Australian Journal of Crop Science AJCS

AJCS 8(12):1663-1670 (2014) ISSN:1835-2707

Mineral gypsum ($CaSO_4.2H_2O$), a promoter of biomass production of sweet sorghum

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Abstract

The sweet sorghum is an alternative bioenergy crop for ethanol production in the off-season of sugarcane in areas where crops are renewed in winter, especially in the Northeast of Brazil. However, in these areas the soil acidity and low levels of basic cations on the subsurface are responsible for reduced productivity of sorghum. The objective of this study was to evaluate the effect of mineral gypsum on nutrients uptake, agricultural/ industrial productivity and production of ethanol from sweet sorghum cultivar IPA 467-4-2. Therefore, a field experiment was set up in Ultisol (Argissolo Amarelo distrocoeso), arranged in randomized blocks, consisting of five treatments as: 0, 2, 4, 6 and 8 Mg ha^{-1} (ton/ha^{-1}) of mineral gypsum in four replications. Results showed that mineral gypsum can promote the percentage and Ca^{2+} content and, conversely, reduce percentage and K^+ content in shoots of sorghum. The gypsum application increased yield of fresh and dry mass of sweet sorghum, variety IPA 467-4-2, besides increasing the theoretical yield of ethanol. The maximum yield of fresh, dry mass and ethanol were 44373.64 kg ha^{-1}, 9056.43 kg ha^{-1} and 2032.18 L ha^{-1}, respectively. The recommended dose of maximum agronomic efficiency was approximately 5.5 Mg ha^{-1}, suggesting gypsum as a raw material in appropriate management of sweet sorghum, especially in soils with high acidity in the subsurface

Keywords: *Sorghum bicolor* Moench, subsurface acidity, nutrient uptake, bioenergy.

Abbreviations: Ca^{2+}_Calcium; Mg^{2+}_Magnesium; K^+_Potassium; P-$H_2PO_4^-$_Phosphorus; S-SO_4^{2-}_Sulphate; N-NH_4^+_Nitrogen; RSbro_reducing sugars in the broth; POL_ percentage of sucrose in solution; TRdS_total reducing sugars; TRcS_total recoverable sugars; Fiber_sorghum industrial fiber; BP_broth purity; PC_ percentage of sorghum POL; Mg ha^{-1}_ ton/ ha^{-1}.

Introduction

Producing energy from agricultural crops has been subject of several studies in recent years (Ragauskas et al., 2006; Zhao et al., 2009; Lavanya et al., 2012). The main goal is to mitigate the greenhouse gases and safety of petroleum energy which exhaust in the near future (Demirbas, 2008). Among the various bioenergy crops such as maize, castor, soybean, sugar beet and sugarcane (Oliveira et al., 2007; Demirbas, 2008; Lavanya et al., 2012), sweet sorghum has been highlighted (Almodares and Hadi, 2009; Guigou et al., 2011; Vasilakoglou et al., 2011). Due to the low yields and the growing demand for biomass energy, the areas allocated to the bioenergy crops, especially in tropical countries, have been expanded, promoting risk of biodiversity loss in these environments (Phalan et al., 2013).

The sweet sorghum can be used as raw material complementary to sugarcane for ethanol production, especially in areas where sugarcane is renewed in winter (May et al., 2011). In many areas, the renewal of sugarcane lands lets up to six months of the year without use. This would be sufficient time for growing a crop of sweet sorghum. Approximately 8.65% of cultivated areas with sugarcane in northeastern Brazil are renewed annually, which corresponds to approximately 96,200 hectares in 2013/14 harvest (CONAB, 2013). Thus, planting of these areas/lands, including sweet sorghum can be used without significant industrial settings in the industrial process for ethanol production. In much of these areas, sorghum can be used for ethanol production, while sugarcane crops are not cultured due to existing soils with high acidity in both surface and subsurface.

Despite sweet sorghum having good yield capacity in acid soils with low fertility (Almodares and Hadi, 2009; Vasilakoglou et al., 2011), its maximum agronomic potential is achieved only with adequate acidity and maximum nutrients availability (Coelho, 2011). In acidic soils major chemical characteristics that impair plant growth correspond to the high concentration of Al^{3+} and low concentration of Ca^{2+} (Sousa et al., 2007), both on surface and subsurface. The surface acidity can be managed with the use of limestone, as widely discussed in the literature (Carvalho and Raij, 1997; Caires et al., 2006b; Soratto and Crusciol, 2008). In deeper soil layers, the most used type of management, especially when it aims at reducing the Al^{3+} and increasing the Ca^{2+} on the subsurface, corresponds to gypsum application (Carvalho and Raij, 1997; Saldanha et al., 2007; Li et al., 2010; Reyes-Díaz et al., 2011).

Some studies showed increased yield of maize, sugarcane and soybeans due to the application of gypsum (Caires et al., 2004; Fernandes et al., 2007; Caires et al., 2011). However, researches showing the gypsum effect on sorghum and ethanol yields are scarce. Therefore, this work aimed to evaluating the effect of mineral gypsum on the nutrient uptake, agricultural/industrial yield and production of ethanol from sweet sorghum grown on acid Ultisol in the Zona da Mata of Pernambuco, Brazil.

Results and Discussion

Nutrient uptake of sorghum was affected by rates of gypsum. On average, sweet sorghum extracted 55.04 kg ha^{-1} $N\text{-}NH_4^+$; 32.01 kg ha^{-1} $P\text{-}H_2PO_4^-$; 104.99 kg ha^{-1} K^+; 21.32 kg ha^{-1} Ca^{2+}; 24.58 kg ha^{-1} Mg^{2+}; and 34.14 kg ha^{-1} $S\text{-}SO_4^{2-}$ (Table 1). The maximum yield of sorghum was about 45 t ha^{-1} (Fig. 1A), where the nutritional requirement was 1.22 kg t^{-1} $N\text{-}NH_4^+$, 0.71 kg t^{-1} $P\text{-}H_2PO_4^-$, 2.33 kg t^{-1} K^+, 0.47 kg t^{-1} Ca^{2+}, 0.55 kg t^{-1} Mg2+, and 0.76 kg t^{-1} $S\text{-}SO_4^{-2}$. It shows that sweet sorghum is very demanding on N and K, as reported by Coelho (2011). Rosolem and Malavolta (1981), mentioned demands of nutrients in sorghum as 3.9, 0.45, and 4.4 kg t^{-1} $N\text{-}NH_4^+$, $P\text{-}H_2PO_4^-$ and K^+ for yields of 60 Mg ha^{-1}, respectively. Although the production level reported by Rosolem and Malavolta (1981) was higher than observed in this work, there is reduction in the demand for $N\text{-}NH_4^+$ and K^+ and increase in $P\text{-}H_2PO_4^-$. Santi et al. (2006) stated that the elements that most limited the sorghum growth were Ca^{2+}, Mg^{2+} and $N\text{-}NH_4^+$. We suggest that the $N\text{-}NH_4^+$ nutrition might be responsible for the lower sorghum yield (45 t ha^{-1}), compared to 60 Mg ha^{-1} which reported by Rosolem and Malavolta (1981). Percentages and contents of Ca^{2+} and K^+ in the shoots of sweet sorghum in the late crop cycle were influenced by mineral gypsum (Table 1 and Fig. 2A, B, C and D). The gypsum application improves the absorption of water and nutrients in different cultures, in particular K^+, $N\text{-}NH_4^+$, $P\text{-}H_2PO_4^-$, Ca^{2+}, $S\text{-}SO_4^{2-}$, and increase the yields (Carvalho and Raij, 1997; Caires et al., 2001a; Fernandes et al., 2007; Rasouli et al., 2013). Increased Ca^{2+} extraction by sorghum is due to the large Ca^{2+} contribution from gypsum (Fig. 2B and D) (Caires et al., 2001a; 2001b; Soratto and Crusciol, 2007). This increased Ca^{2+} extraction in soils treated with gypsum, which particularly allocates at the growth point of plant roots, allows for greater expansion of the root system making it more capable in absorbing water and other nutrients. On the other hand, the percentage and K^+ content in plants is decreased with increasing gypsum application (Fig. 2A). There is a common fact on plant production experiments, in which when biomass increases there is a decrease in percentage of a nutrient. It is called dilution effect. To reduce this effect, the content of nutrient which is absorbed and accumulated by the plant is estimated. In this work; however, there was also decreased content of K^+ extracted by sorghum depending on the gypsum applied (Fig. 2C). A fact suggesting a decreased K^+ flow to the roots which reduces absorption by the plant (Andreotti et al., 2000) due to the effect of the large contribution of Ca^{2+} from gypsum, which increases the soil solution ionic strength and reduces the K^+ activity in the soil. Concomitantly, it may have occurred leaching of K^+ in the form of K_2SO_4 due to the large contribution of SO_4^{2-} promoted by gypsum application, where K^+ can be the accompanying cation in the leaching. Thus, K^+ passes into deeper soil layers, is little accessed by the root system, reducing its absorption. Rosolem and Malavolta (1981), reported the demand for K^+ of sweet sorghum was 4.4 kg t^{-1}. As the maximum crop yield was approximately 45 t ha^{-1} (Fig. 1A) in this study, while the experimental conditions were the same as in that work, sorghum should have extracted approximately 200 kg ha^{-1} K^+. This shows that excess gypsum halved K^+ extraction, which was on average 105 kg ha^{-1} (Table 1). This finding warns that the gypsum application, especially in high doses, may affect the nutrition of K^+, which can reduce plant productivity, suggesting that it is necessary to find an optimal dose that ensures enhanced percentage and Ca^{2+} content, at least not interfering with the proper nutrition of K^+. Contrary to that observed in other studies, there was no significant variation in the SO_4^{2-} absorption by sorghum due to gypsum application (Table 1). The gypsum application generally increases the SO_4^{2-} concentration in the soil (Pauletti et al., 2014), and thereby increases its absorption by plants. Therefore, agreater SO_4^{2-} absorption by sorghum is expected (Carvalho and Raij, 1997; Rasouli et al., 2013). It might be attributed to the solubilized SO_4^{2-} which is leached to deeper soil layers, with the mainly K^+cations, preventing its absorption. This is a viable option because the water used in the incubation period was sufficient to solubilize all the applied mineral gypsum, including the highest dose (8 Mg ha^{-1}). It shows that the amount of water applied may have been excessive at the lower doses; thus, favoring SO_4^{2-} leaching and their accompanying cations. Furthermore, a decreased Mg^{2+} percentages was expected in the plant because of excessive application of gypsum promoting leaching in the soil, as the accompanying cation of SO_4^{2-} (Caires et al., 2006a; Zambrosi et al., 2007; Pauletti et al., 2014). However, this behavior was not observed (Table 1), likely due to previous application of gypsum to lime.

Biomass and theoretical ethanol yield of sorghum

The application of gypsum promoted biomass productivity in sorghum (Fig. 1A and B). Increased crop yields by applying gypsum is well-documented in the literature (Fernandes et al., 2007; Caires et al., 2011; Rasouli et al., 2013) and this fact is attributed to the increased area of operation of the root system and greater nutrient and water absorption by plants (Caires et al., 2006a). An increase of approximately 6500 kg ha^{-1} fresh mass was observed in sorghum when 2 Mg ha^{-1} of gypsum was applied, compared to control (Fig. 1A). The dose of maximum yield was about 5.5 t ha^{-1} gypsum, which promoted maximum yield of fresh mass of 44373.64 kg ha^{-1} similar to that achieved by Aguiar et al. (2006). The highest applied gypsum dose (8 Mg ha^{-1}) decreased the productivity of fresh mass in sorghum (Fig. 1A). This fact occurred probably due to nutritional imbalance by the large amount of Ca^{2+} applied to the soil, which consequently promoted reduced K^+ absorption (Table 1 and Fig. 2A and C) (Andreotti et al., 2000), with consequent reduction in productivity, as previously discussed. Souza (2011) found stability and adaptability of sweet sorghum cultivars that yield was influenced by genotype and the environmental conditions. The mean dry mass production for sorghum variety IPA 467-4-2 is 8-15 Mg ha^{-1} (IPA, 2008). The maximum dry mass yield obtained in this study was 9246.58 kg ha^{-1} (Fig. 1B), in agreement with previous researches (Tabosa et al., 2002; IPA, 2008). However, this production of dry mass is far from that obtained by Curt et al. (1998) with the keller variety grown in Spain, with a density similar to that used in this work planting. The dry mass obtained by these authors was 26700 kg ha^{-1}, i.e. about three times that achieved in this research. We suggest that the genotype, climate and soil conditions may have contributed to the high yield obtained in other reports (Curt et al., 1998). Another reason why the sweet sorghum yield was not quite high might be the earliest harvest (90 days after planting) which is 30 days before its end cycle. This probably led to lower yields values in comparison with the obtained by Curt et al., (1998). As the theoretical ethanol yield is calculated using the production of fresh mass and total reducing sugars, any variation in these parameters influence the production of ethanol.

Table 1. Percentage and content nutrients in sweet sorghum in the late crop cycle depending on the application of mineral gypsum in an Ultisol, Pernambuco, Brazil.

Factors	Percentage						Content					
	Ca^{2+}	Mg^{2+}	K^{+}	$N\text{-}NH_4^{+}$	$P\text{-}H_2PO_4^{-}$	$S\text{-}SO_4^{-2}$	Ca^{2+}	Mg^{2+}	K^{+}	$N\text{-}NH_4^{+}$	$P\text{-}H_2PO_4^{-}$	$S\text{-}SO_4^{2-}$
Gypsum (Mg ha^{-1})	g kg^{-1}						kg ha^{-1}					
0	1.90	2.35	14.66	5.57	3.72	4.61	14.08	15.90	119.46	52.43	34.73	27.13
2	2.23	2.40	12.05	5.17	3.35	4.30	19.60	22.23	108.26	49.19	30.64	26.16
4	2.69	2.99	12.19	7.34	4.25	5.28	23.80	34.74	105.82	69.47	35.01	50.21
6	2.78	2.64	9.58	6.40	3.55	4.09	25.57	24.41	96.10	55.75	32.98	35.43
8	2.91	2.80	11.11	5.90	3.33	4.95	23.53	25.59	95.30	48.37	26.67	31.75
average	2.50	2.64	11.92	6.08	3.64	4.65	21.32	24.58	104.99	55.04	32.01	34.14
							$F_{regression}$					
Rate of gypsum	35.14^{*Ln}	ns	6.01^{oLn}	ns	ns	ns	133.79^{*Qd}	ns	39.33^{*Ln}	ns	ns	ns
C.V. (%)	8.38	13.16	4.89	10.61	4.56	12.86	14.41	17.55	15.96	19.16	16.83	17.26

^{ns} not significant (p>0,05); ^{o} significant (p≤0.01), * significant (p≤0.05), ^{Ln} Linear regression, ^{Qd} Quadratic regression

Table 2. Agro-technological characteristics and production of ethanol from sweet sorghum depending on the application of mineral gypsum in Pernambuco, Brazil.

Factors	Agro-technological characteristics								
	POL	BP	RSbro	PC	TRdS	Fiber	TRcS	Ethanol	
Gypsum (Mg ha^{-1})	%						kg Mg^{-1}	L ha^{-1}	L Mg^{-1}
0	2.57	26.27	5.84	0.67	6.54	14.40	57.52	1440.47	45.70
2	2.68	26.77	5.77	0.70	6.51	14.62	57.33	1735.90	45.55
4	2.76	27.77	5.72	0.81	6.57	14.35	57.86	1972.68	45.96
6	2.59	26.81	5.81	0.74	6.59	14.18	58.01	2117.56	46.09
8	3.24	31.14	5.27	1.02	6.34	16.01	55.80	1806.48	44.34
Average	2.77	27.75	5.68	0.79	6.51	14.71	57.3	1814.62	45.53
				Fregression					
Rate of Gypsum	ns	ns	ns	ns	ns	Ns	ns	14.16^{oQd}	ns
C.V. (%)	31.68	27.72	12.31	59.42	3.76	9.97	3.73	17.42	3.73

^{ns} not significant, * significant (p≤0.05). ^{o}significant (p≤0.01)

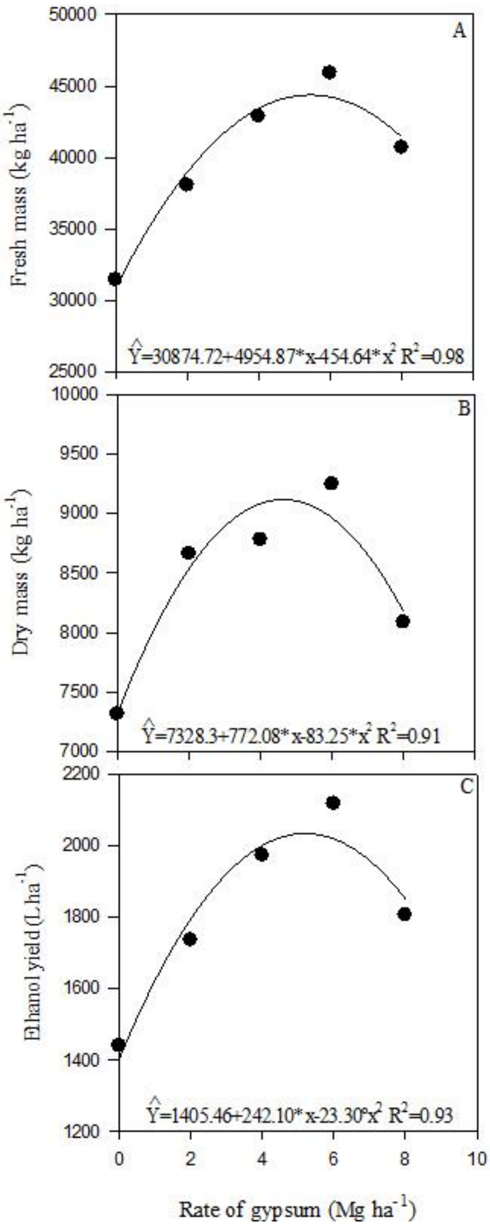

Fig 1. Production of fresh (A), dry (B) mass and theoretical ethanol yield (C) of sweet sorghum depending on the application of mineral gypsum in an ultisol from Pernambuco's Zona da Mata, Brazil.

Thus, just as happened with the production of fresh mass (Fig. 1A), the application of gypsum increased the production of ethanol from sweet sorghum (Table 2 and Fig. 1C). According to Guigou et al. (2011), ethanol yield from sorghum can achieve the same or even higher values than those obtained from sugarcane, which is approximately 8000 L ha^{-1}. However, the mean productivity often reported in the literature varies from 2000 to 7500 L ha^{-1} (Gnansounou et al., 2005; Zhao et al., 2009; Vasilakoglou et al., 2011). In this study the ethanol production was 2032.18 L ha^{-1} at a dose of maximum yield of about 5.5 t ha^{-1} (Fig. 1C). The productivity of ethanol could have been greater if gypsum application increased both biomass and total reducing sugars (Table 2). This could have enhanced ethanol production in line with the production of fresh mass. As the harvest of sweet sorghum

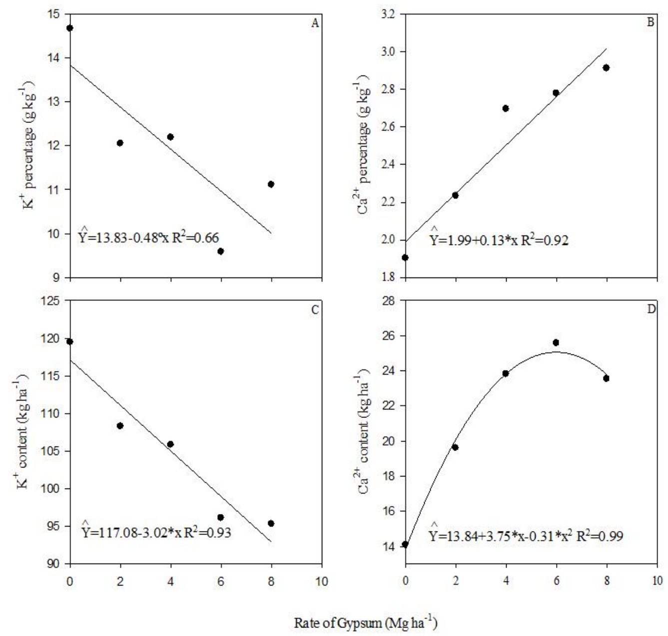

Fig 2. Adjusted regression equations for percentage and content of potassium (A and C) and calcium (B and D) in sorghum depending on the mineral gypsum application.

was anticipated, the total reducing sugars (TRdS) not expressed properly. The production of fresh mass was not also maximized, providing lower ethanol production. However, the average yield of ethanol per ton of sorghum was in agreement with the data obtained by (Guigou et al., 2011), which was approximately 40 L per ton of sorghum (Table 2). As observed in other cultivars of sorghum (Gnansounou et al., 2005; Linton et al., 2011), the IPA 467-4-2 variety is not a source of raw material for ethanol production that can replace sugarcane due to its values of TRdS and productivity. However, it can be an alternative crop in the range of renovation of the sugarcane crops that are planted in winter and during the off-season of sugarcane.

Agro-technological characteristics of sweet sorghum

The agro-technological indicators of sweet sorghum were not affected by gypsum application (Table 2). Teixeira et al. (1997), tested the use of sweet sorghum as supplementary feedstock to sugarcane for ethanol production, obtained values ranging from 4.98 to 6.87% for the technological variable reducing sugars in the broth (RSbro), similar to the mean obtained in this research (5.68%) (Table 3). However, the percentage of sucrose in solution (POL), total reducing sugars (TRdS) and total recoverable sugars (TRcS) were lower than previously reported (Teixeira et al., 1997). This can also be attributed to earlier harvesting of sweet sorghum, which had not enough time to adequately concentrate the sugar. The TRdS is the agro-technological measure of greater importance due to the ethanol industry to evaluate the price per ton of sugarcane on the basis of this parameter (Costa et al., 2011; Simões Neto et al., 2012). The sugarcane is the main source of raw material used for the production of ethanol in Brazil. In an experiment with several varieties of sugarcane, Simões Neto et al. (2012) observed TRdS values ranging between 126.92 and 143.53 kg Mg^{-1}. Costa et al. (2011) was observed average TRdS of 128.48 kg Mg^{-1} when

Table 3. Chemical and physical attributes of the soil on the experimental areas at different depths.

Character	Depth (m)		
	0.0-0.2	0.2-0.4	0.4-0.6
pH	5.33	4.92	4.63
Ca^{2+} ($cmol_c$ dm^{-3})	0.61	0.42	0.35
Mg^{2+} ($cmol_c$ dm^{-3})	0.23	0.17	0.20
K^+ ($cmol_c$ dm^{-3})	0.05	0.04	0.02
Na^+ ($cmol_c$ dm^{-3})	0.06	0.03	0.02
Al^{3+} ($cmol_c$ dm^{-3})	0.19	0.25	0.33
H+Al ($cmol_c$ dm^{-3})	3.50	4.43	4.37
P (mg dm^{-3})	46.11	nd	nd
SO_4 (mg dm^{-3})	5.21	5.62	6.50
SB ($cmol_c$ dm^{-3})	0.95	0.64	0.54
ECEC ($cmol_c$ dm^{-3})	1.14	1.11	0.84
CEC ($cmol_c$ dm^{-3})	4.45	5.07	4.91
Bases sat. (%)	13	12.62	11
Al sat (%)	14.87	20.67	26.92
Total Porosity (cm^3 cm^{-3})	0.46	0.31	0.33
Macro porosity (cm^3 cm^{-3})	0.17	0.11	0.10
Micro porosity (cm^3 cm^{-3})	0.29	0.20	0.23
θ_{CC} (m^3 m^{-3})[1]	0.15	0.21	0.21
θ_{PMP} (m^3 m^{-3})[1]	0.083	0.11	0.14
Useful irrigation level (mm)[1]	7.4	9.7	7.3
Bulk density (g cm^{-3})	1.61	1.80	1.79
Sand (g kg^{-1})	776.4	760.5	728.4
Silt (g kg^{-1})	52.2	36.2	37.3
Clay (g kg^{-1})	171.4	203.3	234.3
Textural class	Sandy clay loam	Sandy clay loam	Sandy clay loam

[1]Data previously obtained by Oliveira (2008). ECEC= Effective cation Exchange capacity (Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+}), CEC= Cation Exchange capacity (Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+} and H^+). nd = not determined.

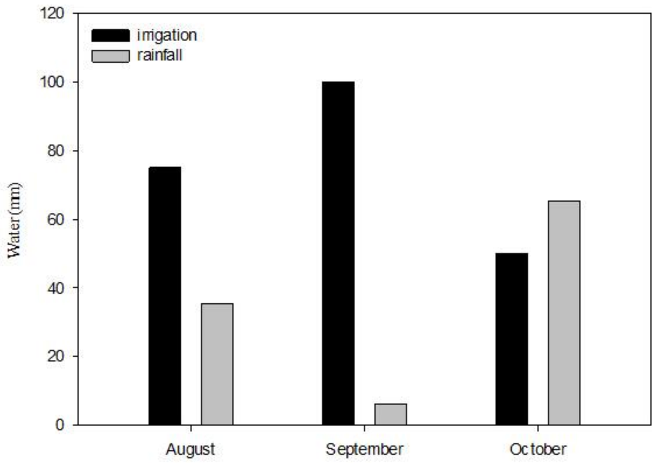

Fig 3. Measuring the amount of water applied by irrigation and from the rainfall during the experiment.

evaluated four cultivars of sugarcane. These values are about three times higher than those obtained in this study in sweet sorghum. Therefore, sweet sorghum can be used complementarily to sugarcane during the off-season and the renewal of sugarcane crops planted in winter, but it is not yet a crop to replace sugarcane, demanding many studies, especially those related to breeding to enhance the sugar concentration and increase its standard TRdS.

Materials and Methods

Localization, soil and environmental characteristics

A field experiment was conducted in the Sugarcane Experimental Station of Carpina (EECAC/UFRPE), Brazil. The EECAC is located under the geographical coordinates 7º51'04'' South latitude and 35º14'27'' West longitude at 178 m altitude, rainy tropical "AS" climate with dry summer according to the classification of Köppen. The soil was classified as hardsetting Ultisol (Argissolo Amarelo distrocoeso) (Alves, 1994). The chemical and physical characterization of the soil before the experiment setting up (Table 3) was performed. Disturbed (Dutch auger) and undisturbed (volumetric ring) samples were collected at 0-0.2, 0.2-0.4 and 0.4-0.6 m. The chemical and physical analyses were performed using the protocols established by EMBRAPA (1997; 2009).

Experimental design and treatments

The experiment was arranged in a randomized block design, consisting of five treatments: 0, 2, 4, 6 and 8 Mg ha^{-1} (ton/ha^{-1}) of mineral gypsum and four replications, totaling 20 experimental units. The plot dimensions were 6.4 × 12 m, with a total area of 76.8 m^2, in order to cover eight crop rows with 12 m long, spaced 0.8 m apart. Each plot corresponded to 32 m^2 (3.2 × 10 m), being eliminated 1.0 m of edging disposed widthwise per plot and two crop rows along the length of the portion, forming a useful plot with four crop rows. The application of gypsum doses was performed casting on the surface without incorporation and remained in this condition for eight months before the procedures necessary for planting sweet sorghum. During this period the experiment received 784.3 mm of water from rainfall and repeated irrigations of 25 mm, always with the goal of keeping the soil field capacity up to 0.6 m depth (Table 3). This incubation aimed at having the time required for the solubilization of mineral gypsum, allowing its displacement to the subsurface.

Sowing of sweet sorghum

The planting of sweet sorghum, using the IPA 467-4-2 variety, was performed in spaced rows of 0.8 m with 12 m long. 25 seeds were sown per meter and thinning of plants carried out two weeks after their emergence in order to obtain a stand of 12 plants per meter. One month before planting, sorghum proceeded to liming and lime incorporation to 0.2 m depth manually with the aid of hoe. A 3.3 Mg ha^{-1} lime (CaO = 49%, MgO = 20% and PRNT = 80.77%) was applied; the amount necessary to increase the base saturation to 60% (Oliveira et al., 2007). A one-year field experiment was performed. We chose only one crop cycle, in three months, because the productivity of sorghum has been the expected for the variety used. Due to this, changes in yield were attributed solely to the effect of the introduced treatments, i.e., the rates of gypsum. The average dry mass obtained in the experiment was 8.5 Mg ha^{-1} while the average productivity according to IPA (2008) is 8 Mg ha^{-1}. Furthermore, Aguiar et al. (2006) observed fresh weight productivity of 44.77 Mg ha^{-1} for the same variety of sorghum. This yield was similar to that obtained with the application of 6 Mg ha^{-1} gypsum, which yielded 45.88 t ha^{-1}. Moreover, in the experiment of Aguiar et al. (2006) there was a greater supply of water, more than 200 mm, than in our study.

Water and nutrient supply

Irrigation level of 25 mm was applied during the months of growing sorghum (August to October) in order to keep the soil at field capacity to a depth of 0.6 m in accordance with the useful irrigation level (Table 3) . In August, irrigation was applied three times, (four times in September and two times in October), supplementing rainfall because it was previously established that monthly sorghum would have about 100 mm of water to develop properly (Fig. 3). Throughout the field trial, the amount of water applied by irrigation and by rainfall was measured, registering accumulation of 332.2 mm of water in the crop area (Fig. 3). Tabosa et al. (2002) state that 300 mm of water is sufficient for adequate growth and production of sorghum. The nutrients N, P and K were applied according to the Manual of Fertilizer Recommendations for the State of Pernambuco (IPA, 2008). The fertilizer used in seeding was 30, 20 and 30 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. After thinning, 60 kg ha^{-1} of nitrogen was top-dressed. Urea, triple superphosphate and potassium chloride were used as sources of N, P and K, respectively.

Nutrient uptake and agro-industrial characteristics

For evaluation of nutrient uptake by plants and agro-industrial characteristics, shoots of 24 plants were collected per plot at the beginning of panicles emergence at 90 days after planting. Thus, 12 plants were used for the assessment of nutrient uptake and 12 referred to the laboratory for industrial chemistry at Petribu Plant for agroindustrial analyses. After harvesting, plants (for measurement of nutrient uptake) were crushed in grinding fodder for collecting a homogeneous sample. The samples were dried at 65 °C until constant weight and then ground in a Wiley mill. The nutrients P-$H_2PO_4^-$, K^+, Ca^{2+}, Mg^{2+} and S-SO_4^{2-} were extracted by nitro-perchloric digestion and the N-NH_4^+ by sulfuric acid digestion, with P-$H_2PO_4^-$ being dosed by colorimetry, K^+ by flame photometry, Ca^{2+} and Mg^{2+} by atomic absorption, S-SO_4^{2-} by turbidimetry and N-NH_4^+ by Kjeldahl micro-distillation (Embrapa, 2009). To calculate the nutrient uptake (kg ha^{-1}), the sorghum yield (kg ha^{-1}) of each treatment in dry weight was multiplied by the nutrient content (g kg^{-1}) obtained from the samples. The agro-technological characteristics were the sucrose content (POL %), sorghum industrial fiber (Fiber %), broth purity (BP %), total recoverable sugar (TRcS kg Mg^{-1}), total reducing sugars (TRdS %), reducing sugars in the broth (RSbro %) and percentage of sorghum POL (PC %).

Biomass and theoretical ethanol yield

The sorghum fresh yield was evaluated by collecting and weighing the useful area of each plot (32 m^2), adding to the weight of 24 plants used previously for analysis of nutrients and agro-technological characteristics, with subsequent estimation for hectare. Sorghum dry yield was calculated by multiplying fresh weight for f (f = dry mass / fresh mass).
To evaluate the theoretical yield of ethanol per hectare, we used the equation below, according to (Vasilakoglou et al., 2011): Ethanol= TRdS (%) × Fresh mass (Mg ha^{-1}) × 6.5 × 0.85 × (1.0/0.79)
Where, TRdS = total reducing sugars (%); 6.5 = conversion factor of ethanol from sugar; = 0.85 fermentation process efficiency; (1.0/0.79) = alcohol specific gravity.

Data analysis

The experimental data were analyzed after checking their normal distribution and homoscedasticity of variance. The analysis of variance was applied to the data and for significant effects regression analysis for the means was applied. Subsequently, we proceeded to select models for the largest significance of the coefficients of the parameters with the highest degree, concomitantly with higher coefficient of determination (R^2). The SAEG® software (SAEG, 1999) was used for statistical analysis and the SigmaPlot® for drawing the graphs and equations.

Conclusions

The gypsum application increased productivity of fresh and dry mass of sweet sorghum, IPA 467-4-2 variety, including increasing in theoretical yield of ethanol. The application of mineral gypsum increased percentage and Ca content and reduced percentage and K content in shoots of sweet sorghum. The maximum recommended dose of agronomic efficiency was approximately 5.5 Mg ha^{-1} (ton/ ha-1). This is the threshold amount of gypsum, beyond that we observed a reduction in sorghum yield. This suggests the gypsum as raw material for appropriate management of sweet sorghum, especially in soils with high acidity on the subsurface. The maximum yield of fresh and dry mass and ethanol was 44373.64 kg ha^{-1}, 9056.43 kg ha^{-1} and 2032.18 L ha^{-1}, respectively.

Acknowledgements

The authors thank financial support provided by CAPES and UFRPE.

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