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SILICON AS A BENEFICIAL ELEMENT FOR SUGARCANE

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ABSTRACT

A number of field and greenhouse studies have demonstrated that silicon (Si) is an important beneficial element for sugarcane (*Saccharum officinarum* L.). Effective management practices utilize Si fertilization on soils deficient in plant-available Si. Thus far, knowledge of the direct effects of Si fertilizers on sugarcane has not advanced as rapidly as for rice. Silica concentration in cultivated plants ranges from 0.3 to 8.4 %. A range of 210-224 million tons of Si or 70-800 kg ha^{-1} of plant-available Si is harvested with the sugarcane crop from arable soils annually. Crop removal of Si by sugarcane exceeds those of the macronutrients N, P, and K. Usually the concentration of Si in sugarcane leaves varies from 0.1 to 3.2%. Higher yield of sugarcane is associated with higher concentration of Si in the leaves. Field and greenhouse experiments conducted in the USA (Florida and Hawaii) and Mauritius demonstrated that application of Si fertilizers had a positive effect on the disease-, pest- and frost-resistance of sugarcane. It was shown that sugarcane productivity increased from 17 to 30 %, whereas production of sugar rose from 23 to 58% with increasing Si fertilization. One of the most important functions of Si was the stimulation of the plant's defense abilities against abiotic and biotic stresses. Literature data demonstrated that improved sugarcane nutrition brought about by fertilization with Si was shown to reinforce the plant's protection properties against leaf freckle, sugarcane rust, and sugarcane ringspot. In addition, Si fertilization has a more positive effect than liming on the chemical and physical properties of the soil.

INTRODUCTION

Beginning in 1840, numerous laboratory, greenhouse and field experiments showed sustainable benefits of Si fertilization for rice (*Oryza sativa* L.), barley (*Hordeum vulgare* L.), wheat (*Triticum vulgare* Vil), corn (*Zea mays* L.), sugarcane, cucumber (*Cucumus sativa* L), tomato (*Lycopersicon esculentum* Mill), citrus (*Citrus taitentis* Risso) and other crops (Epstein, 1999; Liebig, 1840; Matichenkov et al., 1999; Savant et al., 1997). Unfortunately, the present opinion about Si being an inert element is prevalent in plant physiology and agriculture despite the fact that Si is a biogeochemically active element and that Si fertilization has significant effects on crop production, soil fertility, and environmental quality (Epstein, 1999; Matichenkov and Bocharnikova, 2000; Voronkov et al., 1978).

RESULTS AND DISCUSSION

Silicon in the Soil-Plant System.

Silicon is the most abundant element in the earth's crust after oxygen: 200 to 350 g Si kg^{-1} in clay soils and 450 to 480 g Si kg^{-1} in sandy soils (Kovda, 1973). It is the current opinion that Si is an inert element and cannot play an important role in the biological and chemical processes. However many Si compounds are not inert. Silicon can form numerous compounds with high chemical and biochemical activities. Four elements, carbon (C), aluminum (Al), phosphorus (P), and germanium (Ge) surround Si in the Periodic Table of Elements. The properties of Si are somewhat similar to those of the surrounding elements. Only Si can form stable polymers similar to C (Iler, 1979). Silicon is similar to Al in that it can act similarly in formatting minerals (Sokolova, 1985). Silicon can replace P in DNA (Voronkov et al., 1978). Also, Si has similar metallic properties to Ge (Iler, 1979). Usually plants absorb Si more than other elements (Savant et al., 1997). These properties in turn determine silicon's effect on soil fertility and plants.

Soils generally contain from 5 to 40% Si (Kovda, 1973). The main portions of soil Si-rich compounds are represented by quartz or crystalline silicates, which are inert. In many respects, these silicates form the skeleton of the soil. The physically and chemically active Si substances in the soil are represented by soluble and weakly adsorbed monosilicic acids, polysilicic acids, and organosilicon compounds (Matichenkov and Ammosova, 1996). These forms are interchangeable with each other as well as with other crystalline minerals and living organisms (soil microorganisms and plants). Monosilicic acid is the center of these interactions and transformations. Monosilicic acid is a product of Si-rich mineral dissolution (Lindsay, 1979). The soluble and weakly adsorbed monosilicic acids are absorbed by plants and microorganisms (Yoshida, 1975). They also control soil chemical and biological properties (P, Al, Fe, Mn and heavy metal mobility, microbial activity, stability of soil organic matter) and the formation of polysilicic acids and secondary minerals in the soil (Matichenkov et al., 1995; Sokolova, 1985). Plants and microorganisms can absorb only monosilicic acid (Yoshida, 1975). Polysilicic acid has a significant effect on soil texture, water holding capacity, adsorption capacity, and soil erosion stability (Matichenkov et al., 1995).

Using data from the literature on Si removal by different cultivated plants (Reimers, 1990; Bazilevish et. al., 1975) and from the FAO database on world crop production (FAO Internet Database, 1998), it was calculated that 210-224 million tons of plant-available Si is removed from arable soils annually. Harvesting cultivated plants usually results in Si removal from the soil. In most cases much more Si is removed than other elements (Savant et al., 1997). For example, potatoes remove 50 to 70 kg Si ha^{-1}. Various cereals remove 100 to 300 kg Si ha^{-1} (Bazilevich et al, 1975). Sugarcane removes more Si than other cultivated plants. Sugarcane removes 500 to 700 kg Si ha^{-1} (Anderson, 1991). At the same time sugarcane absorbs 40 to 80 kg P ha^{-1}, 100 to 300 kg K ha^{-1}, and 50 to 500 kg N ha^{-1} (Anderson, 1991).

Studies have shown that while other plant-available elements were restored by fertilization, Si was not. Soil fertility degradation started because the reduction of monosilicic acid concentration in the soil initiated decomposition of secondary minerals that control numerous soil properties (Karmin, 1986; Marsan and Torrent, 1989). A second negative effect of reduced monosilicic acid concentration in the soil is decreased plant disease and pest resistance (Epstein, 1999; Matichenkov et al., 1999; Savant et al., 1997).

In recent years we tested the concentration of monosilicic acid, polysilicic acids, and acid-extractable Si in Florida and Louisiana soils (Matichenkov and Snyder, 1996; Matichenkov et al., 1997; Matichenkov et al., 2000). The concentration of monosilicic and polysilicic acids in the soil can be analyzed only from fresh soil samples (Matichenkov et al., 1997). The concentration of acid-extractable Si is positively correlated with biochemically active Si or sources of plant-available Si in the soil (Barsykova and Rochev, 1979).

Selected data on the concentration of monosilicic acid, polysilicic acid, and acid-extractable Si in Histosols, Spodosols, Entisols and Mollisols are presented in Table 1. The lowest concentrations of soluble and biochemically active Si substances are found in the sandy soil (Table 1). Cultivation can increase the concentration of monosilicic acids, probably because plant residuals (especially burned sugarcane leaves) are not removed from the soil. Even so, the concentration of soluble and biochemically active Si-rich compounds remains critically low.

The concentration of monosilicic acid in a native Histosol is usually characterized as being medium to high. The sources of plant-available Si are extremely critical (Table 1), and cultivation results in sharply reduced monosilicic acid levels in the soil. In commercial rice and sugarcane production in the Everglades Agricultural Area, growers usually use Si soil amendments for increased crop production and quality (Datnoff et al., 1997, Savant et al., 1997). Sugarcane usually is grown after rice. The application of Si fertilizer has beneficial effects on both rice and sugarcane (Savant et al., 1999). The concentration of monosilicic acid, polysilicic acid, and acid-extractable Si increased with cultivation (Table 1). The most dramatic increase was observed for acid-extractable Si. This parameter determines the amount of biogeochemically active Si and is a potential source for plant-available Si (Barsykova and Rochev 1979). Native Histosols have extremely low levels of biogeochemically active or plant-available Si. On the other hand cultivated Histosols have medium to high level of monosilicic acid or plant-available Si (Table 1).

The native soils from Louisiana were characterized by a high concentration of soluble and biochemically active Si (Table 1). High levels of biogeochemically active Si were found in accumulative alluvial soils (Kovda, 1973). Louisiana soils were collected in the Mississippi delta and were formed under alluvial accumulative processes. The long period of cultivation of these soils resulted in the decrease of monosilicic acid and acid-extractable Si (Table 1). Most likely this is a result of monosilicic acid absorption by cultivated plants rather than leaching, because monosilicic acid is characterized by a low capacity to move down the soil profile (Matichenkov and Snyder, 1996). However, the content of polysilicic acids increased, which is probably associated with degradation of soil minerals (Matichenkov et al., 1995; Iler, 1979). The decrease of acid-extractable Si supports this conclusion. As a result of agricultural activity, the concentration of plant-available Si was decreased and soil fertility was degraded.

These data demonstrate that Si fertilization is needed for all four soils under investigation to assure adequate Si nutrition of sugarcane and to optimize the fertility of these soils.

Effect of Si on Sugarcane

Silicon fertilizers influence plants in two ways: (1) the indirect influence on soil fertility, and (2) the direct effect on the plant. Most investigations of monosilicic acid effects on soil properties concern their interaction with soil phosphates (Matichenkov and Ammosova, 1996). Silicon fertilizer applied into the soil initiates two processes. The first process involves increases in the concentration of monosilicic acids resulting in the transformation of slightly soluble phosphates into plant-available phosphates (Lindsay, 1979; Matichenkov, 1990). The equations for these reactions are as follows:

$$CaHPO_4 + Si(OH)_4 = CaSiO_3 + H_2O + H_3PO_4$$
$$2Al(H_2PO_4)_3 + 2Si(OH)_4 + 5H^+ = Al_2Si_2O_5 + 5H_3PO_4 + 5H_2O$$
$$2FePO_4 + Si(OH)_4 + 2H^+ = Fe_2SiO_4 + 2H_3PO_4$$

Secondly, Si fertilizer adsorbs P, thereby decreasing P leaching by 40-90 % (Matichenkov et al., 2000). It is noteworthy that adsorbed P is kept in a plant-available form.

Silicon fertilizers are usually neutral to slightly alkaline (Lindsay, 1979). Soluble Si reduces Al toxicity because monosilicic acid reacts with mobile Al and forms slightly soluble aluminosilicates (Lumsdon and Farmer, 1995). This means that Si amendments may be used for improving the chemical properties of acid soils. Numerous field experiments have demonstrated that Si fertilization has more influence on plant growth on acid soils than liming (Ayres, 1966; Fox et al., 1967). Silicon fertilizer can increase plant resistance to heavy metals (Epstein 1999) and toxic hydrocarbons (Bocharnikova et al., 1999). Both effects of Si fertilizer appear to occur through optimization of soil properties and the direct effect on soil microorganisms. Our earlier investigation demonstrated that soil treatment with Si-rich materials increased both water-holding capacity and soil adsorption capacity for ions (Matichenkov and Bocharnikova, 2000).

The direct effect of Si fertilizer on plants is primarily manifested in increasing disease and pest resistance. Data in the literature showed that Si fertilization increased the resistance of sugarcane to sugarcane rust (Dean and Todd, 1979), leaf freckle (Fox et al., 1967), sugarcane ringspot (Raid et al., 1991), leaf disorder (Clements, 1965), and stalk and stem borers (Edward et al., 1985; Meyer and Keeping, 1999). Except for biotic stresses such as pests and plant diseases, Si fertilization increased sugarcane resistance to abiotic stresses such as soil water shortage, cold temperature, UV-B radiation, and for Fe, Al and Mn toxicities (Savant et al., 1999).

The field experiments in Hawaii, Mauritius and Florida demonstrated high response of sugarcane to Si fertilizer (Table 2). It is important to note that Si fertilizer increased not only the productivity of cane but also the concentration of sugar in the plants as well (Table 2). It is probable that Si has a direct effect on biochemical processes in sugarcane that are similar to responses observed for sugar beet (Liebig, 1840).

CONCLUSIONS

Soils used for sugarcane in Florida and Louisiana usually have low concentrations of plant-available

Si and biogeochemically active Si. The removal of Si by sugarcane initiated soil fertility degradation. Cultivated plants tend to have Si deficiency. The application of Si in soil amendments is needed for both optimized soil fertility and improved plant nutrition. The field experiments in Florida, Hawaii, and Mauritius demonstrated the highly beneficial effects of Si fertilizers.

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Table 1. Concentrations of monosilicic acid, polysilicic acid and acid-extractable Si in Histosols, Spodosols, Entisols, and Mollisols (mg Si kg^{-1} of soil).

Soil	Soluble silicon		Acid-extractable silicon
	Monosilicic acid	Polysilicic acid	
Histosol (Florida, Lauderhill series)			
Native	24.3-46.5	0-0.8	15-45
Cultivated without silica fertilizers	13.4-32.4	1.5-2.7	97-127
Cultivated with silica fertilizers	15.3-96.2	1.5-23.4	93-548
Spodosol (Florida,Ancona series)			
Native	1.4-2.3	2.4-12.7	45-75
Cultivated	2.3-6.1	1.7-2.4	42-57
Entisol (Louisiana, Mhoon series)			
Native	19.1-20.3	27.3-29.8	319-325
Cultivated	11.5-14.2	88.9-117.5	279-319
Mollisol (Louisiana, Iberia series)			
Native	23.2-23.8	40.0-58.2	294-415
Cultivated	12.3-19.5	56.3-116.5	171-298

Table 2. The effect of location, soil type, source and rate of fertilizer application on yield of sugarcane and sugar.

Soil	Si fertilizer	Rate, ton/ha	Limestone or fertilizer	Sugar		Cane		Reference
				t/ha	%	t/ha	%	
Aluminos humic Latosol, Mauritius	Electric furnace slag	0	NPK	27.4	100	266.7	100	Ayres, 1966
		0	NPK + lime 4.94t/ha	26.7	97.4	256.8	96.3	
		6.177	NPK	33.8	123.4	313.7	117.6	
Humic Latosol, Hawaii	TVA slag	0	P 0.28t/ha	23.4	100	253	100	Fox et al., 1967
		0	Lime 4.5 t/ha + P 1.112t/ha	20.7	88.5	262	103.5	
		4.5	P 0.28t/ha	31.6	135.0	327	129.2	
		4.5	P 1.112t/ha	32.7	139.7	338	133.5	
Humic Latosol, Hawaii	Calcium silicate	0	-	-	-	131	100	Silva, 1969
		0.83	-	-	-	151	115.3	
		1.66	-	-	-	166	126.7	
Histosol, Florida	Calcium silicate slag	0	-	12.5	100	126	100	Raid et al., 1991
		0	P	18.1	144.8	150	119.0	
		6.7	-	15.8	126.4	156	123.8	
		6.7	P	23.8	190.4	194	153.9	