be adjusted subsequently to the stress, relative to the components already fixed prior to the stress.

The effect of water deficit on soybean yield has been well documented, with the overall conclusion that water deficit imposed during the reproductive stage is the most detrimental to yield. Within the soybean reproductive period, the seed enlargement stage seems to be more sensitive to water stress than the fore stages of either flowering or pod development.

Neyshabouri and Hatfield (1986) reported that semi-determinate soybeans responded more favorably to water stress imposed during the reproductive growth period because of the lack of competing sinks for photosynthate and would be more desirable in water-limited environment. Snyder et al. (1982) reported limiting soil water effects on yield in four indeterminate soybean cultivars with single and double periods of soil moisture stress treatments during reproductive stage. They observed that all the cultivars exhibited similar yield response to single periods of stress, and that preconditioning soybeans for later stress resulted in less yield reduction than if the plants were unconditioned.

The effects of water deficits on soybean seed size

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and quality may be influenced by morphological plant characteristics and the timing of water deficit. Recent evidence indicates that the reduction in seed size is due primarily to a shortening of the filling period rather than an inhibition of seed growth rate (Meckel et al., 1984; Schussler, 1986; Westgate et al., 1989). Since seed growth is dependent upon the supply of assimilates from the maternal plant (source activity) as well as the demand for assimilates within the zygotic tissue (sink activity), both maternal and zygotic factors may contribute to the maintenance of seed growth in water deficient plants.

Pod position also can influence the response of weight per seed to the application of supplemental water. Ramseur et al. (1984) found that irrigation resulted in greater seed number by increasing the number of branch pods. Subsequently, Wallace (1986) reported that irrigation increased weight per seed and pod number in the lower canopy branches compared with similar branches on non-irrigated plants. These results suggest that water availability interacts with pod position to determine weight per seed, thus pod position during a water deficit also may be an important factor in the determination of seed quality.

An occurrence of water deficit during early reproductive growth may increase flower and pod abortion (Korte et al., 1983), thus decreasing seed number and increasing seed weight. Heavy soybean seed can have an increased ability to germinate compared with light soybean seed (Burris et al., 1973). Suchorska (1990) noted that high oxidation-reduction potential was related to high germination capacity. Similar results were reported that increased leachate current or conductive of seed were observed by stressed treatment, which indicated seed may have impared membrane function during germination (Powell, 1986; Dornbos et al., 1989). In addition, Burris (1973) noted that well watered soybean plants with many pods may have lower quality seeds. Therefore, drought-induced variations in seed number and dry weight may influence the response of seed quality to subsequent drought stress.

Soybean frequently experiences water deficits during reproductive growth period, especially R5 to R6, in Korea. However, the response of soybean seed quality to water deficit has yet to be elucidated. The seed number, seed dry weight, and position of the seed during water deficit may affect seed quality. It was hypothesized that the decreased seed number by water deficit at the R2 stage would increase the quality of the remaining seed to later water deficits. Snyder et al. (1982) noted that soybean plants previously imposed by water-deficit at flowering as a preconditioning treatment had a smaller yield reduction from subsequent water deficit, compared with unconditioned plants. The objective of this study was to determine the effects of pod position and growth stage imposed and frequency of water deficit during reproductive growth period on soybean yield and seed quality.

MATERIALS AND METHODS

Cultural details

Two soybean genotypes, Hwangkeum (determinate growth habit with large seed) and Muhan (indeterminate growth habit with medium seed), were sown in June 12, 1998 in pots located inside a transparent vinyl shelter at the Upland Crop Experimental Farm of National Crop Experiment Station, Suwon, Korea. The pot was 28.0 cm deep with a diameter of 20.2 cm filled with soil, sand, and peatmoss mixture. Plants were thinned to one plant per pot at V3 growth stage.

At harvest, stem length, stem thickness and number of pods were determined. Pods were grouped by position on the plant; top one-third of main stem, bottom two-third of main stem, and branches. Seeds were manually shelled from the pods, and counted. After shattering, seeds were oven dried at 65℃ for 48h. Abnormal seeds, such as wrinkled, diseased, etched, discolored, and misshapened seed, were separated from each treatment batch. Only normal seeds were used for determinations of number of seeds, seed yield, single seed weight and its variation at each pod position, and seed quality.

To obtain the whole plant data, the counting data of pods and seeds, and dry weight data were summed over the three pod positions. Each seed on the three pod positions were weighed to calculate the coefficient of variation (CV) of seed size at a given position.

Water-deficit treatment

Water-deficit treatment consisted of single and double water-deficit treatments. For single water-deficit treatment, water deficit was imposed at the full pod (R4), seed formation (R5), and full seed (R6) stages as Fehr and Caviness (1977) suggested, in addition to a non-stressed treatment as control. For double water-deficit treatment, water deficit was imposed at flowering (R2) to decrease potential seed number, and subsequent water deficits were implemented at R4, R5, and R6 stages.

Water deficit was imposed by withholding water at the initiation of a water-deficit treatment. The water-deficit treatment was not irrigated until the plants reached the next growth stage. However, the R5 and R6 water-deficit treatments lasted for approximately 17 and 10 days, respectively, because of the lengthy duration of seed fill. The water-deficit treatments and their duration are listed in Table 1.

Table 1. Duration of different water-deficit treatments.

Stage of[†] treatment	Frequency	Method of treatment	Treatment duration (days)	
			Hwangkeum	Muhan
R2 (Control)	- -	Non-stressed R2[‡]	0 7	0 7
R4	Single Double	R4 R2 + R4	3 10 (7+3)	4 11 (7+4)
R5	Single Double	R5 R2 + R5	16 23 (7+16)	17 24 (7+17)
R6	Single Double	R6 R2 + R6	10 17 (7+10)	11 18 (7+11)

[†] R2; flowering, R4; full pod, R5; seed formation, R6; full seed.
[‡] R2 stage : Hwangkeum (Jul. 25), Muhan (Jul. 27)

Seed quality

After seed germination test for harvested seed, seed quality was determined by oxidation-reduction potential (Eh), seedling weight, and the protein and oil contents. Oxidation-reduction potential was determined with an ORP meter (RM-12P, TOA Elec. Ltd.) for seed quality testing. Ten normal seeds of each treatment were placed in test tube with distilled water and stored at room temperature for 48 hours. After seeds were removed, oxidation-reduction potentials of remaining water were recorded. Remaining seeds of each treatment were ground using miller, HEIKO Sample Mill (Mod. TI-100, Heiko Seisakusho Ltd.). Nitrogen content was measured by boric acid modification of Micro-Kjeldahl method, and used multiplied factor 6.25 to obtain the protein content as the method on Association of Official Analytical Chemists (1995). Oil content was determined by the Soxhlet method.

Experimental design and statistical analysis

The experiment was designed as a split-split-plot design with three replications. The main plot was genotype. The subplot was obtained by imposing water-deficit during flowering (R2), full pod (R4), seed formation (R5), or full seed (R6) stages of reproductive growth as Fehr and Caviness (1977) suggested. A non-stressed treatment was also included in the subplot treatments. The sub-subplot was method of water-deficit treatment, consists of single and double water-deficit treatments.

Collected data were analyzed using a SAS package and significant differences were based on the least significant difference ($P \leq 0.05$). Principal component analyses were performed to classify the effect of drought stress treatments on yield components, such as number of pod, number of seed, and single seed weight, for Hwangkeum and Muhan. Biplot were produced by plotting the principal component scores for drought stress treatments relative to the first two principal components, along with the eigenvector values of the first two principal components for the yield components that were strongly associated with those two principal components. All principal component analyses were performed with the PRIN procedure of SAS (1987).

RESULTS

Yield components and yield

Significant effects were observed for genotypes (G) and growth stage of treatment (S) on seed filling duration, number of seed per plant, single seed weight, and seed yield per plant, but there was non-significant for frequency of water-deficit treatment (F) on all traits. Non-significant interactions were found for all interactions among G, S, and F on all traits. Only the significant effects were discussed in detail, and the data were averaged over single and double water-deficit treatments because there was no significant difference between both of them.

Water deficit at R4 or R5 stage reduced number of seed by 24.6% and 31%, respectively, compared with the control. However, water deficit was imposed at R6 stage, the number of seed was similar to that of control (Table 2). Single seed weight was reduced by water-deficit treatment compared with the control, and the maximum reduction was observed in water-deficit treatment at R6 stage (Table 2).

Seed yield per plant was also reduced significantly at all water-deficit treatments compared with the control, but the difference between water-deficit treatments was not significant. The maximum yield reduction was observed in water-deficit treatment of

Table 2. Influences of imposed growth stage of water-deficit treatment on seed number, single seed weight, and seed yield in Hwangkeum (H) and Muhan (M).

Stage of treatment(S)	Genotype (G)	Seed number	Single seed weight	Seed yield
		plant^{-1}	mg seed^{-1}	g plant^{-1}
Control	H	39.9	309.5	12.5
	M	105.9	235.2	24.0
R4	H	35.3	298.0	10.7
	M	74.7	219.9	15.9
R5	H	28.6	269.8	8.0
	M	72.0	219.8	15.9
R6	H	44.1	258.8	10.7
	M	103.5	182.9	18.4
LSD$_{0.05}$[†]		7.0	34.5	3.5
LSD$_{0.05}$[‡]		17.2	12.9	4.2

[†] LSD is for comparison of means between genotypes, averaged over all stages of water-deficit treatment.

[‡] LSD is for comparison of means between stages of water-deficit treatment, averaged over all genotypes.

R5 stage, and the yield was 65.6% of control (Table 2).

Differences between two genotypes in single seed weight and its variation

Water deficit was imposed at flowering (R2) in an attempt to decrease seed number during later stages of reproductive growth. There was no significant reduction of seed number per plant by water-deficit treatment in Hwangkeum, but significant reduction of seed number was found in Muhan by R5 single water-deficit treatment and R2+R4 and R2+R5 double water-deficit treatments (Table 3). In Muhan, despite the decrease of seed number, the R2+R4 water-deficit treatment did not increase weight per seed compared with the single R4 water-deficit treatment. On the other hand, the R2+R5 water-deficit treatment had a similar weight per seed to non-stressed treatment and increased single seed weight compared with corresponding single R5 water-deficit treatment. This tendency was also observed in Hwangkeum (Table 3). The R6 and R2+R6 water-deficit treatments maintained similar number of seed to that of non-stressed treatment. However, weight per seed was remarkably decreased compared with any other

Table 3. Single seed weight and its variation of Hwangkeum (H) and Muhan (M) harvested at maturity according to method of water-deficit treatment.

Method of water-deficit treatment	Number of seed		Single seed wt.			
			Weight		CV	
	H	M	H	M	H	M
	plant^{-1}		mg seed^{-1}		%	
Non-stressed	42.1	115.7	316.6	231.5	10.4	10.2
R2	38.5	96.2	302.4	230.5	8.7	9.8
R4	31.7	89.1	307.9	227.8	8.8	7.8
R2+R4	39.0	60.3	287.2	212.0	11.4	10.4
R5	28.1	65.9	257.8	215.5	17.8	10.3
R2+R5	30.0	78.0	306.0	235.6	7.0	10.0
R6	44.7	104.9	257.8	186.2	13.3	12.8
R2+R6	43.5	102.1	259.8	179.5	13.4	16.0
LSD$_{0.05}$[†]	32.3		33.5		3.7	
LSD$_{0.05}$[‡]	30.8		33.0		3.2	

[†] LSD is comparison for method of water-deficit treatment within genotype.

[‡] LSD is comparison for genotype within method of water-deficit treatment.

water-deficit treatments (Table 3).

CV values obtained from individual seed weight on a whole plant basis were ranged from 7.0 to 17.8% for Hwangkeum, and 7.8 to 16.0% for Muhan (Table 3). The changes of CV values according to water-deficit treatment in both genotypes were similar. The maximum value was observed at R5 water-deficit treatment in Hwangkeum, and at R2+R6 double water-deficit treatment in Muhan (Table 3). Relationships between the variations of seed size and the single seed weight for over all water-deficit treatments in Hwangkeum and Muhan was illustrated at Fig. 1. Correlation coefficients for both genotypes were negative significant in Hwangkeum (r=-0.751**) and in Muhan (r=-0.661**).

Imposed growth stage of water deficit and pod position

Because the effect of the frequency of water-deficit treatment was not significant in ANOVA for the measured parameters, data presented for the interaction of imposed growth stage of water-deficit treatment by pod position were combined over single and double water-deficit treatments. Significant three-way ANOVA interaction among genotype, imposed growth stage of water-deficit treatment, and pod position were observed at the all measured parameters.

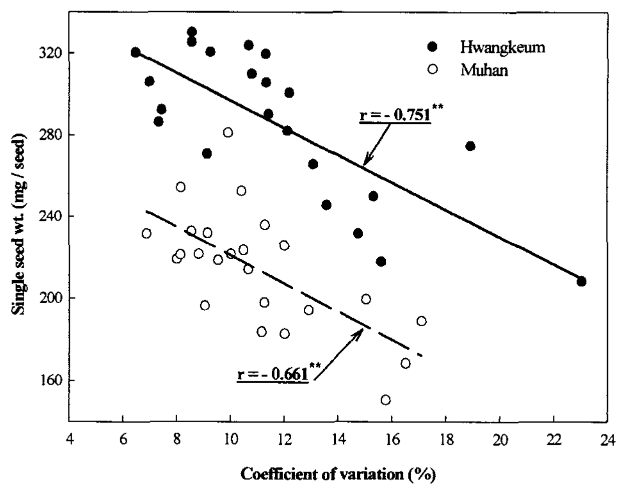

Fig. 1. Relationships between coefficient of variation for seed size and single seed weight, averaged over all water treatments in Hwangkeum and Muhan.

In Hwangkeum, the proportion of branch seed to total number of seed tended to increase compared with that of main stem when water-deficit was imposed at R5 or R6 stage. Especially, branch seed of R6 water-deficit plant had remarkably increased, and its proportion to total seed number were 63.3%. Con-

Table 4. Number of pod, number of seed, and seed yield by imposed growth stage of water-deficit treatment and pod position in Hwangkeum (H) and Muhan (M).

Stage of treatment	Pod position§	Number of pod		Number of seed		Seed yield	
		H	M	H	M	H	M
		plant^{-1}				g plant^{-1}	
Control	Top main	7.5	7.5	12.1	16.7	3.8	3.8
	Bottom main	7.6	3.9	12.8	9.5	4.1	2.3
	Branch	8.1	32.8	15.0	79.6	4.5	17.9
R4	Top main	5.4	6.6	10.0	14.6	3.0	3.1
	Bottom main	6.7	2.8	9.2	7.1	2.9	1.6
	Branch	7.7	27.0	16.1	53.1	4.8	11.2
R5	Top main	3.9	5.5	7.1	14.8	1.9	3.2
	Bottom main	5.3	3.5	9.4	8.3	2.8	2.0
	Branch	7.6	23.6	12.0	48.8	3.2	10.8
R6	Top main	3.4	10.8	6.3	28.3	1.7	5.1
	Bottom main	4.9	6.8	9.9	16.3	2.5	3.1
	Branch	14.3	23.0	27.9	58.9	6.5	10.2
LSD$_{0.05}$†		6.6		13.4		3.3	
LSD$_{0.05}$‡		7.3		15.8		3.9	

† LSD is for comparison of pod position within stages of water-deficit treatment.

‡ LSD is for comparison of stages of water-deficit treatment within pod position.

§ Top main; top one-third of main stem, Bottom main; bottom two-third of main stem.

Table 5. Oxidation-reduction potential (Eh) of soybean seed by imposed growth stage of water-deficit treatment and pod position.

Genotype	Pod position	Eh			
		Control	R4	R5	R6
		mV			
Hwangkeum	Top main	430	409	404	409
	Bottom main	422	410	404	410
	Branch	418	407	401	409
	$LSD_{0.05}$†	11.5			
	$LSD_{0.05}$‡	ns			
Muhan	Top main	404	401	400	405
	Bottom main	406	404	400	408
	Branch	404	401	399	401
	$LSD_{0.05}$†	ns			
	$LSD_{0.05}$‡	ns			

† LSD is for comparison of pod position within stages of water-deficit treatment.
‡ LSD is for comparison of stages of water-deficit treatment within pod position.

sequently, seed yield per plant in Hwangkeum depended greatly upon the seed yield of branches as the water deficit was applied during later reproductive growth period (Table 4).

In Muhan, the number of branch seed was significantly greater than that of any other positions in all treatment stages of water-deficit as well as control. Furthermore, the number of branch seed was greater than total seed number of main stem. However, the proportion of branch seed to total seed was getting lower as the water deficit was imposed during later reproductive growth, from 71.0% for R4 water-deficit treatment to 56.9% for R6 water-deficit treatment (Table 4). This results indicated that water-deficit treatment increased the proportion of main stem seed to total seed number in Muhan.

The canopy position of pods for control including R2 water-deficit treatment altered the expression of seed quality as estimated by oxidation-reduction potential, despite of the more nearly synchronous pod and seed development of a determinate soybean cultivar Hwangkeum. Although their oxidation-reduction potential was lower than that of control, there was no significant difference between pod positions within water-deficit treatments for R4, R5, and R6 stage (Table 5). In Muhan (indeterminate growth habit), there was not significant difference between treatment stages of water-deficit and between pod positions within a treatment stage of water-deficit (Table 5).

Seed quality

Reduction of seed quality by water deficit at R6 stage was not prevented by imposition of water deficit for R2 stage in Hwangkeum. Oxidationreduction potentials of R6 water-deficit seed was not decreased by double water-deficit treatment, compared with the corresponding single water-deficit treatment (Table 6). Oxidation-reduction potential was also decreased by double water deficit, compared with the corresponding single water-deficit treatment in Hwangkeum (Table 6). In Muhan, reductions of seed quality by R5 or R6 water deficits were not found by R2 water-deficit treatment (Table 6).

Protein contents of harvested seed in Hwangkeum was reduced by R4 or R5 single water-deficit treatment, but those of R4- or R5 water-deficit seed were not significantly different from their corresponding double water-deficit treatments by imposition of R2 water deficit. Significant difference was not found at R6 or R2+R6 water-deficit treatments, as compared to non-stressed and R2 water-deficit treatments. But in Muhan, double water-deficit treatments decreased protein content of seed, when compared to their corresponding single water-deficit treatments, such as R4, R5, and R6 (Table 6). On the other hand, oil contents of harvested seed in Hwangkeum and Muhan were increased by double water-deficit treatment, as compared to the corresponding single water-deficit treatment (Table 6).

Principal component analysis

Principal component analyses were performed to classify the effect of water-deficit treatments on yield components, number of pod, number of seed, and single seed weight. Eigen values of two principal components and their contributions to total variance

Table 6. Soybean seed quality in Hwangkeum (H) and Muhan (M) according to method of water-deficit treatment.

Method of water-deficit treatment	Eh[†]		Protein		Oil	
	H	M	H	M	H	M
	mV		%		%	
Non-stressed	431.0	406.9	34.7	37.5	18.7	18.7
R2	416.1	401.9	34.5	36.8	18.6	18.3
R4	409.7	400.2	33.2	34.5	18.3	19.7
R2 + R4	407.9	403.8	33.7	31.7	18.9	20.6
R5	408.9	401.4	32.6	36.4	18.6	18.8
R2 + R5	400.1	397.5	32.8	35.0	19.9	19.5
R6	408.0	404.3	34.7	36.5	18.4	18.3
R2 + R6	410.3	401.7	34.4	34.8	19.2	19.0
$LSD_{0.05}$[‡]	6.8	4.7	1.1	1.4	0.6	0.9

[†] Oxidation-reduction potential.

[‡] LSD is for comparison of method of water-deficit treatments within genotype.

Table 7. Eigen values of two principal components and their contributions to total variance computed from yield components, number of pod, number of seed, and single seed weight, for different method of water-deficit treatments in Hwangkeum and Muhan.

Genotype	Hwangkeum		Muhan	
Component[†]	PRIN1	PRIN2	PRIN1	PRIN2
Eigen value	1.77	0.97	1.96	1.01
Contribution (%)	58.9	32.4	65.3	33.6
Cumulative contribution (%)	58.9	91.3	65.3	98.9

[†] PRIN1 : 1st principal component, PRIN2 : 2nd principal component.

computed from measured yield components for different water-deficit treatments in Hwangkeum and Muhan were shown in Table 7. The first two principal components of the analysis of the water-deficit treatments accounted for 91.3% and 98.9% in Hwangkeum and Muhan, respectively. Eigen vectors of two principal components for Hwangkeum and Muhan indicated that the first principal component could be elucidated as characteristics which increased number of pod and seed but decreased seed weight, and the second principal component as a characteristic which increased single seed weight. Biplot analysis for Hwangkeum indicated that changing patterns of yield components, such as number of pod, number of seed, and single seed weight in water-deficit treatment were roughly classified into five groups (Fig. 2). R2+R5 double water-deficit treatment decreased pod number and seed number, and increased seed weight. On the contrary, Water deficits of R6 or R2+R6 stage increased the pod and seed number, but decreased single seed weight. Water deficit of R5 stage decreased all measured traits. Similarly, in Muhan, increased single seed weight and decreased pod and seed number were observed at R2+R5 water-deficit treatment, and water deficits of R6 or R2+R6 stage also decreased seed weight but increased pod and seed number(Fig. 2).

DISCUSSION

The response of soybean seed quality to water deficit has not yet been elucidated, but apparently it is negatively related to seed number and position of seeds on the plant. A plant with a small reproductive load (double water deficit) may be able to maintain seed quality to a greater extent under subsequently water-deficit than plants with a large reproductive load (single water deficit). In support of this view, Snyder et al. (1982) reported that preconditioned soybean plants were able to maintain yield by partitioning more assimilate to the seed. Therefore, in this experiment, water deficit at R2 stage decreased seed number and reduced reproductive load. However, number of seed from the double water-deficit treatments in this study was not significantly different as compared to the corresponding single water-deficit treatment (Table 3). This result was in agreement with the finding of Smiciklas et al. (1992). On the

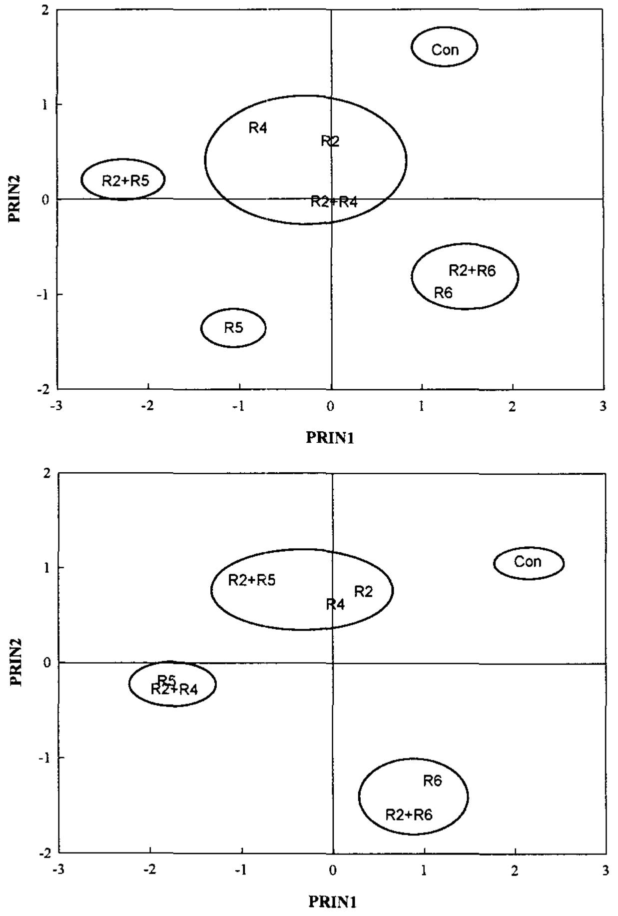

Fig. 2. Bi-plot the first two principal components from analysis of the yield components among water-deficit treatments in Hwangkeum and Muhan.

other hand, the significant difference between treatment stages of water-deficit for the number of seed was observed at R4 and R5 water-deficit treatment except for R6 drought stress treatment for all genotypes combined (Table 2).

Single seed weight tended to decrease significantly as water-deficit was imposed during later reproductive growth period, and its maximum reduction was observed at R6 water-deficit treatment resulted from shorter seed filling duration (Table 2 and 3). This result was well agreed with the conclusion of Shaw and Laing (1966) that the seed enlargement stage seems to be more sensitive to water stress than the prior stages of either flowering or pod development. Recent evidence also indicates that the reduction in seed size was due primarily to a shortening of the seed filling period (Meckel et al., 1984; Schussler, 1986; Westgate et al., 1989). Seed from the double water-deficit treatment, except for the R2+R6 treatment, in Hwangkeum had lower oxidation- reduction potential. It would suggest that those seeds might have impaired membrane function during germination (Powell, 1986; Smiciklas et al., 1992). In Muhan, reductions in seed quality at R5 or R6 water-deficit treatment were not found by the imposition of an R2 water deficit (Table 6). Seed protein content of Hwangkeum was reduced by R4 or R5 single water-deficit treatment, but there was no significant difference between single and double water-deficit treatments within the same treatment stage of water-deficit. Seed protein content in Muhan was increased when double water deficit was treated compared with the corresponding single water-deficit treatment. These difference would be due to their growth habit, determinate or indeterminate, and might require further study for alterations in the source-sink relationship according to water deficit. Since seed growth is dependent upon the supply of assimilates from the maternal plant (source) as well as the demand for assimilates within the zygotic tissue(sink), both maternal and zygotic factors may contributed to the maintenance of seed growth in water deficient plants (Westgate et al. 1989). Seed oil contents of both genotypes were increased by double water deficit, compared with the corresponding single water deficit (Table 6).

The canopy position of pods altered the seed yield response (Ramseur et al., 1984; Wallace, 1986). Seed yield per plant in both genotypes depended greatly upon seed yield of branches regardless water-deficit or non-stress treatment. This result corresponds with the conclusion of Ramseur et al. (1984) that more yield was contributed by branches than by main stem node. However, proportion of branch seed number to total seed number in Hwangkeum was increased as the water deficit was applied during later reproductive growth period, whereas, in Muhan, the proportion was getting lower (Table 4). The pod position altered the expression of seed quality trait (Gbikpi and Crookston, 1981), as estimated by oxidation-reduction potential, for the control including R2 water deficit treatment in Hwangkeum, despite the more nearly synchronous pod and seed development of a determinate soybean (Table 5). However, there was no significant difference between pod positions within water-deficit treatments of R4, R5, or R6 stages, even though their oxidation-reduction potentials were lower than that of control (Table 5 and 6). In Muhan (indeterminate growth habit), the significant difference for oxidation-reduction potential could not be observed in accordance with the water-deficit treatment and the pod position within a treatment stage of water deficit (Table 5 and 6). The decreased oxidation-reduction potential would suggest that these seeds might have impaired membrane function during germination. Suchorska (1990) noted that high oxidation-reduction potential was related to high germination capacity. Similar results were reported that increased leachate current or conductive of seed were observed by stressed treatment, which indicated seed may have impared membrane function during germination (Powell, 1986; Dornbos et al., 1989).

The influence of water-deficit treatment on yield components, such as number of seed, number of pod, and single seed weight, was classified into five groups for Hwangkeum and four groups for Muhan using principal component analysis. However, in both genotypes, R2+R5 water-deficit treatment decreased the number of pod and seed, but increased single seed weight. On the contrary, R6 or R2+R6 stress increased the pod and seed number, but decreased single seed weight (Fig. 2).

In conclusion, water deficit at R2 stage in double water-deficit treatment did not prevent reductions in seed quality and yield from occurring in subsequent water deficit. Water deficit at R5 or R6 stages was as damaging to seed quality as double water-deficit treatments as R2+R5 or R2+R6. In contrast with Muhan, pod position of control in Hwangkeum altered seed quality, despite the characteristics of more synchronous pod formation on a determinate soybean. Therefore, imposing stage of water deficit and pod position within the canopy as well as plant growth habit will be important considerations in estimating soybean seed quality.

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