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Effect of Plant Density on Growth and Sugar Yield of Sweet Sorghum in Jeju Island

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ABSTRACT : A sweet sorghum [*Sorghum bicolor* (L.) Moench] cultivar was planted on 9 and 30 June 2000 at plant densities of 4, 6, 8, 10, and 12 plants m^{-2} to determine the optimum plant density in Jeju region. There were no significant planting date × plant density interactions for most traits measured. Delaying planting from 9 to 30 June delayed 21 days in heading date, and significantly decreased plant height, the number of productive stems m^{-2}, and lodging. Fresh stem yield tended to be higher at the 9 June planting date than at the 30 June planting date, but total sugar and ethanol yields were not significantly affected by planting date. Percentage of soluble solid was higher at the 30 June planting date compared with the 9 June planting date. Fresh stem, total sugar, and ethanol yields quadractically increased from 22.9 to 36.7 t^{-1}, from 1.66 to 2.54 t^{-1}, and from 945 to 1440 L^{-1}, respectively, with increasing plant density. The optimal plant densities for the maximum fresh stem, total sugar, and ethanol were estimated to be 10.7, 9.6, and 9.9 plants m^{-2} respectively.

Keywords : sweet sorghum, planting date, plant density, growth, sugar yield, ethanol yield.

Korea is vulnerable to an energy crisis since almost 100% of oil supply depends on foreign countries. Our nation's dependence on foreign oil can be a serious threat to the economy, jobs and our standard of living when an oil crisis occurs. Approximately 40% of the cars in Brazil operate on 100% ethanol (Renewable Fuels Association, 2000). The remaining cars run on a blend of 22% ethanol (78% gasoline). The U.S.A uses ethanol in 12% of its fuel, mostly at a blend of 10% ethanol. In Brazil, sugar from sugarcane (*Saccharum officinarum* L.) is used to produce ethanol while maize (*Zea mays* L.) grain is currently the major source of ethanol from agricultural products in the USA (Smith *et al.*, 1987).

Sweet sorghum (sorgo) has been grown on small acreage for forage production or syrup in the world. Sweet sorghum was chewed up until 1960s in Korea. Experiments on sweet sorghum as a sugar crop were attempted from 1965 to 1969 (Kim *et al.*, 1995; Son, 1969). However, sweet sorghum as a sugar crop has not been grown commercially in Korea probably because of social and economic reasons.

Sorghum is adapted to a wide range of ecological conditions (Purseglove, 1985). It can tolerate hot and dry conditions, but can also be grown in areas with high rainfall in which waterlogging may occur. Sorghum produce a crop on soils too poor for many other crops. Sweet sorghum as the biomass for fuel oil has such advantages as its high productivity, cheap production cost, easy harvest and storage, and suitable ethanol production (Hoshikawa, 1981). However, Putnam *et al.* (1991) considered potential lodging losses, harvesting and transportation costs, and lack of extraction technologies as the major drawbacks to production of ethanol from sweet sorghum. The yield of ethanol from sweet sorghum has compared favorably with maize in the USA (Putnam *et al.*, 1991). Smith *et al.* (1987) confirmed its adaptability to a wide geographic area in the USA. Hoshikawa (1981) tested four sweet sorghum cultivars in Japan and reported that sweet sorghum appeared to be a suitable crop for ethanol production in Japan. Park & Lee (1991) grew sweet sorghum, sugarcane, and sugar beet (*Beta vulgaris* L.) in the southeastern region of Korea and found that sweet sorghum produced the highest fresh weight and could be most easily grown in the region. Sweet sorghum appears to be a promising crop for a source of ethanol from agricultural products in Korea.

Son (1969) reported that the optimal plant population of sweet sorghum for sugar production ranged from 17.7 to 22.2 plants m^{-2} in the central part of Korea when the branches developed from the lower parts of main stems were removed. Saheb (1997) grew sweet sorghum at 8, 10, and 12 plants m^{-2} in India and found that plant population of 12 plants m^{-2} gave higher fresh stem and juice yields. Optimum plant density may differ between cultivars of sweet sorghum and between locations. The objective of this study was to determine the optimum plant density of recently introduced 'Tamu Roma' sweet sorghum in Jeju region.

MATERIALS AND METHODS

A field study was conducted at the Research Farm of Col-

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Table 1. Chemical properties of top soil (0~10 cm) before the experiment.

pH (1 : 5)	Organic matter (g kg^{-1})	Available P_2O_5 (mg kg^{-1})	Exchangeable cation ($cmol^+ kg^{-1}$)				EC (dS m^{-1})
			Ca	Mg	K	Na	
5.40	83.6	195.4	0.32	0.16	0.45	0.06	0.73

lege of Agriculture, Cheju National University (33°27"20'N latitude, 277 m altitude) on volcanic ash soil during the 2000 summer growing season under rainfed conditions. Soil test values for surface soil (0 to 10 cm) before the experiment were shown in Table 1.

'Tamu Roma' were planted on 9 and 30 June on 60-cm rows with plant spaces of 41.7, 27.8, 20.8, 16.7, and 13.9 cm within a row to obtain plant densities of 4, 6, 8, 10, and 12 plants per m^2. Fertilizer as urea, fused phosphate, and potassium chloride, was applied prior to planting at a rate of 80-60-80 kg ha^{-1} (N-P_2O_5-K_2O). Nitrogen as urea was side-dressed at a rate of 40 kg ha^{-1} at the eight leaf stage. Weeds were controlled by hand weeding. Furathiocarb (Butyl 2, 3-dihydro-2, 2-dimethyl benzofuran-7-yl N, N'-dimethyl-N, N'-thiodicarbamate) at a rate of 0.1 a.i. ha^{-1} was incorporated on 8 August to control oriental corn borer (*Ostrinia furnacalis* Guenée).

Experimental units contained four rows with 3 m long (7.2 m^2). The experimental design was a split-plot arrangement in a randomized complete block with four replications. The main-plots consisted of two planting dates, and the sub-plots five plant densities.

Heading date was recorded as the date when 50% of plants had panicles extended from the boot. Almost all plants lodged because of the powerful typhoon Prapiroon which passed away on 31 September but some plants became upright thereafter. Many leaf blades were torn and some parts of the blades were lost by the typhoon. At harvest, all plots were rated visually for lodging from 0 to 9, with 0 meaning no lodging and 9 meaning all plant lodging.

On 28 November, estimates of fresh stem yield was determined by cutting all plants in 2 m from the two center rows, removing the panicles and leaves, and weighing stems. Eight stems were randomly selected from the yield samples of each plot and the middle 20 cm of the stems were weighed. The stem samples were squeezed with a small juice mixer (Model SJ-64, Sanyo Electric Co., Ltd., Japan) to collect a juice sample. Fermentable sugar content of this sample was measured using a hand-held digital refractometer (Model PR 101, Atago Co., Ltd., Japan) which measures percent soluble solids on the degrees Brix scale. Although this is not a precise estimate of fermentable carbohydrates,

Table 2. Air temperature and precipitation during the growing season of 2000 with the 11-year (1988~1998) average.

Month		Air temperature (°C)						Precipitation (mm)	
		2000			11-yr avg.				
		Max.	Min.	Mean	Max.	Min.	Mean	2000	11-yr avg.
June	Early	23.7	15.1	19.4	23.9	14.0	19.6	15.7	28.6
	Middle	24.6	16.0	20.2	25.0	16.9	20.9	30.2	77.0
	Late	26.5	20.0	22.8	25.6	18.9	22.1	51.7	87.1
July	Early	28.4	20.8	24.3	27.0	20.4	23.7	133.6	76.0
	Middle	30.2	22.3	26.3	29.4	22.6	26.0	2.1	36.0
	Late	31.1	23.0	27.0	30.1	23.0	26.3	30.5	62.4
Aug.	Early	30.4	22.0	25.8	29.9	23.3	26.7	1.7	60.3
	Middle	30.6	22.9	26.3	35.0	23.0	25.7	58.8	98.1
	Late	30.2	22.6	26.0	27.9	21.9	24.8	109.1	82.8
Sept.	Early	26.6	20.7	23.3	27.2	20.5	24.0	21.4	56.0
	Middle	21.9	16.7	19.4	25.0	18.8	21.9	288.5	27.1
	Late	24.0	17.7	19.7	23.1	17.2	20.2	21.6	65.8
Oct.	Early	23.2	15.5	19.0	21.5	14.6	18.2	63.5	12.6
	Middle	19.0	11.9	15.2	20.6	13.0	17.0	2.2	33.8
	Late	19.1	12.9	15.8	18.8	11.7	15.3	47.3	21.4
Nov.	Early	17.2	9.1	12.8	17.5	9.9	13.7	25.5	51.8
	Middle	13.9	7.8	10.6	14.3	9.6	12.2	53.9	19.9
	Late	13.0	4.0	8.2	12.2	6.9	9.72	13.8	33.3

only trace amounts of non-fermentable sugars or starches are usually found in stalk sap (Putman *et al.*, 1991). Total juice sugar yield was estimated by obtaining the product of the fresh stem yield × juice extraction % × Brix. Ethanol yields were calculated assuming 1.77 kg fermentable carbohydrate per liter of ethanol (Putman *et al.*, 1991).

Analysis of variance was used to test significant main effects and interactions. Single degree of freedom contrasts were tested for plant density effects and regression equations were developed on the basis of significant othogonal contrast.

Air temperature and precipitation were obtained from the Jeju Agricultural Experiment Station (4.1 km from the experimental site) and shown in Table 2. Temperatures during the growing season were similar to normal. Rainfall from mid-July to mid-October was not evenly distributed.

Table 3. Significance of analysis of variance for agronomic traits and fresh stem, juice, total sugar, and ethanol yields of sweet sorghum grown at two planting dates and five plant densities.

Source of variation	df	Days to heading	Plant height	Stem diameter	No. of tillers plant^{-1}			No. of productive stems m^{-2}
					Productive	Nonprod.	Total	
Planting date (P)	1	4928***	4514**	16.3	0.90**	0.016	1.12*	37.4**
Error a	3	21	27	2.1	0.01	0.005	0.03	0.4
Plant density (D)	4	219***	117	18.0***	0.49***	0.013	0.42***	51.6***
Linear	(1)	696***	188	70.3***	1.71***	0.005	1.60***	205.4***
Quadratic	(1)	116**	127	1.6	0.23**	0.036	0.08	0.3
Residual	(2)	31	77	0.0	0.01	0.005	0.00	0.3
P × D	4	35	90	1.0	0.06	0.064*	0.03	0.9
Error b	24	12	184	0.6	0.03	0.018	0.04	1.9

Source of variation	df	Lodging	Fresh stem yield	Extracted juice ratio	Soluble solid	Juice yield	Total sugar yield	Ethanol yield
Planting date (P)	1	129.6**	744.8	50.6	8.37*	93.3	1.06	361323
Error a	3	2.7	90.8	8.5	0.76	23.8	0.56	187811
Plant density (D)	4	2.6	234.6***	16.4	0.77	37.9***	1.06***	339003***
Linear	(1)	5.0	730.8***	50.6*	2.02	92.9***	2.70***	887216***
Quadratic	(1)	0.1	134.2**	3.6	0.29	34.8**	1.14**	352775**
Residual	(2)	2.6	36.7	5.7	0.39	12.0	0.21	58011
P × D	4	2.6	10.2	0.7	2.71	2.4	0.05	19104
Error b	24	1.5	11.5	9.6	1.31	3.5	0.08	30096

*, **, ***Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 4. Agronomic traits of sweet sorghum grown at two planting dates and five plant densities.

Treatment	Days to heading	Plant height (cm)	Stem diameter (mm)	No. of tillers plant^{-1}			No. of productive stems m^{-2}	Lodging[†]
				Productive	Nonprod.	Total		
Planting date								
9 June	122	268	20.6	0.48	0.17	0.65	11.0	5.1
30 June	100***	247**	19.3	0.18**	0.13	0.32*	9.1**	1.5**
Plant density (plants m^{-2})								
4	106	258	22.0	0.71	0.09	0.81	6.9	2.5
6	108	262	20.8	0.43	0.19	0.61	8.6	3.5
8	110	256	19.6	0.21	0.18	0.41	9.8	3.5
10	111	259	18.9	0.16	0.16	0.33	11.6	3.0
12	120	252	18.3	0.11	0.14	0.25	13.4	4.0
LSD(0.05)	4	NS	0.8	0.18	NS	0.20	1.4	NS

[†]Lodging at maturity was scored on a 1=upright to 9=prostrate.
*, **, ***Differences between planting dates are significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

RESULTS AND DISCUSSION

Summary of analysis of variance for traits measured are shown in Table 3. There were no significant planting date × plant density interactions for the traits except nonproductive tillers plant^{-1} which is a minor agronomic characteristic. Therefore, only the main effects of the treatments are presented in Table 4 and 5.

Days to heading, stem traits, and lodging

The number of days from planting to heading was 21 days greater for the 9 June planting date compared with the 30 June planting date (Table 4). The lower temperature in June might delay the heading for the 9 June planting date. Heading was quadratically delayed by increased plant density (Table 3, 4, and 6). The reason for this larger response is obscure. Increasing plant density generally retard plant development slightly (Dungan *et al.*, 1958).

Plant height (culm length of main stalk) was significantly affected by planting date but not by plant density. Plant height across plant densities was 21 cm taller for the 9 June planting date than for the 30 June planting date. When averaged across planting dates, plant height ranged from 252 to 262 cm at plant densities of 4 to 12 plants m^{-2}. However, there was no significant difference between plant densities for plant height because of a greater error probably due to the typhoon on 31 September. Lee *et al.* (1989) reported that plant height of sweet sorghum did not significantly decrease with delaying planting from 20 April to 20 June and observed no difference in plant height between 11.1 and 16.7 plants m^{-2}. Son (1969) also showed that plant height of sweet sorghum grown at 7.1 to 33.3 plants m^{-2} ranged from 242 to 253 cm but there was no relationship between plant height and plant density. Stem diameter tended to be greater for the 9 June planting date than for the 30 June planting date ($p<0.10$). Stem diameter linearly decreased with increasing plant density. This confirmed earlier findings of Son (1969).

The number of productive tillers and total tillers plant^{-1} was greater for the 9 June planting date than for the 30 June planting date and thus greater productive tillers plant^{-1} resulted in greater productive stems m^{-2} for the 9 June planting date. As plant density increased from 4 to 12 plants m^{-2}, productive and total tillers plant^{-1} significantly decreased from 0.71 to 0.11 and from 0.81 to 0.25, respectively, while productive stems per m^{-2} linearly increased from 6.9 to 13.4.

At harvest, plant lodging was significantly worse for the 9 June planting date than for the 30 June planting date because typhoon damage was more severe at the earlier planting but not was influenced by plant density. However, increasing plant density generally increase the likelihood of lodging (Dungan *et al.*, 1958). In this experiment, lodging was not associated with stem, juice, total sugar or ethanol yield within a planting date (data not shown).

Fresh stem yield and degrees Brix

Fresh stem yield tended to higher for the 9 June planting date compared with the 30 June planting date ($p<0.10$) (Table 5) because the number of productive tillers plant^{-1} was significantly higher at the 9 June planting date than at the 30 June planting date. Fresh stem yield quadractically increased from 22.9 to 36.7 t ha^{-1} as plant density increased from 4 to 12 plants m^{-2} because productive stems per m^{-2} linearly increased with increasing plant density [r^2=0.70 ($p<0.001$) and 0.60 ($p<0.01$) for the 6 and 30 June planting dates, respectively]. The optimal plant density for the maximum fresh stem yield was estimated to be 10.7 plants m^{-2} (Table 6).

Table 5. Extracted juice percentage, degrees Brix and fresh stem, juice, total sugar, and ethanol yields of sweet sorghum grown at two planting dates and five plant densities.

Treatment	Fresh stem (t ha^{-1})	Extracted juice (%)	Soluble solid (°Bx)	Juice (t ha^{-1})	Total sugar (t ha^{-1})	Ethanol (L ha^{-1})
Planting date						
9 June	36.5	43.5	15.71	15.8	2.47	1403
30 June	27.8	45.8	16.63*	12.8	2.15	1213
Plant density (plants m^{-2})						
4	22.9	45.7	15.85	10.5	1.66	945
6	32.6	45.9	15.85	15.1	2.39	1346
8	33.4	45.5	16.29	15.1	2.48	1401
10	35.2	43.1	16.56	15.1	2.48	1408
12	36.7	43.1	16.29	15.8	2.54	1440
LSD (0.05)	3.5	NS	NS	1.9	0.30	179

*Difference between planting dates is significant at the 0.05 probability level.

Table 6. Regression equations with coefficients of determination relating plant density and various agronomic traits and the calculated optimum plant density (plants m^{-2}) for fresh stem, juice, total sugar, and ethanol yields.

Variable	Regression equation	r^2 or R^2	Optimum plant density
Days to heading	$Y=111.6-2.164X+0.232X^2$	0.933	
Stem diameter	$Y=21.64-0.265X$	0.750	
No. of tillers plant^{-1}	$Y=1.058-0.07X$	0.982	
No. of productive tillers plant^{-1}	$Y=1.542-0.2535X+0.0113X^2$	0.994	
No. of productive stems m^{-2}	$Y=3.66+0.8X$	0.996	
Fresh stem yield	$Y=4.68+5.91X-0.275X^2$	0.923	10.7
Extracted juice	$Y=47.841-0.3975X$	0.771	
Juice yield	$Y=2.28+2.759X-0.139X^2$	0.837	9.9
Total sugar yield	$Y=0.14+0.501X-0.026X^2$	0.905	9.6
Ethanol yield	$Y=101.2+277.17X-14.036X^2$	0.914	9.9

Extracted juice percentage was slightly higher for the 30 June planting date compared with the 9 June planting date ($p<0.10$). Degrees Brix in extracted juice was significantly higher for the 30 June planting date than for the 9 June planting date. The higher extracted juice percentage and degrees Brix for the 30 June planting date might result from the healthier leaves developed after the typhoon because many leaves of the sorghum planted on 9 June were torn by the typhoon. Extracted juice percentage tended to decrease with increasing of plant density.

Juice, total sugar, and ethanol yields

Juice, total sugar, and ethanol yields were slightly higher at 9 June planting date than at 30 June planting date, but the differences between the two planting dates were not significant because fresh stem yield was higher at 9 June planting date while extracted juice percentage and degrees Brix were higher at 30 June planting date (Table 5). Ethanol yield was slightly lower in this study than in a previous study by Park & Lee (1991) who reported that 1800 L ha^{-1} of ethanol was obtained from a sweet sorghum hybrid grown in a southeastern part of Korea. Ethanol yields of fifteen sweet sorghum cultivars ranged from 1505 to 3893 L ha^{-1} in a southern Minnesota, USA (Putnam *et al.*, 1991). Theoretical ethanol production at eight locations in the continental USA ranged from 2129 to 5696 L ha^{-1} (Smith *et al.*, 1987).

Juice and total sugar yields quadractically increased from 10.5 to 15.8 and from 1.66 to 2.54 t ha^{-1}, respectively and ethanol yield from 945 to 1440 L ha^{-1} with increasing of plant density. The optimal plant densities for the maximum juice, total sugar, and ethanol were estimated to be 9.9, 9.6, and 9.9 plants m^{-2}, respectively (Table 6). The optimal plant population of sweet sorghum for sugar production in the central part of Korea was reported to be from 17.7 to 22.2 plants m^{-2} when the branches developed from the lower parts of main stem were removed (Son, 1969). Higher juice yield was obtained at 12 plants m^{-2} in India (Saheb, 1997). The optimum plant density for sweet sorghum appears to related with cultivar (plant size), available moisture, and soil fertility and radiation levels (Purseglove, 1985). The optimum plant density for 'Tamu Roma' sweet sorghum appears to be about 10 plants m^{-2} when grown in volcanic soils of Jeju region.

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