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Effects of Nitrogen Application on Sweet Sorghum (*Sorghum bicolor* (L.) Moench) in the Semi-Arid Tropical Zone of India

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Abstract

Sweet sorghum is a multipurpose crop that has great potential as a bioethanol crop. To make an appreciable profit from cultivating sweet sorghum in the semi-arid tropics (SAT), such agronomic practices as nutrient management need to be standardized. The objective of this study is to determine optimum nitrogen (N) rates for maximizing the grain and sugar yields of sweet sorghum during the rainy season in the Indian SAT. During the 2009 and 2010 seasons, the response of sweet sorghum being grown in an Alfisol to the application of six N rates (0, 30, 60, 90, 120, and 150 kg N ha^{-1}) was evaluated in Patancheru, Andhra Pradesh, India. The chlorophyll content (SPAD reading), cane fresh weight, and grain dry weight increased significantly in line with higher N rates. The volume of juice also increased significantly, although sugar content (brix reading) did not change in line with higher N rates, consequently resulting in a significant increase in sugar yield as computed from the volume of juice and sugar content. There were smaller differences due to N application during the season when soil fertility was at a medium level under high air temperature. Net income, as estimated from cane fresh weight and grain dry weight, increased at rates up to 90 kg N ha^{-1}, and higher N rates did not significantly affect productivity or income, but instead caused severe lodging in 150 kg N ha^{-1} at the harvest stage. Based on these results, an input of 90-120 kg N ha^{-1} could be recommended for maximizing sweet sorghum productivity and farmers' income in the SAT region of India.

Discipline: Biofuel/Crop production
Additional key words: Fertilizer management, grain yield, SPAD reading, sugar yield

Introduction

The soaring prices of fossil fuels recently have triggered the attention of policy makers toward exploring the use of alternative energy sources such as biofuels (e.g., biodiesel, bioethanol). Biofuel production from plant-based biomass is a possible alternative to non-renewable fossil energy sources[2]. The governments of certain developed and developing countries are making the blending of petrol with biofuels mandatory, as well as promoting biofuel usage by providing subsidies. For example in Brazil, which is considered the country having the world's first sustainable biofuels economy, the government authorized

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blending bioethanol in 1931 and mandated a blend of 18 to 25% bioethanol with petrol in 2011[6]. In India, where most agricultural areas are located in the semi-arid tropics (SAT) region[33], the government has approved the National Policy on Biofuels, which proposes blending biodiesel and bioethanol (20%) with diesel and petrol by 2017. Similar biofuel policies are being formulated in the USA, China, Columbia, Indonesia, and Argentina[15].

Maize (*Zea mays* L.) and sugarcane (*Saccharum officinarum* L.) are currently major raw materials used for bioethanol production. However, ethanol production from these materials risks aggravating the competition between biofuels and food, as maize grain and sugarcane juice can be used as food or to make biofuels. In addition, the large-scale production of these biofuel crops is generally expected to result in higher food prices. Rosegrant et al.[21] reported that aggressive biofuel growth would cause dramatic increases in world prices for such feedstock crops as maize and sugarcane.

Sweet sorghum (*Sorghum bicolor* (L.) Moench) is considered a promising bioethanol crop that could ease this conflict, as it produces a sugar-rich cane for ethanol production without hindering the production of grain used for food. In addition, sweet sorghum is characterized by its rapid growth with high biomass productivity, and its wide adaptability with a high drought tolerance. Given its high water use efficiency, sweet sorghum can be grown in dry or SAT regions across the world, and thus provide extra income to poor smallholder farmers.

For sweet sorghum to become a profitable crop in the SAT, its agronomic practices should be optimized to improve productivity and profitability, as well as breeding high-yielding varieties. Nitrogen (N) is the most important nutrient element, while sorghum is known to respond well to N fertilization. There are a number of studies reporting on the positive effects of N application on the yields of grain sorghum and forage sorghum × Sudan grass hybrid[3, 13]. In contrast, relatively few studies have been made regarding the effects of N on sweet sorghum productivity. Turgut et al.[30] investigated the optimum N input for maximizing sweet sorghum yield in a clay loam soil in coastal regions. Reddy et al.[19] also studied the effects of N input on sweet sorghum growth in Vertisols (Pellic Vertisol, FAO classification[7]; Typic Pellustert, USDA classification[27]). However, no applicable information is available regarding the optimum N input in Alfisols (Ferric Luvisol, FAO classification[7]; Udic Rhodustalf, USDA classification[27]) in the SAT. This study was mainly conducted to: 1) determine the optimum N rates for maximizing the grain and sugar yields of sweet sorghum in Alfisols during the rainy season in the Indian SAT, and 2) evaluate the economic benefits of N fertilizer input for sweet sorghum production.

Materials and methods

The study was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Patancheru (17.53 °N, 78.27 °E) near Hyderabad, India, during the rainy seasons (from June to October) in 2009 and 2010. Table 1 lists the soil type and selected chemical properties (at 0-15 cm depth) of the experimental site. It should be noted that two micronutrients — boron (B) and zinc (Zn) — are deficient in most of the Indian SAT, and are important factors affecting crop productivity[20, 24]. Groundnut (*Arachis hypogaea* L.) was the preceding crop at the experimental site in both years.

The experiment was arranged as a randomized complete block design with three replications and each plot measuring 6 × 10 m and 6 × 13 m in 2009 and 2010, respectively. CSH22SS[16] — a promising sweet sorghum hybrid in India — was sown using spacing of 60 cm between rows and 15 cm between plants on 16 June 2009 and 21 June 2010. Six rates of N (0, 30, 60, 90, 120, and 150 kg N ha^{-1}) were applied as urea fertilizer (46% N). These six treatments are hereinafter referred to as 0N, 30N, 60N, 90N, 120N, and 150N, respectively. For each N treatment except 0N, 15 kg N ha^{-1} was applied as basal, and the halves of remaining N were applied as the first and second topdressings at about 30 and 60 days after sowing (DAS), respectively. The other nutrients—phosphorous (P): 40 kg P_2O_5 ha^{-1}, sulfur (S): 200 kg gypsum ha^{-1}, B: 0.475 kg B

Table 1. Soil type and chemical properties of the experimental site

Properties	Year	
	2009	2010
Soil type	Alfisol[a)]	Alfisol
pH (H_2O)	7.9	8.0
EC (dS m^{-1})	0.22	0.37
Organic C (%)	0.64	0.50
Available P (ppm)[b)]	21.5	16.7
Exchangeable K (ppm)[c)]	98.0	119.5
Available B (ppm)[d)]	0.70	0.53
Available Zn (ppm)[e)]	3.83	2.10

a) 'Ferric Luvisol' and 'Udic Rhodustalf' in FAO and USDA classifications, respectively.
b) Tested by using the Olsen method.
c) Extracted by using ammonium acetate.
d) Extracted by using $CaCl_2$.
e) Extracted by using diethylene-triamine-pentaacetic acid (DTPA).

ha^{-1}, and Zn: 50 kg $ZnSO_4$ ha^{-1} — were uniformly applied to all the treatments in both years. Irrigation was done as furrow irrigation at 2, 10, and 42 DAS in the 2009 growing season, and at 3 DAS in the 2010 season.

The plant height of five random plants was recorded at weekly intervals. In addition, an average of SPAD readings at 10 points on the fully expanded uppermost leaves of the five plants was estimated by using a chlorophyll content meter (SPAD-502, Konica Minolta Sensing, Japan). The flowering and physiological maturity stages were defined as the date when the panicle and a seed black layer of 50% of the plants, respectively, were visible. The number of lodged plants was counted before harvesting to calculate the lodging percentage (i.e., number of lodged plants / total number of plants × 100). Sorghum plants were harvested at the physiological maturity stage from areas measuring 9.18 m^2 and 6.48 m^2 in 2009 and 2010, respectively. Twelve plants were randomly selected from among the harvested samples, and the total weight and grain dry weight were recorded after drying at 60℃ for more than 120 h. The leaves of the remaining harvested samples were also stripped, in order to measure cane fresh weight, juice volume, and sugar content (brix reading). The juice was extracted by using a common sugar cane crusher. The brix was measured by using a hand-held refractometer (Master-α, Atago, Japan). Sugar yield was estimated according to Equation (1) below, as reported by Reddy et al.[17]

Sugar yield (t ha^{-1}) = {(brix (%) × 0.8746) + 0.1516} /100 × juice volume (kl ha^{-1}) ------ (1)

A partial budget analysis was conducted to evaluate the economic benefits of N fertilizer input for sweet sorghum production. This analysis can also be applied to analyze the impact of a small production system change on farmers' income[26, 29]. We considered the price of urea fertilizer as an additional expense, and the prices of grain and cane as additional revenue through N fertilizer input. We also assumed that the expenses incurred in other agricultural practices (e.g., irrigation, use of herbicides/insecticides) were the same among all N treatments. The prices of urea fertilizer, grain, and cane in the Indian rupee (Rs.) were used for Rs. 5 kg^{-1}, Rs. 7 kg^{-1} dry weight, and Rs. 0.6 kg^{-1} fresh weight, respectively, according to prevailing market prices in India during the 2010 season.

Statistical analysis was conducted using SPSS software (version 14.0J, SPSS Japan). Analysis of variance (ANOVA) was conducted by using a combined model[11]. The year and treatment were treated as fixed factors, with replication being a random factor. The differences between treatments were tested by the least significant difference at a 5% level of probability when ANOVA was significant. Correlation coefficients between the variables were calculated using the Pearson product-moment method.

Results

1. Meteorological data

Figure 1 shows the cumulative precipitation and thermal time during the growing seasons in 2009 and 2010. The thermal time was calculated by assuming 10℃ as the base temperature for sorghum growth[14]. The 2009 season was characterized by a relatively higher thermal time during the growing season and a shortage of rainfall at the early growth stage. The thermal time at 120 DAS was ca. 135℃·day higher in 2009 than the average from 1974 to 2010 (data not shown). Although furrow irrigation was done three times during the dry spells, the sorghum plants exhibited such drought stress symptoms as leaf rolling in 2009. Heavy rain (having a maximum value of 121.5 mm day^{-1}) after 60 DAS resulted in 829.7 mm of total cumulative precipitation at up to 120 DAS. Well-distributed rainfall was also received during the growing season in 2010, with 867.1 mm of cumulative precipitation at up to 120

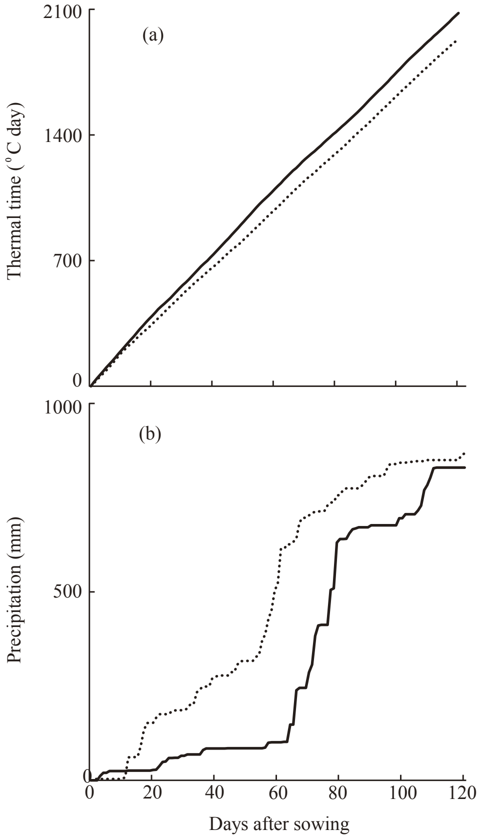

Fig. 1. Cumulative thermal time (a) and precipitation (b) during the 2009 and 2010 growing seasons at the experimental site

Thermal time was calculated by assuming 10℃ as the base temperature for sorghum growth The solid and dashed lines denote 2009 and2010, respectively.

DAS. No drought stress symptoms were observed during the 2010 growing season.

2. Growth stage

Table 2 lists the dates of flowering and physiological maturity, and the grain filling period. The dates of flowering and physiological maturity were significantly delayed in 2009 as compared to 2010, and also delayed more in lower N treatments than in higher N treatments. A significant interaction between the year and treatment indicates larger differences between treatments in 2010 than in 2009 for both the flowering and physiological maturity stages. In particular, both growth stages were markedly delayed in 0N than in the other treatments during the 2010 growing season. The grain filling period did not differ significantly between the six treatments for both years.

Table 2. Days to flowering, physiological maturity, and grain filling period during the 2009 and 2010 growing seasons

Year	Treatment	50% Flowering (DAS[a)])	Physiological Maturity (DAS)	Grain Filling Period (days)
2009	0N	92	119	27
	30N	91	119	28
	60N	90	119	29
	90N	89	117	28
	120N	88	116	28
	150N	88	116	28
	Mean	90	117	28
	LSD	3	1	NS
2010	0N	96	125	28
	30N	88	117	29
	60N	85	113	27
	90N	83	111	29
	120N	82	109	27
	150N	81	109	28
	Mean	86	114	28
	LSD	2	4	NS
ANOVA				
	Year (Y)	*	*	NS
	Treatment (T)	***	***	NS
	Y × T	***	***	NS

a) Acronyms: DAS: days after sowing; LSD: least significant difference ($p = 0.05$); NS: not significant
(Note that *** denotes significance at a probability level of 0.001; * denotes significance at a probability level of 0.05.)

3. Plant height

Figure 2 shows the plant height data on sweet sorghum during the 2009 and 2010 growing seasons. In the 2009 season, although the difference between treatments was not large, plant height tended to be higher in 90N to 150N than in the other treatments. In the 2010 season, a significantly large difference between treatments was observed from the early growth stage. The plant height was significantly lower in 0N as compared to other treatments throughout the growing season (except at 35 DAS), and was significantly higher in 90N to 150N than in 30N to 60N at 57 DAS. Plant height in 0N was also significantly lower before the first topdressing in 2010 but not in 2009, thus suggesting a significant effect of basal N only being applied during the growing season in 2010.

When analyzing plant height at the physiological maturity stage, the interaction between the year and treatment was significant ($p < 0.05$), in that plant height was higher in 2009 than in 2010 for 0N to 60N, but did not differ between both years for 90N to 150N.

4. SPAD reading

The SPAD value was significantly higher in 90N to 150N than in 0N to 60N after 48 DAS in 2009 and after 42 DAS in 2010 (Fig. 3). When comparing SPAD readings among 90N to 150N, there was no significant difference throughout the growing season in both years. There was a slight fluctuation in SPAD reading during the growing season in 2009, but a large one in 2010, thereby meaning a gradually higher SPAD reading as plant growth progressed in the 2010 growing season.

5. Lodging percentage, grain dry weight, and cane fresh weight

Lodging was only observed in the 2009 season (Table 3). Sorghum plants were severely lodged by heavy rain accompanied by strong winds after 60 DAS in the 2009 growing season. In particular, more than 60% of the plants were lodged in 150N treatment due to higher plant height and grain weight. Both grain dry weight and cane fresh weight were significantly higher in 2010 than in 2009, while total dry weight did not differ significantly between both years. The main effect of treatment was significant for total dry weight, grain dry weight, and cane fresh weight in that all were higher in 90N to 150N than in 0N to 60N. A significant interaction between the year and treatment for total dry weight and cane fresh weight suggests that dry weights differed more between treatments in 2010 than in 2009. These trends in total dry weight were in agreement with SPAD reading trends: SPAD readings from 48 to 100 DAS (Fig. 3) correlated significantly with total dry weight at the physiological maturity stage (high-

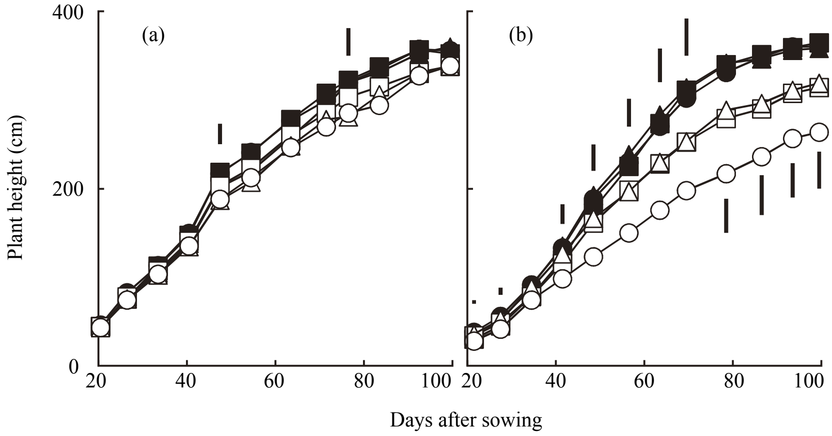

Fig. 2. Plant height during the 2009 (a) and 2010 (b) growing seasons

Vertical bars denote the least significant difference (p = 0.05) between treatments (○: 0N; △: 30N; □: 60N; ●: 90N; ▲: 120N; ■: 150N).

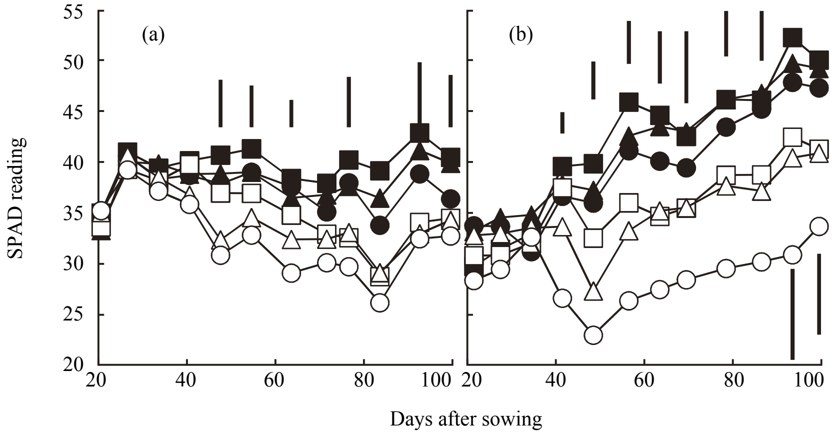

Fig. 3. SPAD reading values during the 2009 (a) and 2010 (b) growing seasons

Vertical bars denote the least significant difference (p = 0.05) between treatments (○: 0N; △: 30N; □: 60N; ●: 90N; ▲: 120N; ■: 150N).

est coefficient: r = 0.98 at 70 DAS; lowest coefficient: r = 0.64 at 48 DAS, n = 12).

6. Juice volume, brix, and sugar yield

Both juice volume and brix are important parameters used to estimate sugar yield. Although brix did not differ significantly between the years or treatments, the juice volume differed significantly between both years and treatments (Table 3). Specifically, it was significantly higher in 2010 than in 2009, and higher in 90N to 150N than in 0N to 60N. A significant interaction between the year and treatment for juice volume showed that the volume of juice between treatments differed more widely in 2010 than in 2009. These trends in juice volume corresponded to those for cane fresh weight, in that a correlation between juice volume and cane fresh weight was significant at $p < 0.001$ (r = 0.97, n = 12).

The main effects of the year/treatment and associated

Table 3. Lodging percentage, yield components, and income increase by harvesting sweet sorghum at the physiological maturity stage

Year	Treatment	Lodging (%)	Total DW[a)] (t/ha)	Grain DW (t/ha)	Cane FW (t/ha)	Juice Volume (kl/ha)	Brix (ºBx)	Sugar Yield (t/ha)	Income Increase (Rs./ha)
2009	0N	13.3	13.0	1.3	32.8	11.6	14.0	1.4	—
	30N	16.7	13.8	1.6	34.0	11.3	14.3	1.4	2627
	60N	26.7	15.1	1.8	37.4	13.8	13.9	1.7	5623
	90N	30.0	16.4	2.5	38.5	16.0	14.7	2.1	11321
	120N	36.7	16.3	2.4	39.2	15.7	13.7	1.9	10334
	150N	63.3	18.3	2.6	39.3	16.0	14.7	2.1	11662
	Mean	31.1	15.5	2.0	36.9	14.1	14.2	1.8	8313
	LSD	30.7	2.7	0.9	NS	3.9	NS	0.5	NS
2010	0N	0.0	12.8	1.1	27.5	7.2	13.3	0.8	—
	30N	0.0	16.0	2.6	43.4	17.3	13.4	2.1	19771
	60N	0.0	16.6	2.9	43.9	17.0	14.3	2.1	21824
	90N	0.0	20.0	3.2	53.4	21.3	14.5	2.7	29053
	120N	0.0	22.3	3.8	61.1	22.7	15.2	3.0	37851
	150N	0.0	22.2	3.9	58.7	22.7	14.8	3.0	36843
	Mean	0.0	18.3	2.9	48.0	18.0	14.2	2.3	29068
	LSD	NS	2.8	1.2	1.6	3.8	NS	0.5	12885
ANOVA									
	Year (Y)	**	NS	**	*	**	NS	**	**
	Treatment (T)	*	***	***	***	***	NS	***	**
	Y × T	*	*	NS	***	**	NS	***	NS

a) Acronyms: DW: dry weight; FW: fresh weight; LSD: least significant difference (p=0.05); NS: not significant; Rs.: rupee (Indian currency)
(Note that *** denotes significance at a probability level of 0.001; ** denotes significance at a probability level of 0.01; * denotes significance at probability level of 0.05.)

interaction were significant for sugar yield, which was significantly higher in 2010 than in 2009, and higher in 90N to 150N than in 0N to 60N, and with a larger difference between treatments in 2010 than in 2009. A stepwise multiple regression analysis, where sugar yield was treated as a dependent variable while juice volume and brix were treated as independent variables, indicated that the relative importance of independent variables in the regression (sugar yield = 0.129 × juice volume + 0.124 × brix – 1.805, $R^2 = 0.998$, $p < 0.001$, $n = 12$) was higher for juice volume (standardized coefficient $\beta = 0.921$) than for brix ($\beta = 0.110$).

7. Increase in income

The net income calculated by partial budget analysis increased in line with the increase in N input as compared to 0N (Table 3). Although not statistically significant in 2009, net income tended to increase up to 90N, but with almost no change from 90N to 150N. And as grain dry weight and cane fresh weight were markedly lower in 0N than in the other treatments in 2010, net income increased considerably with N input. Though it increased drastically up to 120N, net income showed no change from 120N to 150N. The two-year average of net income increased significantly up to 90N, but there was no significant difference in income among 90N, 120N and 150N treatments (statistical data not shown).

Discussion

1. Effect of N input on sweet sorghum growth stage

Environmental stress as in the form of low soil fertility and water content generally delays the onset of the reproductive stage. In the present study, the flowering stage was delayed as N input decreased in both years (Table 2). These results agree with those obtained by Muchow[12], who reported that low N input delayed the growth development of sorghum. The significant delay in the flowering stage in 2009 as compared to 2010 might have been mainly caused by drought stress at the early growth stage in 2009 (Fig. 1 (b)). Manjarrez-Sandoval et al.[10] also reported that drought stress increased the days to flowering in sorghum.

Although a significant effect of environmental stress on the onset of the reproductive stage was observed as described above, some studies have reported the non-significant effects of such stress on the grain filling period. Muchow[13] investigated the effect of N input on the grain filling period of maize and sorghum, and reported that the period increased in line with increasing N input in maize, but not in sorghum. The present study also found that the grain filling period did not differ significantly with either low N input or drought stress at the early growth stage.

2. Effect of N input on sweet sorghum productivity

The growth of sorghum plants was poor without N input (i.e., 0N) in both years (Table 3, Fig. 2). In particular, plant height in 0N was markedly lower in 2010 than in 2009. In addition, a significant effect of basal N application on plant height was only observed in 2010. Soil fertility may be one reason causing these differences in plant growth. According to the soil fertility guidelines observed by ICRISAT[9], soil organic carbon (Table 1) was categorized as being medium in 2009 and low in 2010, indicating higher soil general fertility in 2009 than in 2010. Soil organic matter easily and rapidly mineralizes due to the rewetting caused by rain and/or irrigation[4] after a long dry period of the post-rainy season. Moreover, higher temperatures in 2009 than in 2010 (Fig. 1) might have stimulated the mineralization rate, which is highly correlated to temperature. It is thus likely that the higher soil organic matter and temperature resulted in higher N mineralization in 2009 than in 2010. Therefore, the sorghum plants could have taken up sufficient amounts of mineralized N during early growth even without N input in 2009, thereby affecting the effect of basal N application and achieving better plant growth in 0N in 2009 than in 2010.

Higher precipitation in 2010 (Fig. 1) is considered another reason causing the differences in plant growth in both years. Since Alfisol contains a high ratio of sand and has low water holding capacity[23], water may easily penetrate down through the soil. A high amount of mineralized N may have been carried away with rainfall and lost from the root zone of sweet sorghum in 2010, resulting in N deficiency and poor plant growth in low N input treatments in 2010. However, the fact that there is no direct evidence to support these hypotheses cannot be disregarded, and thus further investigation is necessary to address these issues in detail.

A SPAD reading that correlated strongly with dry matter production (Fig. 3, Table 3) and the leaf N concentration in sweet sorghum[31] was used as an indicator to decide the timing of fertilizer topdressing for satisfying the crop demand for N and minimizing N loss in the crop cultivation systems[5, 32]. In the present study, it was difficult to define a fixed SPAD reading for the timing of fertilizer topdressing due to the different trends in SPAD readings during the growing seasons in both years (Fig. 3). A SPAD reading of 35 may be used as a rough index for the timing of N topdressing, however, as SPAD readings in 90N to 150N were not below the SPAD reading of 35 after 30 DAS in both years (Fig. 3).

The present study indicated that N input increased both grain and sugar yields, with higher sugar yield being attributed to a significant increase in the juice volume and constant brix values as N input increased. These results are well supported by the results reported by Almodares et al.[1] and Reddy et al.[19], who reported that the juice volume of sweet sorghum (but not brix) increased with N input. Saheb et al.[22] also reported a non-significant effect of N input on brix of sorghum. Therefore, both juice volume and cane fresh weight (which correlates to juice volume) must be increased by increasing N input, in order to achieve a high sugar yield in sweet sorghum during the rainy season. Note that brix can also be improved through a breeding program as large variations have been reported in brix between sorghum germplasm[1, 16, 18, 19].

Grain and sugar yields increased significantly up to 90N in both years, and excess amounts of N (i.e., 150N) resulted in severe lodging when sorghum plants were exposed to heavy rain and strong winds (Table 3). These results indicate that N input of 90-120 kg N ha^{-1} is sufficient to obtain maximum grain and sugar yields, while the further application of N fertilizer poses a risk of having negative effects on sweet sorghum production. Turgut et al.[30] observed similar results and reported that the yield of sweet sorghum increased at up to 100 kg N ha^{-1}, but decreased when 200 kg N ha^{-1} was applied under a Mediterranean-type climate in the coastal region of Turkey. Sumantri & Lestari[28] also reported that the millable stalk yield of sweet sorghum increased at up to 90 kg N ha^{-1} but not from 90 to 120 kg N ha^{-1}. The N inputs in those two past studies and in our study are slightly higher than in the study conducted by Reddy et al.[19], who reported that 64 kg N ha^{-1} was sufficient to obtain the maximum sugar yield of sweet sorghum. When considering the reason for the discrepancy between our study and the report by Reddy et al.[19], the latter study used Vertisols, a type of clay-rich soil that has higher soil fertility and water holding capacity than those of Alfisols[23]. Holou & Stevens[8] also reported different effects of N input on the sugar yield of sweet sorghum according to soil type, where N fertilization always increased the sugar yield in clay soil but not in silt loam. Therefore, further studies are needed to reveal the effects of soil type on optimum N input for sweet sorghum, and determine the optimum level of N input in consideration of soil type as well as soil fertility.

A partial budget analysis implied that increasing N input will increase farmers' income considerably (Table 3) as a result of significantly increased grain and sugar yields. This means that sweet sorghum production with optimum N input offers great potential in providing economic benefits to poor rural farmers in the SAT.

Conclusions

Our two-year study revealed that N input had positive effects on both grain and sugar yields that represent major sources of income for farmers growing sweet sorghum in the SAT, but that the application of N at relatively higher rates had negative effects, including severe lodging of the plants. Although a significant effect of basal N application on growth was only observed in one of the two years, total N input of 90-120 kg N ha^{-1} with split application could be recommended for maximizing sweet sorghum productivity and farmers' income. The application of N at rates higher than optimum might result in surface and ground water being contaminated with nitrates, especially in such light texture soils as Alfisols in the SAT[25]. Therefore, it is important to optimize N input for the sustainable production of sweet sorghum, in considering the impact of N input not only on productivity but also on the environment.

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