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Influence of Silicon on Grain Discoloration and Upland Rice Grown on Four Savanna Soils of Brazil

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ABSTRACT

In silicon (Si)-deficient soils, calcium silicate fertilization can reduce rice diseases and increase yields. Experiments were conducted in the greenhouse to investigate the effects of Si on rice yield and grain discoloration in four different savanna soils from Brazil, Typic Acrudox-isohyperthermic (L.Ea), Typic Acrudox-isohyperthermic (L.Va), Rhodic Acrudox-isohyperthermic (L.Rd), and Ustoxic Quartzipsammentic-isohyperthermic (A.Qs). Five Si rates (0, 120, 240, 480, and 960 kg ha⁻¹) were applied to each soil. Silicon applications increased total grain weights and dramatically reduced grain discoloration independent of soil type. In addition, Si concentration increased in the leaves.

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INTRODUCTION

Rice (*Oryza sativa* L.) is an important food crop grown worldwide, especially in soils where the fertility, including plant-available silicon (Si), is low (Anon., 1978). In these Si-deficient soils, addition of Si has been demonstrated as beneficial for both irrigated and upland rice (Jones and Handreck, 1967; Lian, 1976; Okuda and Takahashi, 1964; Savant et al., 1997).

Although Si is not considered an essential element for plant growth and development, addition of this element can decrease the incidence of several important rice diseases (i.e., blast, caused by *Magnaporthe grisea* and brown spot, caused by *Cochliobolus miyabeanus*) and insect pests, while increasing grain yields (Savant et al., 1997). Deren et al. (1994) concluded that the increase in rice yield with added Si was attributable to a greater number of grains per panicle with diseases such as brown spot being negatively correlated with Si concentration in the plant tissue. The Histosols in the Everglades Agriculture Area (EAA) are very low or lacking in Si. By amending these soils with Si, blast and brown spot were reduced by 73-86% and 58-75% in 1987 and 1988, respectively, and rice yields increased 56-88% (Datnoff et al., 1991).

Fungicides and/or resistant cultivars are used in most disease control programs. However, host resistance may not always be practical and when available can break down due to shifts in pathogen races. Fungicides are currently perceived to be potentially harmful to the environment, particularly to the soil and water. Therefore, Si fertilization may offer an encouraging alternative to fungicide use while enhancing host plant resistance (Datnoff et al., 1997).

The Cerrado (savanna) area in Brazil covers more than 300 million hectares. This ecosystem includes mostly Oxisols and Ultisols, low in pH, excess in aluminum (Al), and low in Si. Difficulties in the production and the quality of rice in these areas are associated frequently with drought, low soil fertility, and disease.

Little information is available on the effect of Si on rice growth in the savannas of Brazil. Therefore, the purpose of this study was to investigate the influence of Si on rice growth and grain discoloration in four representative soils from the Cerrado of Brazil.

MATERIALS AND METHODS

The experiment was conducted in the greenhouse, using four Brazilian soils: a Typic Acrustox isohyperthermic (L.Ea), Typic Acrustox-isohyperthermic (L.Va), Rhodic Acrustox-isohyperthermic (L.Rd), and Ustoric Quartzipsammentic-isohyperthermic (AQA), whose chemical, physical, and mineralogical characteristics are given in Tables 1, 2, and 3, respectively.

These soils were collected at a depth of 0-20 cm in the “Triângulo Mineiro” area, air dried, sieved (5-mm), and placed into pots that were fertilized with 50 mg nitrogen (N) dm$^{-3}$ as ammonium sulfate [(NH$_4$)$_2$SO$_4$], 150 mg phosphorus (as P$_2$O$_5$) dm$^{-3}$ as
TABLE 1. Chemical attributes of four soils taken from the top 0-20 cm layer from the savanna of Brazil.

<table>
<thead>
<tr>
<th>Soils*</th>
<th>pH</th>
<th>P**</th>
<th>Si</th>
<th>Al+++</th>
<th>Ca++</th>
<th>Mg++</th>
<th>SB</th>
<th>t</th>
<th>CEC</th>
<th>B.S.</th>
<th>m</th>
<th>O.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mg dm⁻³</td>
<td>cmol dm⁻³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LRD</td>
<td>5.0</td>
<td>16.0</td>
<td>10.5</td>
<td>0.50</td>
<td>3.80</td>
<td>1.60</td>
<td>5.80</td>
<td>6.30</td>
<td>11.8</td>
<td>49</td>
<td>8</td>
<td>41</td>
</tr>
<tr>
<td>LEa</td>
<td>4.4</td>
<td>2.0</td>
<td>6.6</td>
<td>0.70</td>
<td>0.20</td>
<td>0.0</td>
<td>0.26</td>
<td>0.96</td>
<td>7.30</td>
<td>4</td>
<td>73</td>
<td>40</td>
</tr>
<tr>
<td>LVA</td>
<td>5.0</td>
<td>4.0</td>
<td>5.7</td>
<td>0.70</td>
<td>0.20</td>
<td>0.0</td>
<td>0.29</td>
<td>1.00</td>
<td>7.70</td>
<td>4</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>AQa</td>
<td>4.4</td>
<td>56.0</td>
<td>3.3</td>
<td>1.00</td>
<td>0.20</td>
<td>0.10</td>
<td>0.39</td>
<td>1.40</td>
<td>5.20</td>
<td>7</td>
<td>71</td>
<td>15</td>
</tr>
</tbody>
</table>

*(LRd) Rhodic Acruox; (LEa) Typic Acruox; (LVA) Typic Acruxox; (AQa) Umbre Quartzipsammentic.

**P extracted by HCl 0.05N + H₂SO₄ 0.0025N; Si extracted by 0.5 mol L⁻¹ acidic acid; Al, Ca, and Mg extracted by KCl 1N; O.M. = organic matter extracted by the method Walkley-Black; SB = total bases; t = effective cation exchange capacity; CEC = cation exchange capacity at pH 7.0; BS = based saturation; m = aluminum saturation (Vettori, 1969).

calcium dihydrogen phosphate [CaH₂PO₄], and 50 mg magnesium (as MgO) dm⁻³ as magnesium sulfate (MgSO₄·7H₂O). The pots were weighed daily to maintain the soil at field capacity. Two side-dressed fertilizer applications were made at 35 days (0.28 g pot⁻¹) and 45 days (0.14 g pot⁻¹) after planting.

TABLE 2. Soil texture (fraction <2.0mm), total elements (referring to the clay fraction), weathering index (KI), and estimated kaolinite content (Ka).

<table>
<thead>
<tr>
<th>Soil*</th>
<th>Course sand</th>
<th>Fine sand</th>
<th>Silt</th>
<th>Clay**</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>KI**</th>
<th>SiO₂/Al₂O₃</th>
<th>Ka</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LRD</td>
<td>6</td>
<td>22</td>
<td>20</td>
<td>52</td>
<td>12.2</td>
<td>11.9</td>
<td>18.9</td>
<td>1.75</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>LEa</td>
<td>3</td>
<td>6</td>
<td>13</td>
<td>78</td>
<td>17.8</td>
<td>28.2</td>
<td>10.8</td>
<td>1.08</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>LVA</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>74</td>
<td>13.5</td>
<td>29.6</td>
<td>7.8</td>
<td>0.77</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>AQa</td>
<td>22</td>
<td>61</td>
<td>2</td>
<td>14</td>
<td>3.7</td>
<td>3.8</td>
<td>2.6</td>
<td>1.66</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

*Total elements analyzed by the method attack sulfuric (Embrapa, 1979). (LRd) Rhodic Acruxox; (LEa) Typic Acruxox; (LVA) Typic Acruxox; (AQa) Umbre Quartzipsammentic.

**Soil texture made by the pipette method (Embrapa, 1979).

***Molecular ratio.
TABLE 3. Effect of calcium silicate application on the Si content (%) in rice grown in four different soil types from the savanna of Brazil.

<table>
<thead>
<tr>
<th>SOILS</th>
<th>0</th>
<th>120</th>
<th>240</th>
<th>480</th>
<th>960</th>
<th>Means*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si kg ha⁻¹</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LRd</td>
<td>1.78</td>
<td>1.90</td>
<td>2.21</td>
<td>2.56</td>
<td>3.35</td>
<td>2.36 a</td>
</tr>
<tr>
<td>LEa</td>
<td>1.25</td>
<td>1.50</td>
<td>1.65</td>
<td>1.93</td>
<td>2.97</td>
<td>1.88 b</td>
</tr>
<tr>
<td>LVa</td>
<td>1.06</td>
<td>1.41</td>
<td>1.70</td>
<td>2.23</td>
<td>2.97</td>
<td>1.86 b</td>
</tr>
<tr>
<td>AQa</td>
<td>0.90</td>
<td>0.92</td>
<td>1.00</td>
<td>1.63</td>
<td>1.95</td>
<td>1.28 c</td>
</tr>
<tr>
<td>Média</td>
<td>1.25</td>
<td>1.43</td>
<td>1.64</td>
<td>2.09</td>
<td>2.81</td>
<td></td>
</tr>
</tbody>
</table>

D.M.S. 5% = 0.204 (Soils)
D.M.S. 5% = 0.243 (Si rates)
C.V. = 13.2%

*Means followed by the same letters are not significantly different from each other based on Tukey test (P≤0.05).

Wollastonite was used as the Si source. The Wollastonite-calcium silicate (CaSiO₃) (Vansil, EW-20) was supplied by Ipiranga Chemical from São Paulo City. Wollastonite has the following composition: SiO₂ = 51.9% (24.3% Si); calcium (as CaO) = 42.1%; Al₂O₃ = 1.82%; MgO = 1.49%; iron (as Fe₂O₃) = 0.34%; sodium (as Na₂O) = 0.27%; manganese (as MnO) = 0.03%; other = 2.04%; density = 2.9 kg m⁻³ (25°C); pH = 9.8 (solubility -10%). The Wollastonite was mixed and incorporated into each of the four soils to obtain equivalent doses of 0, 120, 240, 480, and 960 kg ha⁻¹ of elemental Si.

Thirty days later, rice seeds were sown. In each pot, five plants of rice (cultivar IAC-165) were grown for approximately 120 days until maturity under upland conditions.

After harvest, the pH and the Ca, Al, Mn, and P soil concentration were determined using the method of Vettori (1969). Soil Si was determined extracting with 0.5M acetic acid (HC₂H₃O₂) (Barbosa Filho et al., 1996). Ten grams of each soil were agitated for 1 hour with 100 mL 1M HCl, H₂O₂. The solution was decanted for 15 minutes, then filtered through filter paper for at least 12 hours. Silicon concentration of the supernatant was determined colorimetrically at 660 nm. The Si analysis in the rice straw was determined by the method described by Elliott and Snyder (1991). Biomass was determined using total grain weight and dry matter per pot. Roots were not included.
FIGURE 1. Effect of Si rates on the grain weight (g pot−1) of the following soils: (LRd) Rhodic Acrudox; (LEa)Typic Acrudox; (LVa)Typic Acrudox; (AQa) Ustoxic Quartzipsammentic.

After harvest, grain discoloration intensity ratings were made based on color, a darkening (brown to black) of the glumes of spikelets (IRRI, 1996) from sporadic discoloration to whole glumes discoloration using a scale where: 0 = seeds without discoloration; 1 = seeds with little discoloration; 2 = seeds with medium discoloration; 3 = seeds with medium-high discoloration; and 4 = seeds with high discoloration.

This was a factorial experiment arranged as a completely randomized design. Data were analyzed by ANOVA and linear regression.

RESULTS AND DISCUSSION

Silicon amendment increased the average weight of rice panicles and grains (Figure 1). The grain average weight increased 128%, 17%, 22%, and 39% for LRd, LEa, LVa, and AQa soils, respectively (Figure 1). Although the LRd soil is known to be younger pedogenetically (>Ki) and has a lower desilication degree in comparison to the other soils (Table 2), this soil had the greatest increase in grain weight (Figure 1). This result probably can be explained by the effect of Si on Fe availability. The higher Fe₂O₃ content in this soil (Table 2), along with excess moisture, probably contributed to increased Fe reduction, and consequently greater availability to the plants. Symptoms of Fe toxicity were not observed in the treatments that had received Si, whereas those symptoms were evident in the untreated controls. Calcium silicate is known to reduce Fe and Mn toxicity. Silicon increases the “oxidizing power” of the roots (Okuda and Takahashi, 1964), making Fe and Mn less soluble, i.e., precipitate on the surface of the roots by increasing the volume and rigidity of the aerenchyma (air-filled spaces in roots) system exposed to the toxic concentration of reduced Fe. Verma and Mine (1989)
verified that the application of 200 mg Si kg\(^{-1}\) to soil in the form of \(\text{Na}_2\text{SiO}_3\cdot\text{H}_2\text{O}\) decreased the Fe translocation from leaves and shoots to the grains under greenhouse conditions. Some authors have suggested that the Si supplied to the plants may alleviate Mn and Fe toxicity not only because it reduces their absorption, but also because it increases the internal tolerance level of the plant to excess of these elements in the tissue (Okuda and Takahashi, 1964; Jones and Handreck, 1967; Lian, 1976).

A visual examination of the rice plants showed that as the Si rate increased, the leaves became more erect in comparison to the control plants. Silicon is believed to be deposited mainly in the cellular wall, increasing the rigidity of the cells (Adatia and Besford, 1986). This, in turn, could elevate the hemicellulose content and lignin content of the cellular walls (Lee et al., 1990). Leaf erectness is an important factor affecting light interception in dense plant populations (Marschner, 1986). The average Si concentration in the leaves varied from 1.25 to 2.81% for the rates 0 and 960 kg Si ha\(^{-1}\), respectively (Table 3). The differences observed among the four soils used are due to Si availability. The amount of available Si was lower in the sandy AQa soil compared to the LRd soil (Table 1), most likely due to the high Fe\(_2\)O\(_3\) present. Jones and Handreck (1963) indicated that Si levels in the soil solution with the same soil pH may be influenced by the amount, kind, and crystallinity of the free sesquioxides.

Rice diseases are known to be reduced when Si concentration in the tissue increases (Datnoff et al., 1997; Datnoff et al., 1991; Osuna-Canizales et al., 1991).
Grain discoloration decreased as the Si application rate increased (Figure 2) as grain discoloration was reduced from 46% in the control to 29% at the highest Si rate (960 kg Si ha⁻¹). This difference corresponds to a 64% reduction in grain discoloration. It is also known that grain discoloration can reduce grain weight, reduce seed germination, and as a consequence lower the market value of the grain (Tanaka, 1986). Several different pathogens are associated with grain discoloration including species like Curvularia, Helminthosporium, and Fusarium.

The amount of Si in rice leaves was directly related to the amount of Si applied to the soil (Figure 3). This may explain why the plant was more resistant to fungal disease (Adatia and Besford, 1986). A mechanical barrier is believed to be created by Si deposition in the leaf epidermis. Silicon also can reduce amino acid and starch formation which promote fungal growth (Takahashi, 1995). Datnoff et al. (1991) observed blast and brown spot reductions of 73% and 86%, respectively, and a 50% yield increase when calcium silicate was applied to organic soils low in plant available Si. The following year, the incidence of disease was reduced 58% and 75%, respectively, for blast and brown spot and yields increased 88%.

Silicon is an immobile nutrient that accumulates with tissue age (Takahashi, 1995). It is quickly transformed into a gel form soon after root absorption. More than 90% of the total Si within in the plant forms a silica gel layer in the leaf cuticle.
Microscopic studies have demonstrated that Si became bound to the cellulose below the cuticle of the flag leaf. Consequently mechanical resistance is improved, reducing fungal penetration and insect attack (Yoshida et al., 1962).

The Si concentration in the plant varied according to soil type (Table 3). The values ranged between 1.25% and 2.81% in the aerial part of the plant. Snyder et al. (1986) concluded that rice should contain at least 3% Si in the shoot to guarantee optimal development and yield of rice grown on Histosols. The Si concentrations in the plant varied according to soil type: AQa (1.28%) < LVa (1.86%) < LEa (1.88%) < LRd (2.36%). The Si in the plant is related to available Si in the soil as is shown in Tables 1 and 3. The amount of clay and silt probably explains the lower Si available from these soils.

In conclusion, four soils from Brazil typical of the ones encountered in the savannas indicated that as rice production expands in this region, fertilization with Si will be needed in order to obtain maximum rice yields and disease control.

CONCLUSIONS

Application of Wollastonite as a Si source increased total grain weight independent of the soil type. Wollastonite also was efficient in supplying plant available Si to rice plants as leaf Si content increased as well as total accumulated of Si in the plant with Si added to the soil. Silicon also dramatically reduced grain discoloration.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Vilmar A. Arantes and Leonilda Avila for their important ideas and suggestions. Also, we would like to thank Mr. Paulo Rabelo for conducting the Si analysis in the laboratory, and to FUNDAÇÃO BANCO DO BRASIL and FAPEMIG for their financial support.

REFERENCES


AVALIAÇÃO DE MÉTODOS DE EXTRAÇÃO DE SILÍCIO EM SOLOS CULTIVADOS COM ARROZ DE SEQUEIÇO(1)

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G. H. SNYDER(4) & C. T. MIZUTANI(5)

RESUMO

Este trabalho teve como objetivo avaliar a eficiência de quatro métodos de extração (ácido acético 0,5 mol L⁻¹, tampão pH 4,0, cloreto de cálcio 0,0025 mol L⁻¹ e água) em estimar a disponibilidade de silício (Si) no solo para plantas de arroz de sequeiro cultivadas em casa de vegetação. Quatro solos, correspondentes às classes Latossolo Vermelho-Escuro álico (LEa), Latossolo Vermelho-Amarelo álico (LVa), Latossolo Roxo distrófico (LRd) e Areia Quartzosa álica (AQa), todos da região do Triângulo Mineiro e ainda não cultivados foram utilizados no estudo. Cinco níveis de Si foram estabelecidos em cada um dos solos. Plantas de arroz foram cultivadas em vasos até a maturação. Como resultado deste trabalho, concluiu-se que o ácido acético 0,5 mol L⁻¹ foi o método que apresentou a melhor estimativa do Si disponível no solo para o arroz de sequeiro. O silício da parte aérea do arroz revelou alta correlação com o Si extráível pelo método ácido acético.

Termos de indexação: disponibilidade, extratores químicos, Latossolos, silicato de cálcio.

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SUMMARY: EVALUATION OF SOIL EXTRACTANTS FOR SILICON AVAILABILITY IN UPLAND RICE

The suitability of four extraction methods (acetic acid 0.5 mol L⁻¹, buffer pH 4.0, calcium chloride 0.0025 mol L⁻¹ and water) for estimating the amount of available Si in soil for upland rice was determined. Four soil types corresponding to the following classes were used: Typic Acrustox - isohyperthermic (LEa), Typic Acrustox - isohyperthermic (Lva), Rhodic Acrustox - isohyperthermic (LRd) and Ustoch Quartzipsammentic - isohyperthermic (AqA), all of them from the Triângulo Mineiro region in Minas Gerais, Brazil. Five Si levels were created in each of the soils by applying calcium silicate. Upland rice was grown to maturity in pots of each soil in greenhouse. Among the extractants studied, the acetic acid 0.5 mol L⁻¹ gave the best estimate for the available Si in soil. The silicon content found in the leaves was highly correlated with extractable Si by the acetic acid 0.5 mol L⁻¹ method.

Index terms: availability, Latosol, extractant, calcium silicate.

INTRODUÇÃO

A análise de silício (Si) no solo não é feita pelos laboratórios de rotina no Brasil. A falta de calibração de métodos para Si tem dificultado aos pesquisadores estudar o papel desse elemento na nutrição das plantas. Sabe-se que o Si é um dos elementos mais abundantes encontrados na crosta terrestre e que a adubação com Si pode resultar em aumento na produtividade de várias culturas como é o caso do arroz, cana-de-açúcar e outras (Fox et al., 1967; Datnoff et al., 1991; Anderson et al., 1991). Esses autores têm relacionado a presença de Si na planta com resistência a pragas e doenças, maior capacidade fotossintética (as folhas ficam mais eretas e a incidência de luz é maior) e tolerância à falta de água. Apesar disso, o Si não é considerado um nutrientes essencial para as plantas.

Sendo o Si um elemento importante para algumas espécies de plantas, é essencial o desenvolvimento de métodos de análise que possam estimar sua disponibilidade no solo. Nesse sentido, Nonaka & Takahashi (1990) desenvolveram um método baseado na incubação do solo por duas semanas a 40°C e usando a água como extrator. Após o período de incubação, o Si é analisado no sobredenatante.

O método de extração com CaCl₂ 0,01 mol L⁻¹ é comumente usado numa série de determinações, tais como cátons trocáveis e pH. Esse extrator tem a propriedade de simular a força iônica da solução e o pH, entretanto, o processo químico envolvido é pouco estudado e pouco tem sido feito para entender a cinética de liberação dos cátons da fase sólida para a solução. Segundo Gibson (1994), a extração do Si com CaCl₂ 0,01 mol L⁻¹ é intensa nas primeiras 24 horas de contato com o solo. A partir daí, a extração é essencialmente linear com o tempo. Nesse caso, o autor acredita que a primeira hora de extração deva refletir melhor a disponibilidade do Si para as plantas; entretanto, reconhece que a quantidade de Si é muito dependente do tempo de extração.

Pesquisadores japoneses são os que mais apresentam trabalhos relacionados com o desenvolvimento de métodos para análise de Si no solo. Para Nonaka & Takahashi (1990), ao contrário do que foi observado por Shiu (1964), tampão de acetato a pH 4,0 é muito forte para estimar a disponibilidade de Si, mas é dos EUA que vem um dos métodos de extração mais utilizados para Si no solo. Snyder (1991) demonstrou que o ácido acetico 0,5 mol L⁻¹, além de prático, tem sido bastante eficiente em identificar solos deficientes em Si. Segundo o autor, esse extrator vai muito bem tanto nos solos orgânicos como nos solos arenosos.

A determinação do Si extraível, além da sua importância para identificação de solos deficientes em Si, tem interesse no estudo de fenômenos pedogenéticos, considerando que a remoção da silica do perfil de solo é um dos principais aspectos do intemperismo químico nos trópicos.

Este trabalho teve como objetivo avaliar a eficiência de quatro métodos de extração em quantificar o Si disponível no solo para plantas de arroz de sequeiro cultivadas em casa de vegetação.

MATERIAL E MÉTODOS

Estudo do Si acumulado na planta

Este estudo foi realizado em casa de vegetação, utilizando amostras da camada de 0-20 cm de profundidade de quatro solos, correspondentes às classes: Latossolo Vermelho-Escurto álico (LEa),

Latossolo Vermelho-Amarelo álico (LVa), Latossolo Roxo distrófico (LRd) e Areia Quartzosa álica (AQA),
todos da região do Triângulo Mineiro (EMBRAPA, 1982) e de áreas ainda não cultivadas. Os resultados das análises químicas, texturais e mineralógicas,
encantam-se nos quadros 1 e 2, respectivamente. Cinco níveis de Si foram estabelecidos em cada solo. O silicato de cálcio (wollastonita - CaSiO₃) foi
fornecido pela empresa Ipiranga Química de São Paulo (produto comercial - Vansil, EW-20). O silicato (51,9% de SiO₂) foi incorporado ao solo 30 dias antes
do plantio nas dosagens equivalentes a: 0 (testemunha), 120, 240, 480 e 960 kg ha⁻¹ de Si, em
vasos que continham 8 kg de terra seca ao ar. O cultivar de arroz plantado foi o IAC-165.

A análise de Si nas plantas de arroz foi feita segundo o método descrito por Elliott & Snyder (1991) adaptado. Posou-se 0,100 g da amostra (tecido foliar)
coletado em plantos de plástico. A seguir, foram acrescentados 2 mL de H₂O₂ (30 ou 50%) mais
3 mL de NaOH (1:1). Depois de agitados, os tubos foram imediatamente colocados na autoclave por um
período de 1h a 123°C e 1,5 atm. de pressão. Uma aliquota do material digerido foi misturado com 2 mL de
molinho de amônia 1:5 (NH₄)₂Mo₇O₂₄.4H₂O: água destilada) para a formação do complexo
amarelado ácido silício-mofóbico [H₄(SiMo₄O₁₆)]. A formação do complexo ácido silício-mofóbico é
máxima entre pH 1,0 e 2,0. Para baixar o pH das amostras, quantidades proporcionais ao volume da
aliquota foram adicionadas de HCl (50%). O ácido
1-amino-2-naftol-4-sulfônico (redutor), utilizado para
eliminar a interferência do P e do Fe, foi substituído pelo ácido oxálico (75 g de (COOH)₂. 2H₂O em
200 mL de água destilada) na proporção de 2 mL por amostra. A leitura do Si nos extratos foi feita em
spectrofotômetro, no comprimento de onda de 410 nm. A quantidade de Si acumulada na parte aérea
(Quadro 1) foi calculada com base na concentração de Si e na produção de matéria seca da parte aérea.

Pretendeu-se, nesta parte do trabalho, quantificar o Si acumulado na parte aérea do arroz para servir
de critério na avaliação dos métodos de extração os quais foram correlacionados com o Si acumulado.

Estudo dos métodos de extração

Para análise de Si, amostras de solo foram retiradas dos vasos cultivados com arroz de sequeiro e
preparadas para análise. As amostras foram secas na temperatura ambiente (TFSA) e posteriormente
peneiradas (< 2,0 mm).

O procedimento de extração foi realizado procurando-se manter a mesma relação solo:solução, isto é, para cada 10 g de solo, foram adicionados
100 mL de extrator. Os extratores utilizados foram:
Ácido acético 0,5 mol L⁻¹ (Snyder, 1991): 100 mL de
ácido acético 0,5 mol L⁻¹ foram adicionados em um
frasco de plástico de 150 mL que continha 10 g de
solo. O frasco de plástico foi tampado e agitado
horizontalmente por uma hora. Passados 30 minutos,
filtrou-se o extrato (funil de plástico), utilizando-se
papel de filtro número 42; Tampão pH 4,0: 100 mL
de uma solução tampada a pH 4,0 de ácido acético
mais acetato de sódio (49,2 mL de ácido acético
concentrado e 14,800 g de acetato de sódio foram
dissolvidos em 1 litro de água destilada e o
pH ajustado para 4,0 com a adição de ácido acético)
foram adicionados em um frasco de plástico de 150 mL
com 10 g de solo e agitados horizontalmente por uma
hora. A seguir, mantiveram-se os extratos em repouso
por 30 minutos e depois filtrou-se o extrato em filtre
plástico e papel de filtro número 42; Cloro de
cálcio 0,0025 mol L⁻¹ (Kilmer, 1965): 100 mL de uma
solução de cloro de cálcio 0,0025 mol L⁻¹ foram
adicionados em frasco de plástico com 10 g de
solo. A seguir, agitou-se horizontalmente por 15 minutos e
depois ficou descansando de um dia para o outro.
No dia seguinte, os extratos foram filtrados (funil
de plástico e papel de filtro número 42); Água:
100 mL de água destilada e desmineralizada foram

Quadro I. Atributos químicos e matéria orgânica referentes à camada de 0-20 cm das amostras de solo
usadas no estudo

<table>
<thead>
<tr>
<th>Solo</th>
<th>pH-H₂O</th>
<th>P</th>
<th>Al⁺</th>
<th>Ca⁺</th>
<th>S</th>
<th>T</th>
<th>V</th>
<th>m</th>
<th>MO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVa</td>
<td>5,0</td>
<td>4,0</td>
<td>0,70</td>
<td>0,20</td>
<td>0,29</td>
<td>7,70</td>
<td>4</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>LEa</td>
<td>4,4</td>
<td>2,0</td>
<td>0,70</td>
<td>0,20</td>
<td>0,26</td>
<td>7,30</td>
<td>4</td>
<td>73</td>
<td>40</td>
</tr>
<tr>
<td>LRd</td>
<td>5,0</td>
<td>16,0</td>
<td>0,50</td>
<td>3,80</td>
<td>5,80</td>
<td>11,8</td>
<td>49</td>
<td>8</td>
<td>41</td>
</tr>
<tr>
<td>AQA</td>
<td>4,4</td>
<td>56,0</td>
<td>1,00</td>
<td>0,20</td>
<td>0,39</td>
<td>5,20</td>
<td>7</td>
<td>71</td>
<td>15</td>
</tr>
</tbody>
</table>

Obs. P extraído com HCl 0,05 mol L⁻¹ + H₂SO₄ 0,00125 mol L⁻¹; Al, Ca extraído com KCl 1 mol L⁻¹; S = soma de bases; T = cálcio
na forma Ca⁺; V = saturação por bases; m = saturação por alumínio; M.O. = matéria orgânica (EMBRAPA, 1979); Latossolo
Vermelho-Amarelo álico (LVa), Latossolo Vermelho-Escuro álico (LEa), Latossolo Roxo distrófico (LRd) e Areia Quartzosa álica
(AQA).
Quadro 2. Elementos totais, índice de intemperismo (Ki), teores estimados de caulinita (Ka) e granulometria da terra fina referentes à camada de 0-20 cm

<table>
<thead>
<tr>
<th>Solo</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>Ki</th>
<th>SiO₂/Al₂O₃</th>
<th>Ka</th>
<th>Areia grossa</th>
<th>Areia fina</th>
<th>Silte</th>
<th>Argila</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVa</td>
<td>13,5</td>
<td>29,6</td>
<td>7,8</td>
<td>0,77</td>
<td></td>
<td>29</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>74</td>
</tr>
<tr>
<td>LEa</td>
<td>17,8</td>
<td>28,2</td>
<td>10,8</td>
<td>1,08</td>
<td></td>
<td>35</td>
<td>3</td>
<td>6</td>
<td>13</td>
<td>78</td>
</tr>
<tr>
<td>LRD</td>
<td>12,2</td>
<td>11,9</td>
<td>18,9</td>
<td>1,75</td>
<td></td>
<td>26</td>
<td>6</td>
<td>22</td>
<td>20</td>
<td>52</td>
</tr>
<tr>
<td>AQA</td>
<td>3,7</td>
<td>3,8</td>
<td>2,6</td>
<td>1,56</td>
<td></td>
<td>8</td>
<td>22</td>
<td>61</td>
<td>2</td>
<td>14</td>
</tr>
</tbody>
</table>

(1) Elementos totais analisados pelo método do ataque sulfúrico (EMBRAPA, 1979). Latossolo Vermelho-Amarelo álico (LVa), Latossolo Vermelho-Escura álico (LEa), Latossolo Roxo distrófico (LRd) e Areia Quartzosa álica (AQA). (2) Relação molecular: % SiO₂/Al₂O₃ x 1.7. (3) Análise textural, método da pipeta (EMBRAPA, 1979).

adicionados em frascos de plástico de 150 mL com 10 g de solo. Daí para frente, o procedimento foi o mesmo do ácido acético.

A determinação do Si no extrato foi feita misturando-se 10 mL do extrato (filtrado/decantado) com 1 mL da solução sulfato-molibdica 7,5% (7,5 g de molibdato de amônia + 10 mL de ac. sulfúrico 9 mol L⁻¹ em 100 mL). Após 10 minutos foram acrescentadas 2 mL da solução ácido tartárico 20% e, após 5 minutos, adicionaram-se 10 mL da solução de ácido ascorbico 0,3%. Depois de uma hora, foi feita a leitura do Si em espectrofotômetro e no comprimento de onda de 660 nm.

RESULTADOS E DISCUSSÃO

Relativamente pouca diferença existe entre os métodos de extração testados quanto à capacidade em estimar a disponibilidade do Si no solo para o arroz de sequeiro. Todos apresentaram elevado grau de correlação com o Si acumulado na parte aérea do arroz. Os coeficientes de determinação (R²) foram de 0,88; 0,84; 0,70 e 0,69, respectivamente, para os extratores ácido acético, água, cloreto de cálcio, 0,025 mol L⁻¹ e tampão pH 4.0 (Figura 1).

O extrator que apresentou o maior coeficiente de determinação foi o ácido acético. Esse extrator, além de ser de simples preparo, também apresenta um custo de reagente bastante baixo e isso facilita seu uso em análises de rotina, isto é, para grande número de amostras. Apesar de o coeficiente de determinação da água ter sido elevado (R² = 0,84), esse extrator apresenta a inconveniência da dispersão que provoca nas partículas de argila, exigindo um tempo muito maior de decantação, antes da filtragem. O ácido acético foi também o extrator que mais extraiu Si do solo (Quadro 3). Esse método extraiu 15, 108 e 108% mais Si que os extratores tampão pH 4.0, cloreto de cálcio e água, respectivamente. A maior capacidade de extração do ácido acético pode, em parte, explicar o maior coeficiente de determinação, visto que quanto maior concentração de Si na solução menores arros de leitura. A água e o cloreto de cálcio foram os que menos extrairam Si. A extração com cloreto de cálcio foi comparável com a água. Resultados semelhantes foram obtidos por Raj e Camargo (1973).

O extrator tampão pH 4,0 foi o que apresentou o menor coeficiente de determinação (R² = 0,69) em relação ao Si acumulado pela planta, o que indica que, para os solos estudados, a liberação do Si da

Figura 1. Relação entre o Si extraído pelos extratores ácido acético 0,5 mol L⁻¹ e cloreto de cálcio (a) tampão pH 4,0 e água (b) e o Si acumulado na parte aérea de plantas de arroz de sequeiro. (** significativo a 1%).
Quadro 3. Silício extraído por quatro métodos em solos cultivados com arroz de sequeiro (tratamento com 960 kg ha⁻¹ de Si aplicado)

<table>
<thead>
<tr>
<th>Método de extração</th>
<th>Solo</th>
<th>Média</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lrd</td>
<td>LEa</td>
</tr>
<tr>
<td></td>
<td>mg dm⁻³</td>
<td></td>
</tr>
<tr>
<td>Tampão pH 4,0</td>
<td>16,4</td>
<td>14,2</td>
</tr>
<tr>
<td>Ácido acético 0,5 mol L⁻¹</td>
<td>23,0</td>
<td>15,0</td>
</tr>
<tr>
<td>Cloreto de cálcio 0,025 mol L⁻¹</td>
<td>9,0</td>
<td>7,0</td>
</tr>
<tr>
<td>Água</td>
<td>8,6</td>
<td>7,8</td>
</tr>
</tbody>
</table>

Figura 2. Teores de Si nas folhas do arroz de sequeiro em função do Si extraído do solo pelo método ácido acético 0,5 mol L⁻¹. (** significativo a 1%).

Examinando a influência do volume da solução extratora para determinado peso de solo, resultados obtidos a partir de 2 amostras fixas de cada solo (total = 8 amostras), nota-se que o Si extraído diminuiu quando se aumentava a relação soluçõesol. (Quadro 4). Valores de 18,1; 10,7 e 4,6 mg dm⁻³ foram obtidos (média dos quatro solos) para as relações soluçõesol de 1:5; 1:10 e 1:25, respectivamente. Isso acontece porque o Si extraível não é totalmente removido em uma ou mesmo várias extrações, pois os solos apresentam grande capacidade de restituir para a solução extratora o Si removido por extrações sucessivas. O tempo de agitação não teve, aparentemente, influência na quantidade extraída de Si. Valores de 9,3; 7,6; 10,7 e 8,9 mg dm⁻³ (média de 8 amostras) foram obtidos para 5, 30, 60 e 90 minutos de agitação, respectivamente (Quadro 4).

Os maiores valores de Si extraível (Quadro 3) foram observados no Lrd (média dos quatro extratores testados). Isso indica que nesse solo há...

Quadro 4. Efeito da relação soluçõesol. e tempo de agitação sobre a extração do Si (mg dm⁻³) pelo método ácido acético 0,5 mol L⁻¹

<table>
<thead>
<tr>
<th>Amostra de solo</th>
<th>Relação sólido soluç.</th>
<th>Tempo de agitação</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1:5</td>
<td>1:10</td>
</tr>
<tr>
<td>LVA - 0²)</td>
<td>10,7</td>
<td>5,4</td>
</tr>
<tr>
<td>LVA - 4²)</td>
<td>23,9</td>
<td>14,2</td>
</tr>
<tr>
<td>LEA - 0</td>
<td>10,2</td>
<td>6,7</td>
</tr>
<tr>
<td>LEA - 4</td>
<td>41,0</td>
<td>15,0</td>
</tr>
<tr>
<td>Lrd - 0</td>
<td>14,1</td>
<td>9,5</td>
</tr>
<tr>
<td>Lrd - 4</td>
<td>27,8</td>
<td>24,5</td>
</tr>
<tr>
<td>AQA - 0</td>
<td>4,1</td>
<td>2,7</td>
</tr>
<tr>
<td>AQA - 4</td>
<td>13,3</td>
<td>7,7</td>
</tr>
<tr>
<td>Médias</td>
<td>18,1</td>
<td>10,7</td>
</tr>
</tbody>
</table>

¹) Tratamento-testemunha. ²) 960 kg ha⁻¹ de Si.
menor chance de observar resposta à adubação com silício. A maior quantidade de Si extraível desse solo está diretamente associada ao menor grau de intemperismo da fração argila (Quadro 2).

CONCLUSÃO

1. O ácido acético 0,5 mol L\(^{-1}\) foi o que apresentou a melhor estimativa de Si disponível no solo para o arroz de sequeiro.

AGRADECIMENTOS

Ao professor Gilberto P. Corrêa, da Universidade Federal de Uberlândia, pelas idéias e sugestões; ao técnico de laboratório Paulo Rabelo, pelo auxílio nas análises de Si; à FUNDAÇÃO BANCO DO BRASIL e à FAPEMIG, pelo auxílio financeiro.

LITERATURA CITADA


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SEPARATA

VIÇOSA - MINAS GERAIS
EFEITO DO SILICATO DE CÁLCIO NO TEOR DE SILÍCIO NO SOLO E NA PRODUÇÃO DE GRÃOS DE ARROZ DE SEQUEIRO(1)

G. H. KORNDÖRFER(2), V.A. ARANTES(3),
G. F. CORRÊA(4) & G. H. SNYDER(5)

RESUMO

Em solos com baixos teores de silício (Si) “disponível”, a adubação com silicato de cálcio (CaSiO₃) pode melhorar as características químicas do solo, tais como o pH, o Ca trocável e o Si “disponível”. Efeito na produtividade do arroz também pode ocorrer em decorrência do aumento da resistência ao acamamento e área fotosintética. Neste trabalho, objetivou-se avaliar a disponibilidade do Si em solos de cerrado. O experimento foi realizado em casa de vegetação com a cultura do arroz de sequeiro, e os tratamentos foram cinco doses de Si (0, 120, 240, 480 e 960 kg ha⁻¹), aplicadas na forma de silicato de cálcio, e quatro solos: Latossolo Vermelho-Escuro álico (LEa), Latossolo Vermelho-Amarelo álico (LVa), Latossolo Roxo distrófico (LRd) e Areia Quartzosa álica (AQa). O delineamento experimental foi o inteiramente casualizado com quatro repetições. Avaliou-se o efeito do silicato de cálcio nos teores de Si, Ca e pH do solo e no rendimento de grãos de arroz. Observou-se aumento nos teores de Ca e nos valores de pH do solo. A recuperação do Si aplicado variou segundo a classe de solo e a dose aplicada. O teor de Si “disponível” no solo variou na ordem LRd > LEa ≤ LVa > AQa. O nível de suficiência de Si no solo foi de 9,8 mg dm⁻³ para atingir 90% da produção máxima.

Termos de indexação: saturação por bases, nível de suficiência, disponibilidade.

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INTRODUÇÃO

Os cerrados brasileiros ocupam, aproximadamente, 200 milhões de hectares, isto é, cerca de 23% do território brasileiro (Ferri, 1963). Essa vasta porção territorial, situada na faixa intertropical brasileira, tem sua maior expressão no Planalto Central com 175 milhões de hectares. Desta área, 112 milhões de hectares são potencialmente mecanizáveis e a maior parte do restante tem potencial para reflorestamento e pecuária. Todavia, durante muito tempo, essa área foi considerada sem valor para a agricultura e de baixo potencial para a pecuária.

Geograficamente, relacionam-se os cerrados com superfícies velhas. Os solos dessas regiões são, portanto, em geral, profundamente intemperizados e lixiviados, com acentuada dessilicatização e pobreza em bases, o que lhes confere uma fração argilosa essencialmente constituída por caulinita e sesquixídeos, com baixa relação molecular SiO₂/Al₂O₃ (relação Kᵢ), algumas vezes inferior a 0,5 (EMBRAPA, 1982, Corrêa, 1989).

Na solução do solo, o H₄SiO₄ comporta-se como um ácido muito fraco, de forma que, em pH 7,0, apenas 0,2% ioniza-se na forma carregada negativamente SiO(OH)₃⁻, diminuindo o grau de ionização com o aumento do pH (McKeague & Cline, 1963). Segundo Alcarde (1992), a ação neutralizante do silicato pode ser explicada de acordo com as seguintes reações:

\[
\text{CaSiO}_3 \leftrightarrow \text{Ca}^{2+} + \text{SiO}_3^{2-} \quad (1)
\]

\[
\text{SiO}_3^{2-} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SiO}_3 + \text{OH}^- \quad (2)
\]

\[
\text{H}_2\text{SiO}_3 + \text{H}_2\text{O} \leftrightarrow \text{H}_4\text{SiO}_4 + \text{H}^+ \quad (3)
\]

Em solos de textura e idade variadas, do estado de São Paulo, Raji & Camargo (1973) verificaram os menores valores de Si solúvel no Latossolo arenoso e os maiores valores num Podzólico argiloso. Isto se deve à reduzida percentagem de argila neste Latossolo, alinhando à menor superfície específica total em relação ao Podzólico menos intemperizado e mais argiloso. Esses autores encontraram teores de Si extraíveis com CaCl₂ 0,0025 mol L⁻¹, variando de 1 a 43 mg dm⁻³. Valores maiores foram encontrados nos solos mais argilosos, havendo também uma relação negativa com o grau de intemperismo. Para os solos com os mesmos teores de argila, os teores de Si solúvel foram maiores nos solos com horizonte B textural do que nos solos com B latossólico.

O excesso de Fe⁶⁺ na solução do solo pode provocar toxidez desse elemento no arroz e causar deficiência de outros micro e macronutrientes essenciais à nutrição da planta (Ponnamperuma, 1972). A presença do Si na planta tem aumentado a tolerância do arroz à toxidez de Mn e Fe, fato atribuído à maior oxidação que esses dois elementos sofrem na rizosfera (Galvez et al., 1989).

O objetivo deste trabalho foi avaliar o efeito do silicato de cálcio como fonte de Si para a cultura do arroz de sequeiro em quatro solos de cerrados, trabalhando com a hipótese de que o aumento na absorção de Si poderia produzir plantas mais eretas, com maior capacidade fotossintética e, como consequência, maior rendimento de grãos.

MATERIAL E MÉTIODOS

O trabalho foi realizado em casa de vegetação, utilizando-se amostras de terra coletadas nos primeiros 20 cm de profundidade de quatro solos, classificados, segundo EMBRAPA (1988) como Latossolo Vermelho-Escurto-ácido (LEA), Latossolo
Vermelho-Amarelo álico (LVA), Latossolo Roxo distrófico (LRD) e Areia Quartzosa álica (AQa), de áreas ainda não cultivadas do Triângulo Mineiro. Os resultados das análises químicas, texturais e mineralógicas encontram-se nos quadros 1 e 2. Na análise dos teores de elementos totais (SiO₂, Al₂O₃ e Fe₂O₃) foi empregado o método de ataque sulfúrico, descrito em EMBRAPA (1979).

As amostras de solos (0-20 cm) foram secadas ao ar, passadas em peneira com 5 mm de abertura de malha e homogeneizadas. Cada vaso, com 8 kg de terra, foi adubado com 1,905 g de N [(NH₄)₂SO₄], 2,329 g de P [(CaH₂PO₄)]·1,385 g de K (K₂SO₄), 2,858 g de Ca (CaSO₄·2H₂O), 1,475 g de Mg (MgSO₄), 0,024 g de Zn (ZnSO₄), 0,008 g de B (H₂BO₃), 0,012 g de Mn (MnSO₄) e 0,012 g de Cu (CuSO₄). Em cada vaso, foram colocadas cinco sementes do cultivar de arroz IAC-165 (altamente sensível à bruzone), mantendo a umidade do solo próxima à capacidade de campo. A capacidade de campo foi determinada com base no consumo médio de água necessário para atingir o ponto de friabilidade do solo. Nessa determinação, foram utilizadas cinco amostras de 1 kg de terra de cada um dos solos testados. Os vasos foram irrigados com água deionizada. A adubação de cobertura foi feita com uréia, 0,28 e 0,14 g vaso⁻¹, aos 35 e 45 dias da semeadura, respectivamente.

Usou-se, como fonte de Si, o mineral wollastonita, que tem sido empregado, com frequência, em estudos com Si. Apresenta, em sua composição, principalmente silicato de cálcio (CaSiO₃). É fornecido pela Ipiranga Química de São Paulo (nome comercial, Vansil, EW-20), com as seguintes características: 24,2% de Si e 30,1% de Ca. O silicato foi incorporado em volume total de solo 30 dias antes do plantio, nas doses equivalentes a 0 (testemunha), 120, 240, 480 e 960 kg har⁻¹ de Si.

Depois da colheita, amostras de solo foram analisadas para pH e Ca, segundo Vettori (1999). Extraiu-se o Si com ácido acético 0,5 mol L⁻¹ (Korndörfer et al., 1999). Dez gramas de solo foram agitadas por 1 h com 100 mL dessa solução extratora. Após esse tempo, esperou-se decantar por 15 min, filtrou-se a solução, deixando-a em repouso por mais 12 h. A determinação do Si foi feita no sobrenadante e em foto-colorímetro, no comprimento de onda de 660 nm. Na determinação do Si, foi utilizada uma adaptação do método descrito por Elliott & Snyder (1991), em que o ácido 1-amino-2-naftol-4-sulfônico, usado como redutor, foi substituído pelo ácido ascórico.

A amostragem para análise foliar foi realizada na época da colheita, coletando-se toda a parte aérea do arroz (colmões + folhas), secando as amostras a 65°C e depois pesando-as. Na análise do Si, foi empregado o método de Elliott & Snyder (1991), cujo procedimento de abertura da amostra (digestão) é feito em autoclave (alta pressão e temperatura) e meio básico (via úmida).

O delineamento experimental foi o inteiramente casualizado com quatro repetições, e a análise estatística foi feita com o auxílio do programa SANEST (Sistema de Análise Estatística).

Uma curva de calibração entre a produção relativa e o teor de Si no solo foi utilizada na obtenção do nível de suficiência de Si no solo. Obteve-se o valor da produção relativa pela divisão do peso de grãos de cada vaso pelo peso de grãos do vaso que apresentou a maior produção e multiplicando-se este resultado por 100. A curva de calibração não incluiu os resultados de produtividade do Latossolo Roxo (LRD), dada a fitotoxicidade de Fe observada nas folhas. O nível de suficiência para o Si no solo foi estabelecido para atingir 90% da produtividade máxima.

Para calcular a recuperação do Si no solo, foram considerados o Si "disponível" após o cultivo, o Si acumulado na parte aérea das plantas e a dose de Si aplicada.

RESULTADOS E DISCUSSÃO

Os teores de Si extraídos variaram com a classe de solo (Figura 1). Os resultados mostram, nos quatro solos, um incremento nas quantidades de Si "disponível" com a aplicação das doses de silicato de cálcio. O Si extraído, após o final do experimento, variou de 10,5-22,9 e 6,6-15,1 mg dm⁻³, respectivamente, para os solos LRD e LEA, e de 5,7-14,5 e 3,2-7,6 mg dm⁻³, respectivamente, para os solos LVA e AQa (Quadro 4).

Segundo Snyder (1991), solos com teores de Si inferiores a 10 mg dm⁻³, extraídos com ácido acético 0,5 mol L⁻¹, deveriam receber adubação com Si para obtenção de rendimentos máximos, enquanto solos com teores iguais ou superiores a 15 mg dm⁻³ não necessitariam de aplicação desse elemento.

Quadro 1. Características químicas dos solos, na camada de 0-20 cm

<table>
<thead>
<tr>
<th>Solo⁴</th>
<th>pH H₂O</th>
<th>P</th>
<th>Al</th>
<th>Ca</th>
<th>S</th>
<th>T</th>
<th>V</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg dm⁻³</td>
<td>cmol dm⁻³</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVA</td>
<td>5,0</td>
<td>0,4</td>
<td>0,70</td>
<td>0,20</td>
<td>0,29</td>
<td>7,70</td>
<td>4</td>
<td>70</td>
</tr>
<tr>
<td>LRA</td>
<td>4,4</td>
<td>0,2</td>
<td>0,70</td>
<td>0,20</td>
<td>0,26</td>
<td>7,30</td>
<td>4</td>
<td>73</td>
</tr>
<tr>
<td>LRD</td>
<td>5,0</td>
<td>1,6</td>
<td>0,50</td>
<td>3,80</td>
<td>5,80</td>
<td>11,80</td>
<td>49</td>
<td>8</td>
</tr>
<tr>
<td>AQa</td>
<td>4,4</td>
<td>4,5</td>
<td>1,00</td>
<td>0,20</td>
<td>0,29</td>
<td>5,20</td>
<td>7</td>
<td>71</td>
</tr>
</tbody>
</table>

⁴Latossolo Vermelho-Amarelo álico (LVA), Latossola Vermelho-Escuro álico (LEA), Latossolo Roxo distrófico (LRD) e Areia Quartzosa álica (AQa). Obs.: P extraído com HCl 0,05 mol L⁻¹ + H₂SO₄ 0,025 mol L⁻¹, Al C extraído com KCl 1 mol L⁻¹; S = Soma de bases; T = Capacidade de troca de cátions a pH 7,0; V = Saturação por bases; m = Saturação por aluminio (Vettori, 1989).
Quadro 2. Teores de elementos totais, índice de interpenetração (Kι), teores estimados de cauitinita (Kα) e granulometria da terra fina, referentes aos 20 cm superficiais dos solos

<table>
<thead>
<tr>
<th>Solos</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>Kι</th>
<th>Kα</th>
<th>Areal grossa</th>
<th>Areal fina</th>
<th>Silte</th>
<th>Argila</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lva</td>
<td>13,5</td>
<td>29,6</td>
<td>7,8</td>
<td>0,77</td>
<td>29</td>
<td>60</td>
<td>100</td>
<td>100</td>
<td>740</td>
</tr>
<tr>
<td>LEa</td>
<td>17,8</td>
<td>28,2</td>
<td>10,8</td>
<td>1,08</td>
<td>38</td>
<td>30</td>
<td>60</td>
<td>130</td>
<td>780</td>
</tr>
<tr>
<td>LRd</td>
<td>12,2</td>
<td>11,9</td>
<td>18,9</td>
<td>1,75</td>
<td>26</td>
<td>60</td>
<td>220</td>
<td>200</td>
<td>520</td>
</tr>
<tr>
<td>Aqa</td>
<td>3,7</td>
<td>3,8</td>
<td>2,6</td>
<td>1,66</td>
<td>8</td>
<td>220</td>
<td>610</td>
<td>20</td>
<td>140</td>
</tr>
</tbody>
</table>

(1) Solos: vide rodapé do quadro 1. (2) Relação molecular: (% SiO₂ / % Al₂O₃) x 1,7. (3) Análise textural, método da pipeta (Embrapa, 1979).

Figura 1. Efeito de doses de Si aplicado, sobre o Si “disponível”, em amostras de solo (0-20 cm).

A aplicação de wollastonita aumentou o pH e o Ca trocável, em todos os solos (Quadro 3). A elevação do pH é explicada pelo aumento na concentração de hidroxilas (OH⁻), conforme pode ser inferido das equações (2) e (3). O silicato de cálcio atuou como corretivo de acidez (Alcarde, 1992). Os teores de Ca no solo também aumentaram em função da composição do silicato (30,1% de Ca). Por outro lado, os aumentos nos teores de Ca trocáveis confirmam que a wollastonita reagiu com o solo durante o período experimental.

Os valores de produção relativa (PR) variaram de 24 a 100% (Quadro 4), quanto menor o índice, maior foi a resposta ao Si aplicado. O estudo de calibração (Quadro 4 e Figura 2) revelou que o nível de suficiência de Si para os solos em questão, e para se atingir 90% da produção máxima, em casa de vegetação, foi de 9,8 mg dm⁻³. Isto é, segundo a interpretação da curva de calibração, o cultivo de arroz de sequeiro em solos com teores de Si “disponível” inferior a 9,8 mg dm⁻³ revelou alta probabilidade de apresentar resposta positiva para a aplicação de silicatos solúveis. Esses resultados, no entanto, precisam ser testados no campo. Segundo Imaiizuë & Yoshida (1958), a aplicação de fertilizante silicatado para o arroz é recomendada quando os teores de Si no solo forem menores que 4,9 mg dm⁻³ de solo (Si extrai-do com acetato de sódio pH 4,0).

Para obter o valor de suficiência (9,8 mg dm⁻³ de Si), foi necessário primeiro definir o melhor ajuste matemático (Figura 2). A análise de regressão mostrou que a equação Y = 142,37 - (164,31/X)² foi a que melhor se ajustou ao conjunto de dados, apresentando o maior coeficiente de determinação (R² = 0,81**). O Latossolo Roxo (LRd) não foi incluído na curva de calibração por causa dos sintomas visuais de toxidez de Fe (avermelhamento na extremidade das folhas) observados, particularmente nas testemunhas. Nos tratamentos que receberam as doses mais altas de silicato, as plantas apresentaram-se normais, isto é, sem sintoma de fitotoxidade.

Resultados da análise de Fe na parte aérea do arroz (dados não apresentados) mostraram valores superiores a 1,100 g g⁻¹. Esses valores indicaram alto nível de fitotoxidez. As razões para a elevada absorção de Fe pelas plantas são atribuídas ao alto teor de óxido de ferro no LR (Quadro 2) e a um descuido no controle de umidade nos vasos. A umidade do solo ficou, por um longo período de tempo, acima da capacidade de campo, acarretando uma condição anaeróbio e, possivelmente, a redução do Fe (Fe³⁺ → Fe²⁺), aumentando, assim, a sua disponibilidade para as plantas. Nos vasos onde foi aplicado silicato de cálcio, o pH do solo foi mais alto se comparado com os vasos sem silicato (Quadro 3). A elevação do pH, ainda que pequena, pode ter contribuído, de modo significativo, para reduzir a disponibilidade do Fe (Fe²⁺) no solo. Uma segunda hipótese apontada é o efeito do Si absorvido pelo arroz no transporte do O₂ até a superfície radicular. Isto é, quanto maior o Si absorvido, maior é o transporte de O₂ e, conseqüentemente, maior é a precipitação do Fe livre (Fe²⁺) e menor a absorção.
Figura 2. Relação entre a produção relativa e o teor de Si “disponível” no solo extraído com ácido acético 0,5 mol L\(^{-1}\) (solo LRd excluído).

Quadro 3. Efeito de doses de Si (γ) sobre os teores de Ca e pH (X) após a colheita do arroz

<table>
<thead>
<tr>
<th>Solo (^{(1)})</th>
<th>Ca trocável</th>
<th>(\gamma = 3,9381 + 0,00292X)</th>
<th>0,92**</th>
<th>pH em CaCl(_2)</th>
<th>(\gamma = 4,5037 + 0,00041X)</th>
<th>0,78**</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRd</td>
<td>0,95**</td>
<td></td>
<td></td>
<td>LEa</td>
<td>0,95**</td>
<td></td>
</tr>
<tr>
<td>LVa</td>
<td>0,75**</td>
<td></td>
<td></td>
<td>AQA</td>
<td>0,87**</td>
<td></td>
</tr>
</tbody>
</table>

\(^{(1)}\) Solos: vide redesp do quadro 1. ** significativo a 1%.

Segundo Barbosa Filho (1987), o Si pode aumentar o número e o diâmetro dos aerênquimas nas plantas de arroz, estruturas responsáveis pela condução do oxigênio das folhas até às raízes.

A recuperação média do Si aplicado ao solo foi de 42%, variando de 12 a 58%, dependendo da dose aplicada e do solo (Quadro 5). A recuperação do Si foi maior nos Latossolos, em comparação com a Areia Quartzosa. Na Areia Quartzosa, em razão do baixo teor de argila e de matéria orgânica e da baixa capacidade de retenção de água, a interação das partículas do silicato com a fase sólida foi menor, explicando, em parte, a menor reatividade desse solo.

O Si “disponível” para as plantas, extraído pelo método acético 0,5 mol L\(^{-1}\), aparentemente não relacionou-se com o teor de Si total do solo (Figura 3). Segundo Jones & Handreck, (1963), para solos de mesmo pH, a quantidade de Si na solução do solo varia em função da quantidade, tipo e grau de cristalinidade dos óxidos de Fe e Al livres. Isso, explica, em parte, a falta de correspondência entre o Si total e o “disponível” no solo.

Segundo esses autores, quando amostras de óxido de ferro e alumínio, com o mesmo grau de cristalinidade, são comparadas, é notória a maior eficiência do oxigênio de alumínio em adsorver ácido monossilicato comparado com o oxigênio de ferro. Essa informação ajuda a explicar os valores mais baixos de Si “disponível” encontrados nos solos LEa e LVa (7 e 6 mg dm\(^{-3}\), respectivamente) comparados com os do LRd (11 mg dm\(^{-3}\), Figura 3), pois os dois primeiros também apresentaram valores mais altos de Al\(_2\)O\(_3\) e SiO\(_2\) (Quadro 2), indicando maior adsorção do Si e, consequentemente, menor disponibilidade para a planta. O Latossolo Roxo distrófico (LRd), substrato basal, é pedogeneticamente menos evoluído que o Latossolo Vermelho-Escurto (LEa) e o Latossolo Vermelho-Amarelo (LVa), ambos de textura muito argilosa, que ocorrem nos chapadões. Consequentemente, o LRd apresentou uma dessilicatação menor, com relação molecular SiO\(_2\)/Al\(_2\)O\(_3\) (Ka) = 1,75 na camada de 0-20 cm de profundidade (Quadro 2). Já os baixos teores de Si “disponível” encontrados no solo AQA (3 mg dm\(^{-3}\), Figura 3) devem-se, em parte, aos baixos teores de
Quadro 4. Efeito de doses de Si no teor de Si “disponível” no solo, no peso de grãos e na produção relativa nos solos LRd, LVa, LEa e AQa

<table>
<thead>
<tr>
<th>Dose de Si aplicado</th>
<th>Si “disponível” no solo</th>
<th>Peso de grãos</th>
<th>Produção relativa(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg ha(^{-1})</td>
<td>mg dm(^{-3})</td>
<td>g vaso(^{-1})</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latossolo Roxo distrófico - LRd</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>10,5</td>
<td>9,45</td>
<td>33</td>
</tr>
<tr>
<td>120</td>
<td>13,0</td>
<td>8,80</td>
<td>24</td>
</tr>
<tr>
<td>240</td>
<td>14,0</td>
<td>10,62</td>
<td>37</td>
</tr>
<tr>
<td>480</td>
<td>15,0</td>
<td>17,39</td>
<td>61</td>
</tr>
<tr>
<td>960</td>
<td>22,9</td>
<td>21,57</td>
<td>76</td>
</tr>
<tr>
<td>Latossolo Vermelho-Escuro álico - LEa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6,6</td>
<td>23,61</td>
<td>83</td>
</tr>
<tr>
<td>120</td>
<td>7,6</td>
<td>22,36</td>
<td>79</td>
</tr>
<tr>
<td>240</td>
<td>9,1</td>
<td>26,48</td>
<td>93</td>
</tr>
<tr>
<td>480</td>
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<td>89</td>
</tr>
<tr>
<td>960</td>
<td>15,1</td>
<td>27,54</td>
<td>97</td>
</tr>
<tr>
<td>Latossolo Vermelho-Amarelo álico - LVa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>5,7</td>
<td>23,34</td>
<td>82</td>
</tr>
<tr>
<td>120</td>
<td>7,8</td>
<td>24,27</td>
<td>85</td>
</tr>
<tr>
<td>240</td>
<td>9,5</td>
<td>28,10</td>
<td>99</td>
</tr>
<tr>
<td>480</td>
<td>11,6</td>
<td>28,09</td>
<td>98</td>
</tr>
<tr>
<td>960</td>
<td>14,9</td>
<td>28,45</td>
<td>100</td>
</tr>
<tr>
<td>Areia Quartzosa álica - AQa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3,2</td>
<td>15,10</td>
<td>53</td>
</tr>
<tr>
<td>120</td>
<td>4,1</td>
<td>17,55</td>
<td>62</td>
</tr>
<tr>
<td>240</td>
<td>4,4</td>
<td>18,48</td>
<td>65</td>
</tr>
<tr>
<td>480</td>
<td>5,7</td>
<td>16,57</td>
<td>55</td>
</tr>
<tr>
<td>960</td>
<td>7,6</td>
<td>21,02</td>
<td>74</td>
</tr>
</tbody>
</table>

(1) Produção Relativa (PR%) = (Peso de grãos no tratamento / peso de grãos no tratamento com rendimento máximo) x 100.

Quadro 5. Recuperação de Si aplicado ao solo em termos de sua extração do solo e absorção pela planta

<table>
<thead>
<tr>
<th>Si aplicado</th>
<th>Si “disponível” no solo</th>
<th>Si acumulado na planta</th>
<th>Total Si(1) solo + planta</th>
<th>Si recuperado</th>
<th>Recuperação(2)</th>
<th>Média</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g vaso(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latossolo Roxo distrófico - LRd</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,00</td>
<td>0,08</td>
<td>1,69</td>
<td>1,77</td>
<td>0,18</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>0,48</td>
<td>0,10</td>
<td>1,85</td>
<td>1,95</td>
<td>0,46</td>
<td>43</td>
<td>44</td>
</tr>
<tr>
<td>0,96</td>
<td>0,12</td>
<td>2,48</td>
<td>2,60</td>
<td>0,83</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>3,84</td>
<td>0,18</td>
<td>3,31</td>
<td>3,49</td>
<td>1,72</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Latossolo Vermelho-Escuro álico - LEa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,00</td>
<td>0,05</td>
<td>1,24</td>
<td>1,29</td>
<td>0,26</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>0,48</td>
<td>0,06</td>
<td>1,49</td>
<td>1,55</td>
<td>0,38</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>0,96</td>
<td>0,07</td>
<td>1,66</td>
<td>1,67</td>
<td>0,88</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>1,92</td>
<td>0,09</td>
<td>1,98</td>
<td>2,07</td>
<td>0,78</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>3,84</td>
<td>0,12</td>
<td>2,90</td>
<td>3,02</td>
<td>1,73</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Latossolo Vermelho-Amarelo álico - LVa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,00</td>
<td>0,05</td>
<td>1,01</td>
<td>1,15</td>
<td>0,27</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>0,48</td>
<td>0,06</td>
<td>1,36</td>
<td>1,42</td>
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<tr>
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<td>Areia Quartzosa álica - AQa</td>
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</tr>
<tr>
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<td>1,07</td>
<td>0,76</td>
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</tr>
<tr>
<td>1,92</td>
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<td>1,65</td>
<td>1,70</td>
<td>1,98</td>
<td>27</td>
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</tr>
<tr>
<td>3,84</td>
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<td>1,99</td>
<td>1,98</td>
<td>2,02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Si “disponível” no solo + Si acumulado na planta. (2) Recuperação do Si aplicado (%) = (Si recuperado / Si aplicado) x 100.
argila e à ausência de minerais primários sensíveis ao ataque com ácido sulfúrico. Este método não solubilizou a fração argila por ser ela constituída de minerais resistentes.

CONCLUSÕES

1. A aplicação do silicato de cálcio na forma de wollastonita aumentou os teores de Si, Ca e os valores de pH no solo.

2. Os teores de Si “disponível” diminuíram na ordem dos solos LRd > LEd = LVa > AQa.

3. O nível de suficiência de Si no solo para atingir 90% da produção máxima de arroz de sequeiro, em condições de casa de vegetação, foi de 9,8 mg dm⁻³.

4. A recuperação do Si variou com a classe de solo e com a dose de Si aplicada.

AGRADECIMENTOS

Ao pesquisador e fitopatologista, Dr. Lawrence Datnoff, da University of Florida, pelas sugestões; ao técnico de laboratório, Paulo Rabelo, pelo auxílio nas análises de Si; à Fundação Banco do Brasil e à FAPEMIG, pelo auxílio financeiro.

LITERATURA CITADA


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Silicon Nutrition and Sugarcane Production: A Review

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ABSTRACT

Silicon (Si) is one of the most abundant elements found in the earth’s crust, but is mostly inert and only slightly soluble. Agriculture activity tends to remove large quantities of Si from soil. Sugarcane is known to absorb more Si than any other mineral nutrient, accumulating approximately 380 kg ha⁻¹ of Si, in a 12-month-old crop. Sugarcane (plant growth and development) responses to silicon fertilization have been documented in some areas of the world, and applications on commercial fields are routine in certain areas. The reason for this plant response or yield increase is not fully understood, but several mechanisms have been proposed. Some studies indicate that sugarcane yield responses to silicon may be associated with induced resistance to biotic and abiotic stresses, such as disease and pest resistance, Al, Mn, and Fe toxicity alleviation, increased P availability, reduced lodging, improved leaf and stalk erectness, freeze resistance, and improvement in plant water economy. This

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review covers the relationship of silicon to sugarcane crop production, including recommendations on how to best manage silicon in soils and plants, silicon interactions with other elements, and laboratory methodology for determining silicon in the soil, plant and fertilizer. In addition, a future research agenda for silicon in sugarcane is proposed.

INTRODUCTION

Integrated management of 13 physiologically essential nutrients, namely six macronutrients (nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg)) and seven micronutrients (iron (Fe), manganese (Mn), zinc (Zn), boron (B), copper (Cu), molybdenum (Mo), and chloride (Cl)) are generally considered by agronomists for increasing and sustaining crop yields. However, there are non-essential elements, that under certain agroclimatic conditions, enhance plant growth by promoting several physiological processes. Although not considered essential, these elements are said to be functional nutrients (Mengel and Kirkby, 1982). At times they are so important that they can be regarded agronomically essential to sustainable crop production. As far as rice (Orzya sativa L.) and sugarcane (Saccharum officinarum L.) crops are concerned, Si is such an element.

Members of the grass family accumulate large amounts of Si in the form of silica gel (SiO₂·H₂O) that is localized in specific cell types. The function of Si in plants has been proposed as i) support for cell walls (resistance to lodging); ii) deterrence to pests and pathogens; iii) reduction in water loss by evapotranspiration; iv) reduction in certain heavy metal toxicities, and v) an essential element for normal development in some species.

Several reports in the literature suggest that Si nutrition has a definite agronomic role in sugarcane crop cultivation, especially on weathered tropical soils such as Oxisols, Ultisols, Entisols, and Histosols (organic soils). Sugarcane absorbs large amounts of Si from soil. According to Samuels (1969), at 12-months the above ground parts contained 379 kg ha⁻¹ of Si, compared with 362 kg ha⁻¹ of K and 140 kg ha⁻¹ of N. Rose et al. (1974) reported the removal of 408 kg ha⁻¹ of total Si from soil by a sugarcane crop (tops + millable cane) yielding of 74 t ha⁻¹. The removal of Si from soil could be more important in intensively cultivated areas. As a result of the Si export of this magnitude, a temporary depletion of bio-available Si in soils could also be a possible factor of declining yields of ratoon crops. In other words, there may be an apparent need for consideration of Si nutrient management in developing appropriate integrated nutrient management system for sustainable sugarcane production, especially in certain ecoregions having Si-deficient weathered soils and organic soils.

This paper intends to review available literature on Si nutrition of sugarcane and to summarize potential agroeconomic benefits of Si management in sugarcane cultivation. Suggestions for research on soil and plant testing are discussed for
determining the need for Si application in sugarcane farming so that sugar productivity could be increased and/or sustained over a long period of time in certain agroclimatic regions.

**SILICON IN SOIL.**

Silicon, after oxygen, is the most abundant element in the earth’s crust, with soils containing approximately 32% Si by weight (Lindsay, 1979). Because of its *abundance in the biosphere*, the *essentiality of Si as a micronutrient for higher plants* is very difficult to prove. Even highly purified water contains about 20 nM Si (Werner and Roth, 1983) and; correspondingly, the leaves of Si accumulator plants that were subjected to a so-called no-silicon treatment usually contain between 0.5-1.9 mg Si g⁻¹ leaf dry weight.

Literature on forms of Si and their reaction in soils has been reviewed by McKeague and Cline (1963a, 1963b); Jones and Handreck (1967); Mitchell (1975); Lindsay (1979); Hallmark et al. (1982); Drees et al. (1989); and Tan (1994).

With increasing rainfall and laterization in warm sub-humid and humid tropical ecoregions, the soils are characterized by a lowering of base saturation and Si content, accompanied by the accumulation of iron and aluminum oxides (desilication) (Figure 1). Desilication is a continuing process mitigated by Si recycling. Silicon is released by the weathering of minerals, but only part is lost by drainage or in a crop ecosystem that is regularly harvested or burned. Inversely, soluble Si may be introduced by runoff, capillary ascension from the water table, or by aeolian, alluvial or any other deposition of silicate material at the soil surface.

According to Baker and Scrivner (1985), the potential leaching losses of Si in the Menoflo soil series (fine-silt, mesic Typic Hapludalfs) were approximately 54.2 kg ha⁻¹ yr⁻¹, which is approximately 200 times greater than the estimated losses for Al, 0.27 kg ha⁻¹ yr⁻¹.

Leaching of Si from the soil and plant uptake are also important in determining Si concentrations in soils (Kittrick, 1969). The concentration of soluble Si in soils is undoubtedly dynamic, where equilibrium conditions are the exception rather than the rule. Changes in moisture content related to alternating wetting-drying cycles in the soil may influence Si concentration in solution more readily than the other processes. Quartz is lost from soils upon weathering; consequently, perturbations of the Si equilibrium must occur, and these reduce the soluble Si concentrations. In soils, quartz is generally concentrated in sand and silt fractions, with secondary quantities in the clay fraction. The parent material of the soil generally dictates which size fraction will have the maximum quartz content. The quartz content of the clay fraction generally ranges from 0 to 250 g kg⁻¹, depending on the parent material and degree of weathering (Tedrow, 1954; Borchardt et al., 1968; Le Roux, 1973); although it may be as high as 750 to 850 g kg⁻¹. Generally, the most highly weathered soils have the lowest content of quartz (Jackson and Sherman, 1993).
A summary of the main reactions/transformations influencing Si concentration in soil solution is shown in Figure 2.

The solid-phase of Si occurs in various discrete and associated forms in soils in well-ordered (quartz) and disordered polymorphs (e.g., opal), and clay-mineral lattice structures. The solubility of disordered or amorphous Si polymorphs in soils at an ambient temperature and neutral pH is approximately 50 to 60 mg Si L\(^{-1}\); whereas that of quartz is much lower, commonly 3 to 7 mg Si L\(^{-1}\) (Alexander et al., 1954; Krauskopf, 1959; Blatt, 1979; Dapples, 1979; Hallmark et al., 1982). The liquid-phase of Si in soil is more complex, but agronomically important. It includes Si in soil solution mainly as monosilicic or orthosilicic acid [H\(_2\)SiO\(_4\) or Si(OH)\(_4\)\(_2\) and may range from 1 to 40 mg Si L\(^{-1}\) (McKeague and Cline, 1963a; Beckwith and Reeve, 1964; Jones and Handreck, 1963, 1967; Crook, 1968; Elgawhary and Lindsay, 1972), with 16 to 20 mg Si L\(^{-1}\) most common in soils near field capacity (Hallmark et al., 1982).

According to Elgawhary and Lindsay (1972), a solid-phase that is less soluble than amorphous Si, but more soluble than quartz controls Si in soil solution. Others
FIGURE 2. Main transformation/process influencing silicon concentration soil solution (Savant et al., 1997).

have suggested that amorphous Si coatings formed due to dehydration (McKeague and Cline, 1963c), kaolinite and montmorillonite (Kittrick, 1969), a surface aluminosilicate component (R) of variable composition (Weaver and Bloom, 1977), and/or opal (Wilding et al., 1979) might regulate the amount of Si in the soil solution. As monosilicic acid loses water, it forms so-called silica gel until the proper moisture content is reached. When the dissolved Si in soil solution exceeds 65 mg Si L⁻¹, polymerization of Si usually occurs and a mixture of monomers and polymers of Si(OH)₄ and Si-organic compounds may be found in soil solution at a given time (Tan, 1994; Matuchenkov and Ammosova, 1996).

The solubility of Si (both crystalline and amorphous) is essentially constant between the pH limits of 2 and 8.5, but increases rapidly above 9. The rapid rise in solubility above 9 is due to ionization of monosilicic acid, as illustrated below:

\[
\text{Si(OH)}_4 + \text{OH}^- \rightarrow \text{Si(OH)}_3 \text{O}^- + \text{H}_2\text{O}
\]

\[
\text{H}_2\text{SiO}_4 + \text{OH}^- \rightarrow \text{H}_3\text{SiO}_4^- + \text{H}_2\text{O}
\]
The relationship observed by Ayres (1966) between Si in the sugarcane leaf and soil Si extracted by 0.5 N ammonium acetate (pH 4.0), implies that the plant uptake of Si is governed by the concentration of Si in the soil solution. If the concentration of monosilicic acid, although varying in soils of same pH, is being maintained at a steady level by soil reserves, the highly weathered soils are bound to become severely depleted in Si if continuously cropped with sugarcane.

The concentration of Si in soil solution seems to be controlled more by chemical kinetics than by thermodynamics (Hallmark et al., 1982), and apparently has no relationship to the total in the soil (Figure 3). However, where Si in solution is higher (soluble Si), the plant content of this element generally is greater (Korndörfer et al., 1999a). According to Drees et al. (1989) the dissolution kinetics of soil Si are influenced not only by nature of Si polymorphs but also by a myriad of soil factors such as organic matter, redox potential, metallic ions, phyllo-silicates, sesqui-oxides, surface area, surface coatings, and overall soil solution dynamics. Organic compounds such as alginic acid, ATP, and amino acids may enhance the dissolution of soil Si (Evans, 1965). Crook (1968) as is demonstrated by the high rates of dissolution of soil Si, including quartz, to leachates containing organic matter, with
the Si going into solution as complexes Si-organic molecules. However, Douglas et al. (1984) did not find a correlation between the large concentrations of soluble organic carbon and monosilicic acid movement in the leachate. Sadzawka and Aerine (1977) reported that humus protected soil Si from dissolution and at the same time prevented Si from adsorption by soils. These observations suggest that the role of soil organic matter in Si dissolution is rather complex and needs further clarification. As particle size decreases or surface area of particles increases, the dissolution rate of Si minerals increase (Iler, 1955; Huang and Vogler, 1972; Lidstrom, 1968). Chemisorption of metallic cations (Al, Fe, etc.) to SiO₂ reduces its dissolution rate, probably due to the formation of relatively insoluble coatings (Jones and Handreck, 1963; Beckwith and Reeve, 1964; Lidstrom, 1968). Soil moisture dynamics seem to play an important role in determining the concentration of Si in soil solution. Evaporation of soil water may result in deposition of amorphous Si coatings that may later be involved in Si dissolution (McKeague and Cline, 1963b).

Silicon sorption in soils is pH-dependent. Low pH results in less sorption, and greater sorption occurs at higher pH (McKeague and Cline, 1963b). A highly significant correlation (r=0.989**) was obtained by Wong You Cheong et al. (1968) using 4 different great soil groups, between extractable Si and pH. Many researchers believe that sesquii-oxides, especially Al oxides, are largely responsible for much of the capacity of soils to sorb soluble Si, with the maximum capacity between pH 8 and 10 (Beckwith and Reeve, 1964; Drees et al., 1989). Adsorption studies of monomeric Si by volcanic ash soils suggest that the pH effect was primarily related to the total number of sites available for Si sorption at a given pH (Wada and Inoue, 1974). Gibson (1994) has determined the kinetics of Si release from soils. He observed relatively rapid removal of Si from soil during the first hour of extraction with 0.01 M CaCl₂, which continued steady for 144 hours. Si sorption by soil appears to be controlled by a second order reaction kinetics (Brown and Mahler, 1987). Jones and Handreck (1963) also showed that iron oxides and especially aluminum oxides were very effective in sorbing monosilicic acid. Therefore, the solubility of Si in soils of the same pH was influenced by the free sesqui-oxides present.

Although the Si sorption process was found to depend on soil pH and sesquioxides, it appears that the equilibrium Si concentration was controlled by amorphous Si deposited at the surfaces of soil particles (Brown and Mahler, 1987). Lopes (1977), working with six soils from different regions of Brazil concluded that, in general, an increase in pH increased Si adsorption and that the adsorption of Si by the soils decreased P adsorption, especially around pH 7.

In general, the pH-dependent sorption-desorption of Si by sesqui-oxides and clays can result in faster establishment between solid and liquid phases of Si in soil than dissolution-precipitation phenomenon (McKeague and Cline, 1963a; Beckwith and Reeve, 1964, Jones and Handreck, 1963). A typical pH-dependent adsorption of Si(OH)₄ by sesqui-oxides can be illustrated by the following reaction:
\[
\text{Si(OH)}_4 + \text{[SiO(OH)]} + \text{H}^+ \\
\text{[Si(OH)]} + \text{Fe(OH)}_3 \rightleftharpoons \text{Fe(OH)}_3 \text{OSi(OH)_2} + \text{OH}^-
\]

The primary processes of chemical weathering of soil silicate are hydration, solution and carbonation; hydrolysis; chelation; oxidation and reduction (Sticher and Bach, 1966). In intensive weathering in sub-humid and humid tropical region, soil Si is lost through leaching. In a climate characterized by wetting and drying, leaching of Si would be greater than in a climate that is continuously moist (Baker and Scrivener, 1985). Based on a mathematical model, potential leaching losses of Si from Hapludalf (Menzro series) could be approximately 54 kg ha\(^{-1}\) yr\(^{-1}\). As a result of desilication, soils have distinct mineralogical systems that can be ranked with respect to Si-content and Si-solubility, as follows: 2:1 clays > 1:1 clays > Al and Fe oxides (Fox et al., 1967b). Saturation extracts of Oxisols of Puerto Rico generally contained less Si (2.4 mg dm\(^{-3}\) Si in solution) than that of Ultisols (5.8 mg dm\(^{-3}\) Si in solution) (Fox, 1982). Soluble Si in red, gray upland, gray lowland and dark red soils of Okinawa, Japan, under sugarcane cultivation, ranged from 0.9 to 46 mg Si 100 g\(^{-1}\) and was positively related to soil pH (Oya et al., 1989; Oya and Kina, 1989). In general, Si concentration in solution of highly weathered soils such as Ultisols and Oxisols is several times less than those soils in temperate regions (McKeague and Cline, 1963c; Juo and Sanchez, 1986; Foy, 1992). This may be a possible factor of lower productivity of sugarcane on tropical soils.

Table I presents the variation found in extractable Si in several soils with accompanying determinations of total Si content of leaves growing of these soils. A sample of sandy soil from near Ocala contained approximately twenty times as much soluble Si as did a sample of Terra Ceia from Oklawaha. Among the organic soils, the highest sample contained eight times as much soluble Si as the lowest. Okeechobee muck from Pahokee carries 3.7 times as much extractable Si as the sample of Everglades peat from Belle Glade (Bair, 1966).

Application of silicates increased the water-soluble P as the rate of application increased, despite the fact that the pH of the soil also increased. The result suggests that the Si effect is not to reduce the formation of insoluble calcium phosphates, but rather to reduce the adsorption of P by the freshly precipitated Fe and Al hydroxides. McKeague and Cline (1963b, 1963c) reported that freshly precipitated hydroxides of polyvalent metals such as Al and Fe are highly effective in Si sorption.

Calcium silicate may neutralize the soil acidity (see equations below) with the formation of silicic acid and could thus diminish the solubility of such elements as Mn, Fe, and Al.

\[
\text{CaSiO}_3 + \text{H}_2\text{O} \rightleftharpoons \text{Ca}^{2+} + \text{SiO}_3^{2-} \\
\text{SiO}_2^{2-} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{SiO}_3^{-} + \text{OH}^- \\
\text{H}_2\text{SiO}_3^{-} + \text{H}_2\text{O} \rightleftharpoons \text{SiO}_4^{2-} + \text{H}_2\text{O} + \text{OH}^-
\]
TABLE 1. Soluble and total soil silicon compared with silicon content in sugarcane leaf.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Si in soil Soluble</th>
<th>Si Total</th>
<th>Si leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocala. Rd. 315</td>
<td>0.0178</td>
<td>42.7</td>
<td>–</td>
</tr>
<tr>
<td>Fellsmere</td>
<td>0.0110</td>
<td>41.4</td>
<td>1.18</td>
</tr>
<tr>
<td>Pahoke</td>
<td>0.0071</td>
<td>4.7</td>
<td>1.00</td>
</tr>
<tr>
<td>Oklawaha</td>
<td>0.0042</td>
<td>12.2</td>
<td>1.56</td>
</tr>
<tr>
<td>Florahome</td>
<td>0.0042</td>
<td>4.3</td>
<td>0.46</td>
</tr>
<tr>
<td>Florahome</td>
<td>0.0037</td>
<td>4.3</td>
<td>1.06</td>
</tr>
<tr>
<td>Canal Point</td>
<td>0.0028</td>
<td>2.2</td>
<td>0.40</td>
</tr>
<tr>
<td>Fellsmere</td>
<td>0.0025</td>
<td>38.0</td>
<td>0.09</td>
</tr>
<tr>
<td>Belle Glade</td>
<td>0.0019</td>
<td>0.7</td>
<td>0.15</td>
</tr>
<tr>
<td>Oklawaha</td>
<td>0.0009</td>
<td>3.1</td>
<td>2.05</td>
</tr>
</tbody>
</table>

Source: Adapted from Bair (1966).

The addition of CaCO₃ to soil reduced Si solubility, mostly because of a change in pH of the soil (more alkaline pH). The effect of soil pH is shown by Ayres (1966), who found that liming a soil decreased the uptake of Si by various plants including sugarcane.

Amounts of opal phytoliths in soils commonly range from <1 to 30 mg kg⁻¹ on a total soil basis. As much as 500 to 750 g kg⁻¹ of the total contributed to soils by many grass and forest species is in the <5 um size fractions (Jones and Beavers, 1964; Wilding and Drees, 1971). Coarser opaline constituents are more stable and easier to fractionate from soils, but finer ones are often more valuable for plant taxonomic purposes.

Several interrelated factors govern concentrations of biogenic opal, which may vary by several orders of magnitude from one geographical area to the next. These include plant species, soil factors (pH, soluble Si, reactive Fe and Al sesqui-oxides, hydrology, etc.), climate, geo-morphology, and opal stability (Jones and Handreck, 1967; Wilding and Drees, 1971).

Quantities of biogenic opal in soils commonly decrease with depth. The maximum concentration usually occurs in the surface or subjacent horizon, whereas a minimum occurs 50 to 100 cm below the surface unless a buried Paleosol is present (Wilding and Drees, 1971; Jones and Beavers, 1964).

SILICON IN WATER

Irrigation water could be a potential source of Si for sugarcane, because the following forms of Si may occur in natural waters: ionic and molecular Si, aggregate
Si (as colloidal, solid and/or gel), Si adsorbed onto sesqui-oxides, organic-Si complexes (humites), metal-Si complexes and in living organisms, plankton, detritus, etc. (Mitchell, 1975; Tan, 1994). The monomeric form of Si (H$_4$SiO$_4$) has been recognized to be the main form. However, the overall composition of forms of Si is influenced by several factors such as pH, temperature, degree of super saturation, and the presence of other substances.

Rain water contained less than 0.2 mg dm$^{-3}$ Si and was considered not enough to be of agronomic importance (Whitehead and Feth, 1964; Fox et al., 1967a, 1967b). In Hawaii, mountain water at about 300 m contained only 2.5 mg dm$^{-3}$ Si whereas irrigation water pumped from wells near sea level contained 30 mg dm$^{-3}$ Si (Fox et al., 1967a). Well water from Kerala state (India) having weathered soils, contained less Si (2.4 to 3.2 mg dm$^{-3}$ Si) than irrigation water from dam (5.6 mg dm$^{-3}$ Si) (Nair and Ayer, 1968). Kobayashi (1960) observed for Japanese rivers that the average dissolved Si in those flowing through regions of sedimentary rocks was 4.7 mg dm$^{-3}$ Si whereas it was 21 mg dm$^{-3}$ Si for those in the neighborhood of volcanic rocks. Sadzawka and Aomine (1977) have reported similar observation in river waters from the volcanic ash area of central Chile. Silicon contents of 23 to 28 mg dm$^{-3}$ Si have been reported for deep ground water (Dapples, 1959).

**SILICON NUTRITION IN SUGARCANE**

There is ample evidence that different species uptake greatly different amounts of Si. Legumes and other dicotyledons have much lower levels than monocotyledons, for example, the Gramineae. Sugarcane is a Si accumulator plant, which strongly responds to Si supply. The Si form that which sugarcane usually absorbs has no electric charge (H$_4$SiO$_4$) and is not very mobile in the plant. Because the uptake of undissociated H$_4$SiO$_4$ may be nonselective and energetically passive, and its transport from root to shoot is in the transpiration stream in the xylem, the assumption has sometimes been made that the movement of Si follows that of water (Jones and Handreck, 1965). The silicic acid is deposited mainly in the walls of epidermal cells, where it is integrated firmly into the structural matter and contributes substantially to the strength of the stem.

The distribution of Si within the shoot and shoot parts is determined by the transpiration rate of the part (Jones and Handreck, 1967). Most of the Si remains in the apoplasm mainly in the outer walls of the epidermal cells on both surfaces of the leaves as well as in the inflorescence bracts of graminaceous species and is deposited after water evaporation at the end of the transpiration stream, (Hodson and Sangster, 1989). Silicon is deposited either as amorphous b (SiO$_2$ + H$_2$O, 'opal') or as so-called opal phyloliths with distinct three-dimensional shapes (Parry and Smithson, 1964). The preferential deposition of Si in the apoplasm of epidermal cells and trichomes is reflected in similarities between surface features of leaf and structure of Si deposits (Lanning and Eleuterius, 1989). The epidermal cell walls are impregnated with a firm layer of Si and become effective barriers against both
TABLE 2. Effect of Wollastonite in an Oxisol on the Si content in the plant and soil and Si accumulation by the aerial part of the sugarcane plant.

<table>
<thead>
<tr>
<th>Si applied kg ha⁻¹</th>
<th>Si in the tissue %</th>
<th>Si accumulated g pot⁻¹</th>
<th>Si in the soil mg dm⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.70</td>
<td>0.36</td>
<td>14</td>
</tr>
<tr>
<td>116</td>
<td>0.89</td>
<td>0.43</td>
<td>17</td>
</tr>
<tr>
<td>231</td>
<td>1.41</td>
<td>0.68</td>
<td>19</td>
</tr>
<tr>
<td>462</td>
<td>1.77</td>
<td>0.74</td>
<td>30</td>
</tr>
<tr>
<td>924</td>
<td>1.93</td>
<td>1.03</td>
<td>46</td>
</tr>
</tbody>
</table>

Source: Adapted from Rodrigues (1997).

fungal infections and water loss by cuticular transpiration. Despite that, there is increasing evidence for the necessity to modify the traditional view of Si deposition in the cell walls as a purely physical process leading to mechanical stabilization (rigidity) of the tissue and acting as a mechanical barrier to pathogens.

Silicon may be involved in cell elongation and/or cell division. In a field study, plant crop height was quadratically related to the rate of Si applied, while plant crop stem diameter was linearly related (Elawad et al., 1982a). Gascho (1978) reported that application of TVA slag and Na silicate to greenhouse grown sugarcane increased plant height. Pluckett (1971) indicated that some of the effects of Si on sugarcane were longer stalks with larger diameters and increased number of suckers. These observations on cane and observations for other crops suggest a possible role of Si in cell elongation and/or cell division (Elawad et al., 1982a, 1982b).

Ayres (1966) determined that only 15% of the total plant Si are present in sugarcane stalks at 14 months. The leaf sheaths on the best cane-growing soils contained about 2.5% Si. Using the sixth leaf sheath, Halais (1967) suggested critical levels of 1.25% of Si and 125 mg dm⁻³ of Mn. If the Si level was below this value, Si responses could be expected. Under field conditions, in Florida, Anderson (1991) suggested that at least 1% Si (~2.1% SiO₂ in the leaf dry matter) is required for optimal cane yield. At 0.25% Si the yield drops to about 50%. According to Rodrigues (1997), increasing Si rate from 0 to 924 kg ha⁻¹ using Wollastonite, resulted in substantial increase of the Si content in the leaves from 0.7 to 1.93% and Si in the soil from 14 to 46 mg dm⁻³ (Table 2).

Better Si-accumulating cultivars may have the advantage of requiring lower rates of Si fertilizer or less frequent applications. A relatively narrow base of sugarcane germplasm demonstrated significant variability for Si content in leaf tissue (Deren et al., 1993). Körndörfer et al. (1998) also found that sugarcane cultivars have different capacities to accumulate Si in the leaves. The Si levels in the leaf were of 0.76, 1.64 and 1.14% respectively for the cultivars: RB72454, SP79-1011, and SP71-6163.
POTENTIAL BENEFITS OF SILICON MANAGEMENT

Increased Yields

Research work demonstrating the use of silicate slag as a source of Si for sugarcane has been largely conducted in Hawaii, Mauritius, and Florida. Yield responses are great enough that sugarcane grown in the Everglades (South Florida) is routinely fertilized with calcium silicate when soil tests indicate the need. However, Si fertilization requires large quantities of slag (generally 5 Mg ha⁻¹), making it quite costly (Alvarez et al., 1988). Yields of cane and sugar in Hawaii have been increased 10-50% on soils low in Si, and many sugar plantations regularly apply calcium silicate in responsive fields (Ayres, 1966; Clements, 1965a; Fox et al., 1967b). Increased yields of sugarcane in fields have been reported in Mauritius (Ross, 1974) and Puerto Rico (Samuels, 1969); while in South Africa (Preez, 1970) and Brazil (Gascho and Korndörfer, 1998), several sources of silicate increased sugarcane yields in pots.

In 1961, D’Hotman reported large increases in sugarcane yields from massive applications of finely ground basalt to soils in Mauritius. In similar work, Halais and Parish (1964) found increased Si in leaf sheaths and increased yields of sugarcane with the application of basalt dust. Ayres (1966) found that the Si of calcium silicate slag acts as a growth stimulant for sugarcane on low Si soils in Hawaii.

The benefits of Si fertilization are generally observed in sugarcane grown on Si-deficient soils such as weathered tropical soils and Histosols. Ayres (1966) obtained increases in tonnage of sugarcane amounting to 18% in cane and 22% in sugar for plant cane crop following the application of 6.2 t ha⁻¹ of electric furnace slag to aluminous humic ferruginous Latosols in Hawaii. The beneficial effect of the slag lasted on low Si soils for four years, and the first ratoon crop produced about 20% more cane and sugar. In Mauritius, calcium silicate slag applied at 7.1 t ha⁻¹ to low Si soils (less than 77 mg dm⁻³ Si extractable with modified Truog’s extractant) at planting gave annual cane increases that were economically profitable over a 6-year cycle. A net return from the application of calcium silicate could be expected if the total Si level in the third leaf lamina was below 0.67% of Si or if the acid-soluble soil Si was below 77 mg dm⁻³ Si (Ross et al., 1974) (Table 3).

Based on the results of a 3-year study, Gascho and Andreia (1974) concluded that Si is beneficial and probably essential for sugarcane grown on organic and quartz sand soils of Florida. For TVA calcium silicate slag applied at 4.9 to 11.6 t ha⁻¹ to muck and soils, Gascho (1979) observed significant positive response at all seven muck locations and two out of four sand locations. The economic analysis of the results of these field tests showed profitability of Si management under the given field conditions (Alvarez and Gascho, 1979). With the addition of calcium silicate slag (obtained from El SIGLO Corporation, Columbia, TN) at 6.7 t ha⁻¹, yields of five inter-specific hybrids of sugarcane were increased by an averages of 17.2% and 21.8% during 1989 and 1990, respectively (Raid et al., 1992).
TABLE 3.  Average silicon content of 3rd leaf lamina (free of the midrib) collected in the peak growth stage (7.5 months after harvest).

<table>
<thead>
<tr>
<th></th>
<th>Si - Dry matter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.45</td>
<td>0.42</td>
</tr>
<tr>
<td>7.1 t Calcium Silicate</td>
<td>0.71</td>
<td>0.56</td>
</tr>
<tr>
<td>14.2 t Calcium Silicate</td>
<td>0.85</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Source: Ross et al. (1974).

Ross et al. (1974) observed that there was marked increase in sugarcane yield with calcium silicate applications throughout the cycle (Table 4).

In Brazil, only a few experiments have been done on the effect of Si on sugarcane yield. Casagrande (1981) observed little effect on yield when 4 t ha$^{-1}$ of cement was applied (Table 5). The same results are observed for the amount of sucrose (Pol).

Rice and sugarcane are grown in rotation in the Everglades Agriculture Area, Florida. From this rice-sugarcane rotation, both economic and agronomic benefits have been observed (Alvarez and Snyder, 1984; Snyder et al., 1986). Anderson et al. (1986 and 1987) observed that a single application of silicate slag to Terra Cea muck prior to planting of rice increased production of rice and sugarcane in rotation, but to a lesser extent than the slag applied prior to cane planting. In an investigation to determine multi-year response of sugarcane (cv. CP72-1020), the application of 20 t ha$^{-1}$ of slag (100% passing through 40 mesh screen) increased cumulative cane yield as much as 39% and sugar yield as much as 50% over three crop years (Anderson, 1991).

Since Si plays the role of a beneficial nutrient in sugarcane, it improves cane plant growth. Application of TVA and Florida calcium silicate slag (up to 20 t ha$^{-1}$)

TABLE 4.  Effects of calcium silicate on average cane yields of 2 cultivars.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Plant cane</th>
<th>Ratoon</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>40.0</td>
<td>78.4</td>
<td>53.8</td>
</tr>
<tr>
<td>7.1 t Calcium Silicate</td>
<td>63.5</td>
<td>92.2</td>
<td>62.1</td>
</tr>
<tr>
<td>14.2 t Calcium Silicate</td>
<td>68.5</td>
<td>96.2</td>
<td>64.5</td>
</tr>
</tbody>
</table>

Source: Adapted from Ross et al. (1974).
**TABLE 5.** Sugarcane yield, Pol ha\(^{-1}\) and Pol % of cane obtained for cultivars NA56-79 and IAC48/65 (plant cane and ratoon) with cement application.

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>Plant cane</th>
<th>Cement - t ha(^{-1})</th>
<th>Ratoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>NA56-79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pol **% cane</td>
<td>16.2</td>
<td>15.9</td>
<td>16.1</td>
</tr>
<tr>
<td>Pol - t ha(^{-1})</td>
<td>17.5</td>
<td>17.8</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IAC48/65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pol **% cane</td>
<td>14.7</td>
<td>15.3</td>
<td>15.1</td>
</tr>
<tr>
<td>Pol - t ha(^{-1})</td>
<td>17.5</td>
<td>19.0</td>
<td>19.3</td>
</tr>
</tbody>
</table>

*Percentage of sucrose in the sugarcane juice or stalk.*
Source: Casagrande et al. (1981).

A few reports on agronomic benefit in sugarcane from silicate application in Indonesia, Malaysia and South Africa are seen in the literature.

In field trials at two non-irrigated sites in South Africa conducted during 1983-1985 on fine-textured acid soil (pH 4.5), steel slag from Japan was applied at a rate of 1-3 t ha\(^{-1}\) before planting cane. The results of the trials indicated increase in cane and sugar yields in the plant and ratoon crop (Allorentung, 1989). Preez (1970) has reported positive yield responses of sugarcane to applied silicate materials to South African soils.

Recycling of nutrients in bagasse furnace ash (BFA) may have some agronomic value as a source of Si. Pan et al. (1979) incorporated BFA containing 28% Si at rates of 12, 24, 36, and 48 t ha\(^{-1}\) into Malaysia soils before planting. They observed the highest cane yields of 119 and 127 metric t ha\(^{-1}\) at 36 and 48 t BFA ha\(^{-1}\); 13 and 20% more than the control, respectively, and also sugar yields 15 and 20% more than the control, respectively. Lee et al. (1965) reported similar increases in plant cane and the succeeding ratoon canes from massive application of BFA to
Taiwanese soils. Further field investigations into recycling of Si for developing a practice using reduced rates of BFA would be rewarding.

**Induced Resistance to Stress**

Under field conditions, crop yields are adversely affected by biotic stresses such as pests and plant diseases, and abiotic stresses such as soil water shortage, cold temperature, UV-B radiation, Fe, Al, and Mn toxicities, etc. Appropriate Si management of crops may offer some practical solutions to these stress problems (Savant et al., 1997).

*a) Disease Control*

In sugarcane, small rust-colored or brownish spots on the leaves of cane growing on highly weathered soils characterize a leaf disorder called freckling. In severe cases, affected lower leaves may die prematurely and can affect cane yield. Freckled plants are less efficient in performing photosynthesis not only because they have less leaf but also because many leaves are freckled. This leaf disorder was corrected by application of silicate materials (Clements, 1965b). Ayres (1966), Fox et al. (1967b), and Wong You Cheong et al. (1972) have also noticed that leaf freckling symptoms in sugarcane were gone following Si treatments.

Elawad et al. (1982a) observed significant decrease in percent freckling in the plant crop as well as the ratoon crop with application of 20 t ha⁻¹ of TVA slag to muck soil. The mechanism for the disappearance of leaf freckling in sugarcane following Si application is still not well understood. Clements et al. (1974) attributed leaf freckling mainly to the presence of toxic levels of Fe, Al, Mn, and Zn in the soil solution. However, Gascho (1978) stated that the development of freckled leaves is an expression of the plant's need for Si.

Si is deposited in the epidermal tissue mechanically deters hyphae invasion (Takahashi, 1996). Furthermore, Si physiologically promotes ammonium assimilation and restrains the increase in soluble nitrogen compounds, including amino acids and amide, which are instrumental for the propagation of hyphae (Takahashi, 1996).

Recently, Raid et al. (1992) investigated the influence of cultivar and soil amendment with calcium silicate slag on foliar disease development in sugarcane hybrids (Table 6). Severity of sugarcane rust (*Puccinia melanocephala* H. Syd. and P. Syd) was not affected by application of silicate slag. However, they noticed significant reduction in severity of ring spot with the addition of the slag (*Leptosphaeria sacchari* Breda de Ham) by an average of 67% across the five cultivars studied. Si is known to be deposited at the external surface of cell walls of plants, thus forming a mechanical barrier to penetration of the pathogen causing ringspot but not to that of rust in sugarcane (Kunoh, 1990; Raid et al., 1992). A hypothesis has been presented that the polymerized Si acids fill up apertures of cellulose micelle constituting cell walls and make up a Si cellulose
TABLE 6. Effect of cultivar and soil amendment with calcium silicate slag on leaf silicon concentration, ringspot (Leptosphaeria sacchari) severity.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Slag Rates</th>
<th>Si Tissue</th>
<th>Ringspot Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t ha⁻¹</td>
<td>%</td>
<td>Leaf 4</td>
</tr>
<tr>
<td>CP72-1210</td>
<td>0</td>
<td>0.28</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>0.67</td>
<td>7.3</td>
</tr>
<tr>
<td>CP74-2005</td>
<td>0</td>
<td>0.29</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>0.59</td>
<td>3.1</td>
</tr>
<tr>
<td>CP80-1827</td>
<td>0</td>
<td>0.29</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>0.55</td>
<td>1.7</td>
</tr>
<tr>
<td>CP70-1133</td>
<td>0</td>
<td>0.28</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>0.54</td>
<td>4.2</td>
</tr>
<tr>
<td>CP72-2086</td>
<td>0</td>
<td>0.25</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>0.73</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Source: Adapted from Raid et al. (1992).

membrane. This membrane is supposed to be mainly responsible for protecting the plant from some diseases and insects (Yoshida et al., 1969).

b) Pest Control

While studying the influence of UV-B radiation and soluble Si on growth of sugarcane, Elawad et al. (1985) additionally observed increased resistance of sugarcane to stem borer (Diatraea saccharalis F.) with improved Si nutrition. Newly hatched D. saccharalis larvae, when starting their attacks on sugarcane plants, do so by feeding on epidermal tissue of the sheath, leaves and developing internodes in the immature top of the plants. The presence of Si crystals in these tissues should hinder the feeding of the insect, which in this phase has rather fragile mandibles. Plants like sugarcane and rice, with high Si contents, seem to interfere in the feeding of larvae, damaging their mandibles. It is possible that plants with higher Si contents in their tissue would have a higher level of resistance to the infections by such pests.

The high Si levels in Na₂SiO₃ treated plants may have served as a deterrent to the borers (Table 7). A significant negative relation was observed between leaf Si content and shoot borer incidence. Sugarcane varieties with a higher number of Si cells per unit area in the leaf sheath portion 5 to 7 cm from the base were found resistant to the shoot borer (Rao, 1967). The percentage of the incidence of borer damage was less in sugarcane (var. GPB 5) treated with bagasse furnace ash and silicate slag than in untreated sugarcane (Pan et al., 1979). It is interesting to note
TABLE 7. Influence of Si on plant resistance to stem borer (*Diatraea saccharalis*), Si in the TVD leaf and dry weight of sugarcane plants.

<table>
<thead>
<tr>
<th><strong>Na₂SiO₃</strong></th>
<th><strong>Numbers plants attacked</strong></th>
<th><strong>Percent of total</strong></th>
<th><strong>Dry weight</strong></th>
<th><strong>Si leaf</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>g plot¹ (40 L)</td>
<td>%</td>
<td>g plant¹</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>44</td>
<td>73</td>
<td>450</td>
<td>0.29</td>
</tr>
<tr>
<td>68</td>
<td>12</td>
<td>20</td>
<td>482</td>
<td>1.39</td>
</tr>
<tr>
<td>136</td>
<td>4</td>
<td>7</td>
<td>505</td>
<td>2.39</td>
</tr>
</tbody>
</table>

*Source: Adapted from Elawad et al. (1985).*

that increased application of N fertilizers alone increased the incidence of sugarcane stalk borer (*Eldana saccharina*, Walker) in Mali (Coulibaly, 1990), and that of another borer (*Chilo auricillus* Dudgeon) in India (Sukhija et al., 1994). The increase of the borer's incidence may be partly due to the formation of softer stalks resulting from the lower than adequate levels of plant Si required for strengthening of the stalk cells (Jones and Handreck, 1967; Lewin and Reimann, 1969). In other words, the borer incidence could have been prevented by application of Si together with N fertilizers (Maxwell et al., 1972).

c) *Toxicities Alleviation*

According to Clements (1965b), there is a positive effect of applying soluble silicates in areas where sugarcane absorbs excess amounts of certain elements such as Mn, and where the plant is unable to absorb Si to maintain a sheath level at or beyond 0.7% Si (dry weight). The most important negative factor was the Mn/SiO₂ ratio, i.e., the lower the ratio, the better plants grow. The two dominant factors affecting yield of sugar were Ca and Si, the latter being outstanding. The level of Si which appears adequate is about 0.7%, and the best ratio is in the 30 to 50 range.

The main effect of the Si on alleviating manganese toxicity was to distribute the Mn more evenly through the leaves, thereby preventing it from collecting into localized areas which become necrotic (Jones and Handreck, 1965; Jones and Handreck, 1967; Vlamis and Williams, 1967).

d) *Freeze Alleviation*

Freeze damage during the winter in the sub-tropical areas in the continental United States (including Florida, Louisiana, and Texas) and south of Brazil is one of the major constraints in sugarcane production (Irvine, 1963 and 1968; Tai and Miller, 1986). Cultivation and cold tolerant varieties can reduce freeze damage to
leaves and stalks and the failure of the ratoon crop. In Florida, it has been noted that there is an increased tolerance to freeze damage of commercial sugarcane in areas treated with calcium silicate (Ulloa and Anderson, 1991). Results of strip tests with silicates suggest that applications of silicates have ameliorated mild freeze effects on sugarcane (Rozelle, 1992a, 1992b, 1992c). According to Ulloa (quoted from Rozelle, 1992a, 1992b, 1992c), silicate slag-treated cane resisted deterioration caused by a deeper freeze in Florida. These limited observations on Si-induced cold tolerance in sugarcane, however, warrant additional field studies.

e) Water Economy

Water stress under field conditions is common and affects cane yields. Improved Si nutrition may reduce excessive leaf transpiration (Wong You Cheong et al., 1972).

One of the symptoms associated with Si deficiency is the excessive rate of transpiration. The rate of transpiration of Si-deficient plants increased by about 30% over the rate of control plants (Lewin and Reimann, 1969) (rates were measured as grams of water lost through transpiration per gram of dry weight per day). Okuda and Takahashi (1965) obtained a similar result, but found that in barley the effect was small (less than a 10% difference between Si-deficient and control plants). This observation suggests a role for Si in the water economy of the plant. An increased rate of transpiration in Si-deficient plants could explain the wilting that may occur, particularly under conditions of low humidity, and could also help to explain the increased accumulation of Mn and other mineral nutrients in the aerial parts of Si-deficient plants. The rate of transpiration is presumably influenced by the amount of silica gel associated with the cellulose in the cell walls of epidermal cells. Hence, a well-thickened layer of silica gel should help to retard water loss, while epidermal cell wall with less silica gel will allow water to escape at an accelerated rate.

Since this role of Si nutrition may result in water economy and may be important in water management, field research on this potential beneficial has merit.

f) Reducing Lodging and Improving Erectness

One other effect of increased plant Si content, which has been reported in literature, is the increased mechanical strength of plant tissue, which results in reduced lodging.

Under field conditions, particularly in dense stands of sugarcane, Si can stimulate growth and yield by decreasing mutual shading by improving leaf erectness, which decreases susceptibility to lodging. Leaf erectness is an important factor affecting light interception in dense plant population and, hence, photosynthesis. In rice, Si supply increased the photo-assimilation of carbon, especially after heading, and promoted the translocation of assimilated carbon to the leaves. This effect of Si on
leaf erectness is mainly a function of the Si depositions in the epidermal layers of the leaf panicle (Takahashi et al., 1982).

Sucrose Inversion

Few investigations of the role of Si in sugarcane have considered the mechanism by which it affects sugarcane tonnage production. However, Alexander et al. (1971) has undertaken the task of finding the role that Si plays in the synthesis, storage and retention of sucrose in the sugarcane plant. He found that sucrose inversion in sugarcane juice samples was delayed for several days by adding sodium metasilicate immediately after milling. Chromatographic evidence suggests that at low levels metasilicate forms a physical complex with sucrose which prevents the union of invertase with its substrate. The hypothetical fructose-silicate configuration is retained even after sucrose is inverted, thereby preventing fructose from being metabolized by microorganisms. Fructose appears to be the preferential hexose for microbial growth, i.e., most suitable carbon source. The effective preservation of fructose by silicates may constitute a bacterial repression operating in addition to the invertase-inhibitory action.

Next to K, Si is the most extensive constituent of ash in sugarcane juice. It is the highest component of millable stalks ash and represents an even greater percentage in leaves. However, silicates in cane are believed to be one of the major contributors to mill roll wear.

SILICON MANAGEMENT

Agromonic practices for Si management mainly include Si fertilization and plant Si recycling.

Silicon Fertilization

Research work on Si nutrition has been reported in Australia, South Africa, Brazil, Taiwan, India, Mauritius, Puerto Rico, the United States, and other countries. Si fertilization has been practiced in Hawaii and Florida in the United States, and in Mauritius. For effective use of Si fertilizers, it is essential to have adequate knowledge of physical and chemical characteristics of Si sources, and when, and at what rate and how (methodology) to apply them.

a) Silicon Sources

The usual carrier for Si is calcium silicate and this material can also supply Ca to a Ca-deficient soil. The Hawaiian Cement Corp. first manufactured calcium silicate in August 1965.

Gescho and Korndörffer (1998) working with four different soils groups from Brazil and several Si sources (Wollastonite, thermal-phosphate, calcium silicate
and basic slag) concluded that thermal-phosphate was the most effective source to supply both Si and P to the rice plant (Table 8 and Figure 4).

In several studies, no attempt was made to maintain constant Ca levels with increasing calcium silicate applications. It is important to separate Si from Ca effects. Ayres (1966) reasoned that since both calcium silicate and calcium carbonate treatments had increased yields, the calcium supply probably was not the factor causing higher yields in their studies. Teramishi (1968) concluded that yield increases from calcium silicate applications could not be attributed to Ca supply in his experiment since plant Ca was above the critical level for sugarcane and also since calcium carbonate had been added to the zero Si plots to maintain pH and supply adequate Ca.

According to Ross et al. (1974), calcium silicate applied to low Si soils at planting increase annual cane yield over a 6 year cycle (Table 4) and well demonstrated the residual effect from this source.

For research purposes, many different Si sources have been tested: Wollastonite (CaSiO₃), cement kiln fired (fused) calcium silicate, Portland cement (9 to 23% Si), di-calcium ortho-silicate (Ca₂SiO₄), calcium metasilicate, mini-granulated calcium metasilicate, electric furnace slag (by-product of furnace production of elemental P), blast furnace slag, basic slag, Thomas slag, mill furnace ashes, crushed basalt, volcanic cinder, and others (Rozeff, 1992a, 1992b, 1992c) (Table 9).

Since 1970, Hawaiian Sugar Planter Assoc. researchers have tested several silicate materials and their findings can be summarized as follows:

a) Based on extractable Si, siliceous materials can be grouped as: low level (18 to 250 mg dm⁻³ Si) materials such as mill furnace ash, rock dust, and steel slag; intermediate level (2,200 to 9,800 mg dm⁻³ Si) materials such as blast furnace slag and coarse calcium silicate; and high level (30,750 to 91,500 mg dm⁻³ Si) materials such as Portland cement, fine calcium silicate, and Hawaiian cement calcium silicate (HSPA, 1979).

b) The degree of Si solubility from siliceous materials was dependent on particle size and chemical composition (HSPA, 1979).

c) Extractable Si levels were higher in the finer silicate particles (HSPA, 1980).

d) A long-term comprehensive approach to study residual silicates from application of siliceous materials to soils is required.

e) Calcium metasilicate was generally much more soluble and readily available to sugarcane than calcium ortho-silicate. Mini-granules of calcium metasilicate, which were small, spherical (50 to 150 mesh) made from fine (100 to 200 mesh) material using 2% sodium oxide as a binder, were agronomically equivalent to fine ungranulated calcium metasilicate (HSPA, 1982). According to Datnoff et al. (1992), a fine grade of Si fertilizer was best for increasing Si content and grain yield. Rice yields increased relative to the control by 20-26%, 18%, and 4-11% for the fine, standard, and pelletized forms, respectively in 1990/1991. Agronomic feasibility of mini-granulation of CaSiO₃ has been confirmed by
### TABLE 8. Total and citric acid soluble silicon in Si sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Total Si (indicated by supplier)</th>
<th>Total Si %</th>
<th>Si - soluble by citric acid</th>
<th>Soluble portion %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Silicate Slag*</td>
<td>---</td>
<td>21.1</td>
<td>14.8</td>
<td>70</td>
</tr>
<tr>
<td>Wollastonite - Calc. Silicate</td>
<td>24.2</td>
<td>23.1</td>
<td>Trace</td>
<td>0</td>
</tr>
<tr>
<td>Minas Liga - Basic Slag**</td>
<td>41.2</td>
<td>39.2</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>Magnesium Silicate - course</td>
<td>---</td>
<td>27.8</td>
<td>Trace</td>
<td>0</td>
</tr>
<tr>
<td>Magnesium Silicate - fine</td>
<td>---</td>
<td>27.7</td>
<td>Trace</td>
<td>0</td>
</tr>
<tr>
<td>Piau - Basic Slag**</td>
<td>---</td>
<td>8.5</td>
<td>6.9</td>
<td>82</td>
</tr>
<tr>
<td>Thermalphosphate Yoorin</td>
<td>---</td>
<td>10.8</td>
<td>10.4</td>
<td>96</td>
</tr>
</tbody>
</table>

* *Elemental P Electric Furnace by-product (Monsanto/Calcium Silicate Corp.).
** *By-product of iron manufacture.


![Graph](image)

**FIGURE 4.** Phosphorus and silicon level in the soil after 18 months of thermal-phosphate application (Kontöderfer, 1998).
TABLE 9. Total and soluble Si content of some silicon fertilizers and location.

<table>
<thead>
<tr>
<th>Material</th>
<th>Location</th>
<th>Total %</th>
<th>Soluble* %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag - electric furnace</td>
<td>Alabama</td>
<td>18.2</td>
<td>3.960</td>
</tr>
<tr>
<td>Slag - open hearth (ground)</td>
<td>Alabama</td>
<td>6.9</td>
<td>1.720</td>
</tr>
<tr>
<td>Slag - open hearth</td>
<td>Alabama</td>
<td>2.0</td>
<td>1.660</td>
</tr>
<tr>
<td>Hi-cal silicate limestone (ground)</td>
<td>Kendrick</td>
<td>0.2</td>
<td>0.016</td>
</tr>
<tr>
<td>Hi-cal silicate limestone (ground)</td>
<td>Brooksville</td>
<td>3.4</td>
<td>0.026</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Lebanon</td>
<td>0.4</td>
<td>0.023</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Venice</td>
<td>4.5</td>
<td>0.023</td>
</tr>
<tr>
<td>Rock phosphate</td>
<td>Florida</td>
<td>3.6</td>
<td>0.025</td>
</tr>
<tr>
<td>Colloidal phosphate</td>
<td>Dunnellon</td>
<td>10.8</td>
<td>0.023</td>
</tr>
<tr>
<td>Fuller's earth</td>
<td>Georgia</td>
<td>35.1</td>
<td>0.023</td>
</tr>
</tbody>
</table>

*2 g of fertilizer + 50 mL ammonium acetate 0.5 N, pH 4.8 (30 min agitation).

Source: Adapted from Bair (1966).

the results of Medina-Gonzales et al. (1988). When containing high amounts of Si, both granular and powered slag are equally efficient (Schaffer and Henze, 1962). These are useful findings because they offer potential the option of mini-granulation of fine silicate sources for solving their handling problem (Jakeway, 1983).

Working on three acid soils, Preece (1970) tested various Si-containing materials on cane growth, and showed that, with the exception of metasilicate slag (soil B; Balgowan - 63% clay) and cement, all the silicate treatments showed increase yield with increasing Si concentration in the plant. The CaCO₃ had the opposite effect (Figure 5 and Table 10).

In addition to the solubility of Si in silicate sources, reactions of applied Si with organic and inorganic colloid might influence their bio-availability. Therefore, the soil-silicate reactions may need consideration for developing Si management for a given eco-region (Bair, 1966; Medina-Gonzales et al., 1988).

Since slag is a by-product of industry, in addition to containing Ca and Si, it may contain various other elements or contaminants, some of which may under certain conditions have favorable and/or unfavorable effects on sugarcane growth. Although calcium silicate slag contains trace amounts of non-recovered P, significant amounts of P (up to 67 kg ha⁻¹) could be added to soil using commercial rates of slag (up to 6 to 7 t ha⁻¹). However, Anderson et al. (1992) have reported that P applied through slag was biologically not available to sugarcane, probably due to its low solubility.
In short, by using information on the chemical and physical nature of a Si source, it should be managed to fully realize its agronomic potential benefits, and assure that adverse effects on soil and human health, if not eliminated, are reduced to a minimum.

b) Rate of Application

Silicon application rates are mainly influenced by the chemical makeup of the Si source, Si levels in the soil, and in the plant. In Hawaii, the first silicate recommendation for plant cane was made in 1962 for 7.5 tons ha\(^{-1}\) of TVA (Tennessee Valley Authority) slag. In 1970, 4.94 t ha\(^{-1}\) of Hawaiian Cement corporation calcium metasilicate (CaSiO\(_3\)) was recommended. The reduction in the rate was due to the greater reactivity of CaSiO\(_3\) as compared with TVA slag. Subsequently, in 1971 a tentative recommendation of 1.2 to 2.5 t ha\(^{-1}\) of CaSiO\(_3\) was made for ratoon cane, if the soil Si level was between 64 to 78 kg ha\(^{-1}\). Based on the economic evaluation of field trials conducted on McBryde and Lihue plantations during 1976 to 1982, the following CaSiO\(_3\) recommendations for sugarcane in Hawaii have been revised based on soil and plant Si indexes:
<table>
<thead>
<tr>
<th>Soil series</th>
<th>Amendments</th>
<th>Level t ha(^{-1})</th>
<th>Soil pH</th>
<th>Mn in tops G kg(^{-1})</th>
<th>Mn:Si X 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balgowan (71% clay)</td>
<td>Control</td>
<td>0</td>
<td>4.67</td>
<td>360</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>CaSiO(_3)</td>
<td>4.5</td>
<td>4.7</td>
<td>278</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>CaSiO(_3)</td>
<td>9.0</td>
<td>4.8</td>
<td>283</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>CaSiO(_3)</td>
<td>18.0</td>
<td>5.0</td>
<td>223</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Blast Furnace Slag</td>
<td>4.5</td>
<td>5.1</td>
<td>363</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Blast Furnace Slag</td>
<td>9.0</td>
<td>5.3</td>
<td>283</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Blast Furnace Slag</td>
<td>18.0</td>
<td>5.6</td>
<td>170</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Cement</td>
<td>4.5</td>
<td>5.1</td>
<td>246</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Cement</td>
<td>9.0</td>
<td>5.4</td>
<td>163</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Cement</td>
<td>18.0</td>
<td>5.8</td>
<td>56</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>4.5</td>
<td>5.0</td>
<td>270</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>9.0</td>
<td>5.3</td>
<td>166</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>18.0</td>
<td>5.6</td>
<td>69</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>4.5</td>
<td>5.1</td>
<td>307</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>9.0</td>
<td>5.4</td>
<td>197</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>18.0</td>
<td>5.8</td>
<td>67</td>
<td>22</td>
</tr>
<tr>
<td>(B) Balgowan (63% clay)</td>
<td>Control</td>
<td>0</td>
<td>4.5</td>
<td>338</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>4.5</td>
<td>5.0</td>
<td>230</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>9.0</td>
<td>5.1</td>
<td>128</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>18.0</td>
<td>5.4</td>
<td>57</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>4.5</td>
<td>4.9</td>
<td>183</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>9.0</td>
<td>5.1</td>
<td>117</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>18.0</td>
<td>5.6</td>
<td>67</td>
<td>19</td>
</tr>
<tr>
<td>(C) Trevanian (24% clay)</td>
<td>Control</td>
<td>0</td>
<td>4.6</td>
<td>428</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>4.5</td>
<td>5.6</td>
<td>93</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>9.0</td>
<td>6.2</td>
<td>59</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Metasilicate Slag</td>
<td>18.0</td>
<td>7.2</td>
<td>46</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>4.5</td>
<td>5.8</td>
<td>90</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>9.0</td>
<td>6.7</td>
<td>85</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>CaCO(_3)</td>
<td>18.0</td>
<td>7.3</td>
<td>67</td>
<td>13</td>
</tr>
</tbody>
</table>

Source: Adapted from Freez (1970).

(1) For fields not fertilized with CaSiO\(_3\), for two or more consecutive crops, apply 4.48 t ha\(^{-1}\) CaSiO\(_3\) to the current crop if soil Si levels are at or below the critical level of 112 kg ha\(^{-1}\).

(2) For fields to which CaSiO\(_3\) was applied to one or both of the preceding crops (plant cane and ratoon), apply 2.24 t ha\(^{-1}\) CaSiO\(_3\) to the current crop if the soil Si levels are at or below the critical level of 78 kg ha\(^{-1}\). Thereafter, apply 2.5 t ha\(^{-1}\) to each succeeding crop if soil Si levels fall below 78 kg ha\(^{-1}\).
(3) The critical levels for the “crop log” sheath Si (0.7%) and the Mn/SiO₂ ratio=75 established by Clements (1965a) remain the same; if sheath Si levels of “crop log” samples are less than 0.7% or the sheath Mn/SiO₂ ratios are above 75, apply 2.5 t ha⁻¹ of Ca₃SiO₅ to the current crop (Hagihara and Bosshart, 1984).

In Florida, a rate of 7 to 9 t ha⁻¹ of TVA slag or other similar finely ground slag has been recommended under the following specified conditions (Kidder and Gascho, 1977):

a) The land in question must be located more than five km from Lake Okeechobee.

b) Soil pH must be less than 8.

c) Leaves of sugarcane grown on the soil in question must have shown heavy freckling symptoms.

d) Calcium silicate slag used as the soil amendment must be ground finer than 60 mesh.

e) Slag must be applied broadcast and disked into the soil prior to planting the cane. When the slag is applied to sandy soils with Mg test levels below 120 (according to Everglades Research and Education Center, laboratory test), concurrent Mg fertilization at the rate of 40 kg Mg ha⁻¹ at planting is suggested as a precaution (Kidder and Gascho, 1977).

c) Timing and Frequency of Application

Generally, all Si is applied to soil before planting. In Florida, if response to the applied Si is obtained in the first year of application, no further applications of slag are needed for at least four years (Kidder and Gascho, 1977). Florida farmers grow sugarcane in rotation with rice. Silicate slag applications prior to a sugarcane crop and prior to a rice crop in rotation with sugarcane have shown positive agronomic response. These two timing applications of slag were agroeconomically evaluated in the three crop production systems: before rice, before sugarcane and before rice-sugarcane rotation. Results of the evaluation indicated that, under the costs and prices assumed, it was more profitable to apply the slag prior to the rice crop in the rice-sugarcane rotation (Alvarez et al., 1988).

d) Method of Application

In order to apply Si to sugarcane, calcium silicate is broadcast and then incorporated into the soil before planting. The silicate material should be used in the same manner as limestone in liming sugarcane soils. Big cane plantations employ two types of mechanical spreaders, “E-Z Flow” spreader and a centrifugal broadcast spreader, a so-called spin spreader (Jakesway, 1983). Broadcasting of the slag using the E-Z Flow spreader is more uniform but has a narrow zone of coverage (26 to 46 m). Its rotating parts such as bearings wear prematurely because silicate slag is abrasive. Trafficking many times for uniform coverage contributes to soil compaction. Broadcast (spin) spreaders deliver wider coverage for every pass,
but broadcasting is less uniform than the E-Z Flow spreader. Plantations have reported handling and application problems in fields under windy conditions.

Generally, slag materials are incorporated into the soil as soon as possible after broadcasting to avoid caking on the ground surface. This is usually performed with a disc harrow, which is followed by complete land preparation (Jakeway, 1983).

The particle size of the Si fertilizer is important in increasing Si content of leaves and subsequent disease control (Datnoff et al., 1992). Particle size is associated with increased surface area; consequently, the distribution and dissolution of smaller Si particles mixed in the soil is enhanced and the probability of root particle contact is increased. Combining fine particles into pellets probably results in less Si-soil contact, leading to reduced Si availability to the crop, although some particle degradation could occur during soil incorporation. The particle should be of a size and well mixed with the soil. If very fine, Si sources create dusty conditions and can adversely affect material handling and application performance in the field. Special precautions are necessary for avoiding exposure of workers to the dust. This dust problem may limit the use of silicate slag for sugarcane in developing countries where it will be mainly applied manually. Mini-granulation of fine calcium silicate materials seems to be a potential alternative for addressing the dust problem. Small particle size increases the effectiveness of silicate materials. Harada (1965) called attention to the superiority of finely ground TVA slag compared with coarsely ground, 16 mesh (<1.6 mm) material.

Plant Silicon Recycling

Plant Si recycling is another option available for supplying Si to sugarcane. It should be considered for developing region-specific integrated nutrient management systems that are essential for sustainable sugarcane production.

In several reports, positive effects on the growth and yield of sugarcane have been reported for the application of trash (dried leaves left in field after harvesting cane), bagasse, bagasse furnace ash, and filter-press cake. However, plant materials generally are applied as sources of organic carbon (organic matter) and their positive effects are normally attributed to increase in availability of N, P, and K in soil and, at times, to the improvement in soil chemical and/or physical properties of soil (King, 1955; Yang, 1958; Story, 1963; Pao, 1973; Eavis and Chase, 1973; Prasad, 1976a, 1976b; Medina, 1979; Cooper and Abu Idris, 1980; Shinde et al., 1990, 1993; Jonathan et al., 1991; Orlando Filho et al., 1991; Kathiresan, 1991). It is possible that some of the effects observed could be also due to Si supplied through these plant materials.

In spite of the potential value of plant material as a source of Si, its proper recycling is not common among sugarcane farmers. Some of the probable reasons for this could be bulkiness of the material, additional labor cost of recycling practices, and low cost-benefit ratios. Moreover, polymerized Si in the plant is largely
associated with non-easily decomposable polysaccharide fractions such as cellulose, hemi-cellulose, etc. The rate of their decomposition is also slowed down because of their wide C:N ratio (nearly 120:1). For rapid decomposition of trash in soil or during composting, the use of cellulolytic fungi together with reduction of its C:N ratio appears to a practical solution. Mixed culture of fungi, namely Aspergillus flavipes, Penicillium chrysogenum, Cochliobolus spicifera, Rhizopus oryzae and Trichoderma viride have produced good results in the preparation of trash compost and when applied onto the trash spread in furrows. Shinde et al. (1990, 1993) have used the mixed fungi (1 kg culture m³) for enhancing decomposition of chopped and non-chopped trash applied (2.5, 5.0, 7.5 t ha⁻¹) in furrows before planting cane and those of ratoon cane. The trash was supplemented with 8 kg of urea and 10 kg ha⁻¹ of a single super phosphate. They observed improved plant growth and increased yield of plant as well as ratoon cane. Bagasse is used as mill fuel and as such plays a valuable part in the sugar-mill economy. In this process, a large amount of bagasse furnace ash is produced during each grinding season. This product has been regarded as a waste material, and piles of it accumulate in the factory compound. However, it might have a function in Si soil amelioration. As the main constituent of bagasse furnace ash is silica (as high as 28% Si), it might also have some effect in increasing sugarcane yield. In practice, the cost of transportation must be taken in account. Pan et al. (1979) showed a 20% increase in cane yield as a result of bagasse application. However, there was decline in sucrose content with increasing application of bagasse furnace ash. Pan et al. (1979) reported increased cane yields (GPB 5 cultivar) due to the incorporation of bagasse furnace ash (28% Si).

TESTING OF SOIL, PLANT, AND SILICON SOURCES

Under certain agroclimatic conditions, sugarcane responds positively to soil application of Si sources. There is, however, a need to test soil, plant and silicate materials used as Si sources for making Si management in sugarcane efficient and affordable for farmers.

Analysis of Si by atomic absorption spectrometry (AAS) or colorimetric techniques requires that Si be in solution. When analysis of soluble or extractable forms of Si is performed, this requirement is easily met; however, when total Si analysis is desired, dissolution is made difficult by the presence of silicates and aluminates.

Soil Testing

Since plants absorb Si from soil, it is important to understand its forms and reactions in soils. Silicon forms may be defined in terms of total, extractable, and soluble. As the name implies, total Si comprises all forms of Si that may be present and can be solubilized by strong alkali fusion or acid-digestion bomb methods.
Extractable Si represents those forms removed by less severe dissolution agents, such as sodium dithionite, ammonium oxalate, weak alkalis, and sodium pyrophosphate. These extractants remove Si of intermediate stability that are often found associated with crystalline or amorphous soil components. Soluble Si represents the most labile form in soils and consists primarily of monomeric silicic acid; soluble Si occurs in interstitial soil solutions when determination is desired.

Observations on a sugarcane field at the Everglades Research and Education Center (Florida), showed that the concentration of Si in sugarcane was 1.0-1.2% in leaves, 0.68-0.84% in nodes and 0.42-0.67% in internodes (dry weight). Based on these data and average sugarcane harvest data (80 t ha\(^{-1}\) of fresh mass), it was determined that nearly 100 kg ha\(^{-1}\) of Si are removed with each harvest. Data in 1992 at the Everglades Research and Education Center (Belle Glade, FL) showed that for each harvested crop between 50 to 450 kg ha\(^{-1}\) of Si are removed every year. The total amount of plant available Si makes up not more that 45 kg ha\(^{-1}\) of Si (sum of mobile and potentially soluble Si in the 0-10 cm layer) in Histosol and less than 6 kg ha\(^{-1}\) of Si in Spodosol. Consequently, the total balance of Si on agricultural fields is negative in both soils.

Since the 1960s, sugarcane scientists in Hawaii, Mauritius, and Florida have been working on soil testing to assess Si status of soils. Several chemical extractant procedures have been developed to determine plant-available Si status of sugarcane soils (Table 11).

Plant-available Si in soil seems to be influenced by several factors, such as pH, clay content, parent material and its weathering, and chemical procedure. Therefore, sugarcane scientists are faced with a challenge to develop and adopt a simple-to-use, but dependable, soil testing procedure that is appropriate for a given agroclimate.

The most common chemical extractant used is 0.5 \(M\) ammonium acetate (\(\text{NH}_4\text{OAc}\), pH 4.8). This use has produced encouraging results. In Florida, an agronomic response to silicate application can be obtained when Si extracted from air-dry soil with acetate buffer (pH 4.85) is greater than 100 mg dm\(^{-2}\) (Kidder and Gascho, 1977). The acetate buffer-extractable Si can be determined using a new colormetric procedure that is superior to earlier methods in terms of color stability, and sensitivity (Yanai et al., 1996). Although 0.01 \(M\) CaCl\(_2\), extractant mimics the ionic strength and pH of soil solution, it has been used for studying the chemical kinetics of Si release from soils and not for bio-available Si in soils (Gibson, 1994). The phosphate extractant with 3.5 pH adjusted with acetic acid (\(\text{HAc}\)) may have some advantages because it seems to extract adsorbed Si (capacity factor) as well as water-soluble Si (intensity factor) from soil (Fox et al., 1967a; Khalid et al., 1978). Korndörfer et al. (1999b) working with upland rice and four different soils concluded that among the extractants tested, the acetic acid 0.5 \(M\) gave the best estimate for the available Si in the soil.

Shaking time and temperature can affect Si extracted from soil. Most of soluble Si seems to be released within the first hour of shaking (Gibson, 1994). Therefore,
### TABLE 11: Chemical extraction procedures used for assessing plant-available Si in sugarcane and rice soils.

<table>
<thead>
<tr>
<th>Extraction procedure</th>
<th>Main Si form</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 10 g soil + 100 mL water, 4 h shaking high centrifugation (24,000 g) used for clarification</td>
<td>Ionic</td>
<td>Fox et al. (1967a)</td>
</tr>
<tr>
<td>- 10 g soil + 100 mL of solution containing 500 ppm P as Ca(H₂PO₄)₂ and 0.1 N (H₄N₄O₄) OAc, pH 3.5</td>
<td>Adsorbed and soluble</td>
<td>Khalid et al. (1978)</td>
</tr>
<tr>
<td>- 1 g soil + 100 mL of solution 0.02 N H₂SO₄ containing 3g (NH₄)₂SO₄ per liter, 30 min shaking</td>
<td>Soluble</td>
<td>Fox et al. (1967a)</td>
</tr>
<tr>
<td>- 10 g soil + 50 mL of 0.5 M NH₄OAc (pH 4.8), 30 min shaking</td>
<td>Soluble</td>
<td>Bair (1966)</td>
</tr>
<tr>
<td>- 10 g soil + 50 mL of 0.5 M NH₄OAc (pH 4.8), 1h shaking</td>
<td>Soluble</td>
<td>Fox et al. (1967a)</td>
</tr>
<tr>
<td>- 10 g soil + 50 mL of 0.5 M NH₄OAc (pH 4.85), 4 h shaking</td>
<td>Soluble</td>
<td>Kidder and Gascho (1977)</td>
</tr>
<tr>
<td>- 5 g soil + 100 mL of 0.5 M NH₄OAc (pH 4.8), 4 h shaking</td>
<td>Soluble</td>
<td>Medina-Gonzales et al. (1988)</td>
</tr>
<tr>
<td>- 4 g soil + 50 mL of HC₂H₃O₂ 0.5 M</td>
<td>Available</td>
<td>Barbosa Filho (1996)</td>
</tr>
<tr>
<td>- 10 g soil + 100 mL of HC₂H₃O₂ 0.5 M</td>
<td>Available</td>
<td>Korndörfer et al. (1999b)</td>
</tr>
</tbody>
</table>
a 4-hour shaking period used by many workers should be adequate for routine soil testing. The use of wider soil:extractant ratios of 1:5 or 1:10 is common, perhaps to minimize desorption of Si by soil.

Plant uptake of Si was most closely related to Si in the soil where a 1:10 (soil: 
\( \text{NH}_4\text{OAc} \)) extractant was used. The "\( \tau \)" value for the water extraction method increased as soil pH decreased, indicating the Si solubility and Si uptake from applied silicates increased as pH decreased (Medina-Gonzalez et al., 1988).

Recently, Matichenkov and Snyder (1996) have used a 1:5 soil to water ratio for extraction of so-called mobile forms of Si from south Florida soils. According to them, it is possible to determine monosilicic acids, polysilicic acids and organo-Si compounds in the water extract. However, the practical significance of these fractions in sugarcane nutrition is not clear.

Other factors such as soil sampling, storage time and extent of drying could also affect Si status of soil samples. The process of soil drying in field and/or laboratory may increase aggregate stability and resistance to dispersion (Jersak et al., 1992); and, therefore, can affect the extractability of soil Si. Usually various extractions from dry soil samples are used for research of mobile forms of soil Si substances (Barsykov, and Rochiev, 1979; Nonaka and Takahashi, 1986). Results of dry soil extractions do not reflect actual contents of mobile Si forms. Drying of soil samples leads to essential change in the equilibrium between soluble and solid Si substances. The soluble Si compounds (monosilicic, polysilicic acids and organo-Si substances) are adsorbed on soil particles, being dehydrated in the process. To restore the natural equilibrium between various Si substances, it is necessary to immerse the soil sample in water for about one month (Sadzawka and Aomine, 1977). In addition, by using only dry soil extraction it is impossible to determine the distribution among monosilicic acids, polysilicic acids and organo-Si substances, which play very different roles in various soil bio-geochemical processes (Matichenkov and Animosova, 1996). Therefore, it is necessary to develop new, highly informative methods of investigating mobile Si compounds in soil.

Plant Testing

Plant testing for Si status mainly consists of leaf tissue sampling and its chemical analysis. Since analytical errors are relatively small, perhaps more attention should be given to proper leaf tissue sampling and preparation.

Halais (1969) described details of leaf tissue sampling and its preparation. According to them, leaves from primary stalks should be sampled when there has been no water stress during the fortnight preceding the sampling and no wind damage resulting in shredding of leaves. Workers on Mauritius have sampled third to sixth leaf sheaths of plant and ratoon crops generally at boom stage (Halais, 1966, 1967, 1969). However, Ross et al. (1974) sampled the middle section (10 cm) of the third leaf lamina free of midrib in the peak growth stage of ratoons.

Fox et al. (1969) used the system of numbering tissue for plant samplings for securing crop log samples. Leaves were designated in numerical order counting
the spindle cluster as number 1. The spindle cluster was defined so that the sheath of leaf 3 was well elongated. The internodes were given the same number of the leaf sheath attached at the upper end of the node. The entire blade was used for the leaf blade sample. Total Si was determined by ashing ground plant tissue in a nickel crucible. Soluble Si was estimated in 5 to 10 fresh plant samples using 2% trichloro-acetic acid (TCA). They found that soluble Si in plant tissue gave more useful information about the Si-status of the plant, but the fraction was found unstable with time. A good relation of TCA-soluble Si in the sheath to watersoluble Si in soils was observed (Fox et al., 1967b).

In Florida, sampling of randomly selected 10 to 20 top-visible dewlap (TVD) leaves (youngest fully expanded leaves) with midribs has been a common practice (Elawad et al., 1982b; Anderson et al., 1987; Anderson, 1991; Raid et al., 1992). Response to silicate application is probable in Florida soils if total Si of TVD leaves is less than 1.0% (Kidder and Gascho, 1977).

For the determination of total Si in plant tissue, a rapid gravimetric procedure developed by Elliott et al. (1988) or an autoclave-induced digestion procedure for colorimetric determination of Si in rice plant tissue (Elliott and Snyder, 1991) may be used with necessary modifications.

Silicon Source Testing

In general, calcium silicate has been used as a Si source for sugarcane. Unfortunately, there are no proven methods for assessing the availability of Si in potential Si sources. Effectiveness of silicate material as a Si source for crops depends mainly on its particle size and chemical reactivity. In general, a finer Si source is more effective in supplying Si to sugarcane and rice (Datnoff et al., 1992). Hagihara (1981) used 100-mesh silicate material for their evaluation studies in sugarcane. Medina-Gonzalez et al. (1988) studied calcium silicate materials having two ranges: 0.25 to 0.84 mm (20 to 60 meshes) and 0.07 to 0.15 mm (100 to 200 meshes). They found, in general, decreased Si availability with increased particle size. These examples suggest that particle size of silicate materials must be defined when evaluating their chemical reactivity.

Chemical reactivity of silicate materials to be used as an Si source for sugarcane can be determined using three types of testing procedures (see also Table 12):

1) Direct Chemical Extraction: In this procedure, Si is directly extracted from silicate materials with chemical solution such as 0.5 M NH₄AOx.

2) Indirect Chemical Extraction After Soil Incubation: The silicon source to be evaluated is incubated with soil at near field capacity for varying periods and the chemical extractant is used to determine Si released in the soil from the Si source. Medina-Gonzalez et al. (1988) used three extractants: shaking in water (soil:water ratio, 1:10) for four hours; displacing water from saturated soil in leaching tubes after equilibrating for two days; and shaking soil for one hour with 0.5 M NH₄AOx in a ratio 1:20.
TABLE 12. Chemical extraction procedures used for assessing Si sources for plant-available Si.

<table>
<thead>
<tr>
<th>Chemical procedure</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 2 g of Si source + 50 mL of 0.5 M NH₄OAc (pH 4.8), shaking for 30 min.</td>
<td>Bair (1966)</td>
</tr>
<tr>
<td>- Si source (100 mesh) + 0.5 M NH₄OAc (pH 4.85), shaking for varying periods</td>
<td>Hagihara (1981)</td>
</tr>
<tr>
<td>- 10 g of Si source + 1 g polyethylene. Leach with Tris buffer (pH 7) using a peristaltic pump for 56 hours</td>
<td>Barbosa Filho (1996)</td>
</tr>
<tr>
<td>- 0.2 g Si source (65 mesh) + 0.5 g H-resin Amberlite (IRC-50, pK 6.1) + 400 mL water, shaking for 4 d (100 rpm) at 35°C</td>
<td>Barbosa Filho et al. (1996)</td>
</tr>
<tr>
<td>- 1 g of Si source + 150 mL of 0.5 M HCl shaking for 1 h at 30°C (commonly used in Japan)</td>
<td>Kato and Owa (1990)</td>
</tr>
<tr>
<td>- 1 g of Si source + 150 mL of 0.5 M NH₄OAc (pH 4.0), shaking for 1 h at 30°C (NH₄OAc buffer prepared by diluting 49.2 mL acetic acid and 14.8 g anhydrous sodium acetate to 1 L, pH adjusted to 4.0 with acetic acid or sodium acetate)</td>
<td>Barbosa Filho (1996)</td>
</tr>
<tr>
<td></td>
<td>Barbosa Filho et al. (1996)</td>
</tr>
</tbody>
</table>

3) Biological Extraction: Medina-Gonzales et al. (1988) used an adaptation of the method devised by Stanford and Dement (1957) for short-term biological extraction of Si using a previously developed mat of sugarcane roots.

RESEARCH AGENDA

There are certain areas relevant to Si nutrition and its management that need to be investigated for making sugarcane production economically more viable and sustainable during the 21st century.

1. Regional Si Status Surveys of Soils and Waters: Due to desilication process, weathered soils (Alfsols, Inceptisols, Oxisols, Ultisols, etc.) of the sub-tropics and tropics (D’Hoore and Coullier, 1972) and problematic organic soils (Histosols) are most likely to be low or deficient in plant-available Si. They may not be able to support healthy and productive growth of crops that absorb relatively large amounts of Si from soil. In other soils, intensive cultivation of high yielding sugarcane cultivars having very short fallow periods, may show signs of temporary depletion of bio-available Si. Decreasing
trends in yields of ratoon crops could be an example of the temporary depletion. In order to address these soil Si related issues, periodical Si status surveys of soils, plants and waters should be helpful for sustaining sugarcane yields over a long time. The better understanding of soluble or plant-available Si in soil during crop growth may assist formulating efficient region-specific integrated nutrient management systems for sugarcane.

2. Development of Efficient Management Practices of Si Sources: Improved utilization of Si sources by plants through their proper management is essential for higher agronomic efficiency. Research should continue to develop efficient Si management practices for sugarcane for increasing value-cost ratios and eventually affordability of Si sources for small farmers of developing countries. Application of Si sources appropriately integrated with the use of different organic manure, and other conventional fertilizers, especially soluble P sources warrant consideration.

3. Development of Biotechnology for Si Management: There are research areas in which biotechnology for using Si sources could be rewarding in the future. Two areas of research are i) use of cellulolytic fungi for enhancing decomposition of sugarcane trash and ii) use of silicate-dissolving bacteria as a part of integrated nutrient management system.

At present, Si in trash is not effectively recycled. Generally, most of the trash is burned in the fields. For the trash that is placed for mulching in the furrows of the ratoon crop or that is composted, efficient microbial organisms, especially cellulolytic fungi, may speed up its decomposition and could help the recycling of plant Si. Yadav (1977), Shinde et al. (1990), and Shinde et al. (1993) have identified efficient cellulolytic fungi. Genetic engineering approaches for developing efficient microorganisms that can decompose trash at an accelerated rate should be considered.

Reports in the literature suggest that microorganisms are involved in Si cycle (transformations) in nature (Vintikova, 1956; Tryshina, 1964; Krumbein and Werner, 1983). Certain bacteria seem to possess an ability to decompose siliceous rocks and minerals (Vintikova, 1956), and aluminum-silicates and quartz sand (Kol’chugina et al., 1985). Webley et al. (1960) of the Macauley Institute of Soil Research, Aberdeen, observed decomposition of amorphous synthetic silicates, crystalline Wollastonite, apophyllite and olivine that were incorporated into molten agar by a species of Pseudomonas. According to Vintikova (1964), soil bacteria lacking a mucous coat were more effective than those of the mucous type were. Vintikova (1956) and Surman (1958) have studied some morphology and physiology of silicate bacteria. Several beneficial effects of silicate bacteria, so-called silico-bacterial, are reported on maize (Vintikova, 1964); vegetables (Aleksandrov, 1958; Zak and Mukhutdinov, 1964) and wheat (Aleksandrov, 1958). The beneficial effects of
silicate-decomposing bacteria on Si-accumulating plants, such as sugarcane, are not seen in the literature, but if confirmed, would be very useful for crops like sugarcane. Biotechnology to identify and/or to develop new genetically engineered strains of bacteria having the ability to decompose insoluble silicates should be on the research agenda.

4. Foliar Application of Si—Is it effective? Plants are known to absorb some nutrients through leaves. However, very little information is reported about Si absorption through sugarcane leaves (Alexander, 1968; Alexander, 1969). Foliar spraying of soluble Si as 0.1 to 0.2 mg L⁻¹ solution of Na₂SiO₃ (Okamoto, 1993) and 1% solution of sodium silicate (Hooda and Srivastava, 1996; Parvar and Hedges, 1979) on leaves of rice plants has been reported with favorable effect on plant growth. Jayabadi and Chockalingam (1990) conducted field experiments to develop management practices for mitigating effects of drought on sugarcane. When drought was imposed by irrigating only once a week during summer (May and June), they observed increased yields of sugarcane (var. CO 6304) due to spraying 2.5% sodium metasilicate. The effect was attributed to a reduced rate of transpiration. If the observation that a foliar spray of soluble Si improves plant growth and yield in sugarcane is confirmed, an appropriate Si management practice for alleviating the effect of drought could be developed for sugarcane. According to Schmug and Franck (1985), under intensive systems of fertilization and plant protection, the possibilities of using the yield-promoting effect of Si are limited mainly to foliar application.

5. Genetic Research for Efficient Si-accumulating Sugarcane Cultivars:
Genetics plays an important role in nutrient uptake by plants including that of Si. Genotype variability for Si content exists in sugarcane (Deren et al., 1993). Better Si-accumulating sugarcane cultivars may have the advantage of requiring lower rates of Si fertilizers or their less frequent applications. While using a genetic approach for development and/or screening of genotypes for certain desirable traits, consideration of a Si-accumulation trait will be rewarding.

6. Interaction Between Silicon Nutrition and UV-B Radiation: Ambient ultraviolet-B (UV-B) flux in the tropics, the major sugarcane growing area, is among the highest on the earth's surface because the stratospheric ozone layer is naturally thinner and because solar angles are higher near the equator than at the higher latitudes. With the depletion of stratospheric ozone caused by chlorofluorocarbons, increased UV-B flux may adversely affect sugarcane yields. Crop cultivars having differential ability to absorb Si from soil may also differ in sensitivity to UV-B, which could be detrimental to their growth. In rice, certain biochemical and physiological variables were more sensitive to UV-B than other variables and shoot dry weights were reduced by 21% and 23% for the most UV-B sensitive cultivars, namely IR45 and IR74 (IRRI, 1990). The workers at IRRI also noticed increased leaf Si in UV-B sensitive but not in tolerant rice cultivars. These observations may be applicable to sugarcane. Gascho (1978), Wong You Cheong et al. (1972), and ElAwad et al. (1985) suggest
that solar UV-B radiation may have caused leaf freckling in Si-deficient sugarcane grown under direct sunlight. Supporting this, Elwad et al. (1985) could not obtain this UV-B effect under greenhouse conditions. Therefore, research to enhance UV-B radiation on selected sugarcane cultivars, having different abilities to absorb Si from soil, and screening of sugarcane germplasm for their responses to increased UV-B radiation, with and without a Si supply, may be initiated now to address probable UV-B radiation effects, a potential future environmental problem.

7. **Tolerance to Salt Stress**: Si influences water use by reducing cuticular transpiration (Jones and Handreck, 1967; Lewin and Reimann, 1969; Yoshida, 1975). Reports suggest that, by improving Si nutrition of plants, it may be possible to reduce their internal water stress and thereby make them withstand salt stress better (Yoshida, 1975; Matoh et al., 1986; Miyake, 1993). These results may be applicable to sugarcane and, if demonstrated, they could be used for making salt-affected sugarcane soils more productive.

**GLOSSARY**

**abiotic**: Non-living basic elements of the environment, such as rainfall, temperature, wind, and minerals.

**adsorption**: The attraction of ions or compounds to the surface of a solid. Soil colloids absorb large amounts of ions and water.

**adsorption complex**: The group of organic and inorganic substances in soil capable of adsorbing ions and molecules.

**aluminosilicates**: Compounds containing aluminum, silicon, and oxygen as their main constituents. An example is microcline, KaSi$_2$O$_6$.

**available nutrient**: That portion of any element or compound in the soil that can be readily absorbed and assimilated by growing plants. ("Available" should not be confused with "exchangeable").

**bagasse**: The dry pulp remaining from sugar cane after extraction of the juice.

**base saturation percentage**: The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen and aluminum. It is expressed as a percentage of the total cation exchange capacity.

**basic silicate**: A by-product in the manufacture of steel, containing lime, phosphorus, and small amounts of other plant nutrients such as sulfur, manganese, and iron.

**broadcast**: To scatter seed or fertilizer on the surface of the soil.
**calcium metasilicate**: A white powder, CaSiO₃, insoluble in water, used as an antacid, and as a filter for paper.

**calcium silicate**: Any of the silicates of calcium—calcium metasilicate, dicalcium silicate, and tricalcium silicate.

**cation**: A positively charged ion; during electrolysis it is attracted to the negatively charged cathode.

**cation exchange**: The interchange between a cation in solution and another cation on the surface of any surface-active material, such as clay or organic matter.

**cation exchange capacity**: The sum total of exchangeable cations that a soil can adsorb. Sometimes called total-exchange capacity, base-exchange capacity, or cation adsorption capacity. Expressed in centimoles of charge per kilogram (cmol, kg⁻¹) of soil (or of other adsorbing material, such as clay).

**clay**: (1) A soil separate consisting of particles <0.002 mm in equivalent diameter. (2) A soil textural class containing >40% clay, <45% sand, and <40% silt.

**decomposition**: Chemical breakdown of a compound (e.g., a mineral or organic compound) into simpler compounds, often accomplished with the aid of microorganisms.

**desorption**: The removal of sorbed material from surfaces.

**diatomaceous earth**: A geologic deposit of fine, grayish, siliceous material composed chiefly or wholly of the remains of diatoms. It may occur as a powder or as a porous, rigid material.

**diatoms**: Algae, having siliceous cell walls that persist as a skeleton after death; any of the microscopic unicellular or colonial algae constituting the class Bacillariaceae. They occur abundantly in fresh and salt waters and their remains are widely distributed in soils.

**essential element**: A chemical element required for the normal growth of plants.

**evapotranspiration**: The combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants.

**exchange capacity**: The total ionic charge of the adsorption complex active in the adsorption of ions. See also anion exchange capacity; cation exchange capacity.

**fertilizer requirement**: The quantity of certain plant nutrient elements needed, in addition to the amount supplied by the soil, to increase plant growth to a designated optimum.
fungi: Eukaryote microorganisms with a rigid cell wall. Some form long filament cells called hyphae that may grow together to form a visible body.

gibbsite: Al(OH)$_3$—An aluminum trihydroxide mineral most common in highly weathered soils, such as Oxisols.

goethite: FeOOH—A yellow-brown iron oxide mineral that accounts for the brown color in many soils.

granulation: The process of producing granular materials. Commonly used to refer to the formation of soil structural granules, but also used to refer to the processing of powdery fertilizer materials into granules.

hematite: Fe$_2$O$_3$—A red iron oxide mineral that contributes red color to many soils.

Histosol: Soils formed from materials high in organic matter. Histosols with essentially no clay must have at least 20% organic matter by weight (about 78% by volume). This minimum organic matter content rises with increasing clay content to 30% (85% by volume) in soils with at least 60% clay.

hyphae: Filament of fungal cells. Actinomycetes also produce similar, but thinner, filaments of cells.

imogolite: A poorly crystalline aluminosilicate mineral with an approximate formula SiO$_4$Al(OH)$_2$. It occurs mostly in soils formed from volcanic ash.

leaching: The removal of materials in solution from the soil by percolating waters.

lime (agriculture): In strict chemical terms, calcium oxide. In practical terms, a material containing the carbonates, oxides and/or hydroxides of calcium and/or magnesium used to neutralize soil acidity.

lime requirement: The mass of agricultural limestone, or the equivalent of other specified liming material, required to raise the pH of the soil to a desired value under field conditions.

limestone: A sedimentary rock composed primarily of calcite (CaCO$_3$). If dolomite (CaCO$_3$, MgCO$_3$) is present in appreciable quantities, it is called a dolomitic limestone.

lodging: Falling over of plants, either by uprooting or stem breakage.

micas: Primary aluminosilicate minerals in which two silica tetrahedral sheets alternate with one alumina/magnesia octahedral sheet with entrapped potassium atoms filling between sheets. They separate readily into visible sheets or flakes.

muck: Highly decomposed organic material in which the original plant parts are not recognizable. Contains more mineral matter and is usually darker in color than peat. See also muck soil; peat.
muck soil: (1) A soil containing 20 to 50% organic matter. (2) An organic soil in which the organic matter is well-decomposed.

oxidation: The loss of electrons by a substance; therefore, a gain in positive valence charge and, in some cases, the chemical combination with oxygen gas.

Oxisols: Soils with residual accumulations of low-activity clays, free oxides, kaolin, and quartz. They are mostly in tropical climates.

particle size: The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods.

productivity (soil): The capacity of a soil for producing a specified plant or sequence of plants under a specified system of management. Productivity emphasizes the capacity of soil to produce crops and should be expressed in terms of yields.

reaction (soil): The degree of acidity or alkalinity of a soil, usually expressed as a pH value or by terms ranging from extremely acid for pH values <4.5 to very strongly alkaline for pH values >9.0.

residual material: Unconsolidated and partly weathered mineral materials accumulated by disintegration of consolidated rock in place.

calcareous: Grassland with scattered trees; often a transitional type between true grassland and forest.

silica: A white or colorless crystalline compound, SiO₂, occurring as quartz, sand flint, agate, and many other minerals and used to make glass, and concrete. Also called silicon dioxide.

silica gel: A highly adsorbent gelatinous form of Si, used as drying and humidifying agent.

silica/alumina ratio: The molecules of silicon dioxide (SiO₂) per molecule of aluminum oxide (Al₂O₃) in clay minerals or in soils.

silica/sesquioxide ratio: The number of molecules of silicon dioxide (SiO₂) per molecule of aluminum oxide (Al₂O₃) plus ferric oxide (Fe₂O₃) in clay minerals or in soils.

silicate: Any of numerous compounds containing silicon, oxygen, and a metallic or organic radical, occurring in most rocks except limestone and dolomite.

silicious: Containing, resembling, relating to, or consisting of Si; growing in soil rich in Si.

siliceous acid: A jellylike substance, SiO₂·nH₂O, produced when sodium silicate solution is acidified.

silicon: Symbol Si. A nonmetallic element occurring extensively in the earth’s crust; used in glass, semiconducting devices, concrete, brick, refractories, pottery, and silicones.
silocone: Any of a group of semi-inorganic polymers based on the structural unit $R_nSiO_x$ where $R$ is the organic group (extremely stable in high temperature, and water-repellent), used in adhesives, lubricants, protective coatings, paints, and electrical insulation.

slag: A product of smelting, containing mostly silicates.

soil amendments: Any substance other than fertilizers, such as lime, sulfur, gypsum, and sawdust, used to alter the chemical or physical properties of a soil, generally to make it more productive.

tetrahedral sheet: Sheet of horizontally linked tetrahedron-shaped units that serve as one of the basic structural components of silicate (clay) minerals. Each unit consists of a central four-coordinated atom (e.g., Si, Al, Fe) surrounded by four oxygen atoms that, in turn, are linked with other nearby atoms (e.g., Si, Al, Fe), thereby serving as interunit linkages to hold the sheet together.

Ultisol: Soils that are low in bases and have subsurface horizons of alluvial clay accumulations. They are usually moist, but during the warm season of the year some are dry part of the time.

wilting point (permanent wilting point): The moisture content of soil, on an oven-dry basis, at which plants wilt and fail to recover their turgidity when placed in a dark, humid atmosphere.

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Silicon
IN AGRICULTURE

Program Agenda and Abstracts

September 26-30, 1999 • Lago Mar Resort
Fort Lauderdale, Florida USA
Welcome to the Silicon in Agriculture Conference!

We are pleased that you have joined us for the first international conference on silicon in agriculture. We are gathered together with colleagues from around the world to discuss the role and function of this important element in agriculture.

We have designed a program that covers many aspects of this element, keeping our overall objective for good science and a good time on a parallel course.

An important aspect of the conference will be getting to know our colleagues in silicon science on a personal basis. We hope that this interaction will lead to the identification of the most important topics for future research, and the formulation of techniques, conventions, and strategies for conducting these studies in collaborative efforts with new-found colleagues cutting across disciplines and international borders.

The organizing committee is very appreciative of the financial support we have received to help defray conference expenses. Our sponsors are recognized in this book, and we ask that you join us in thanking them for their contribution. Without their support, programs like this would not be possible.

The IFAS Office of Conferences and Institutes (OCI) also deserves a special note of appreciation for handling the many details that have gone into organizing this conference. The Silicon in Agriculture Conference Coordinator, Ms. Nikki Rogers, and the conference planning team will be available to assist you throughout the conference.

We look forward to making your stay at the Lago Mar Resort and Club a memorable one; we hope you will find the conference both enjoyable and thought provoking.

Sincerely,

Lawrence E. Datnoff
Gaspar H. Korndorfer
George H. Snyder

Silicon in Agriculture Organizing Committee
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Agenda and Topics

Sunday, September 26, 1999
4:00pm-6:00pm  Registration
6:00 pm-8:00pm  Welcome Reception

Monday, September 27, 1999
7:30am  Continental Breakfast (Fountainview Lobby)
8:00am  General Session (Lakeview)
8:00am  Dr. Lawrence Datnoff (USA) – Welcome
8:10am  Dr. Emanuel Epstein (USA) – Silicon in Plants: Facts vs. Concepts (p. 3)
9:10am  Dr. Jian Feng Ma (Japan) – Silicon as a Beneficial Element for Crop Plants (p. 3)
10:10am  Refreshment Break (Fountainview Lobby)
10:30am  Dr. John Raven (UK) – Silicon Transport at the Cell and Tissue Level (p. 4)
11:30am  Lunch (on your own)
12:00pm-5:30pm  Poster Presenters Set-up displays (Oceanview North and Oceanview South)
1:30pm  Dr. Allan Sangster (Canada) – Silicon Deposition in Higher Plants (p. 4)
2:30pm  Dr. Wim Voogt (Netherlands) – Silicon in the Nutrient Solution for Soilless Grown Horticultural Crops (p. 5)
3:30pm  Refreshment Break (Fountainview Lobby)
4:00pm  Dr. Gaspar Korndorfer (Brasil) – Effect of Silicon on Yield (p. 5)
4:30pm  Dr. Christopher Deren (USA) – Plant Genotype, Silicon Concentration, and Silicon Related Responses (p. 6)
5:00pm  Evening Free (dinner on your own)

Tuesday, September 28, 1999
7:30am  Continental Breakfast (Fountainview Lobby)
8:00am  General Session (Lakeview)
8:00am-12:00pm  Poster Presenters Set-up displays (Oceanview North and Oceanview South)
8:00am  Dr. Richard Belanger (Canada) – The Mode of Action of Silicon as a Disease Preventing Agent in Cucumber (p. 6)
9:00am  Dr. Lawrence Datnoff (USA) – Use of Silicon to Reduce Fungicides and Enhance Host Plant Resistance (p. 7)
9:30am  Dr. George Snyder (USA) – Methods for Silicon Analysis in the Plant, Soil and Fertilizers (p. 7)

10:00am  Refreshment Break (Fountainview Lobby)

10:30am  Dr. Gary Gascho (USA) – Silicon Sources for Agriculture (p. 8)

11:00am  Dr. Vladimir Matichenkov (Russia) – The Relationship of Silicon to Soil Physical and Chemical Properties (p. 8)

11:30am  Lunch (on your own)

1:30pm  Dr. Jose Alvarez (USA) – Economics of Silicon (p. 9)

2:00pm  Dr. Suzanne Berthelsen (Australia) – Silicon Research Down Under: Past, Present and Future (p. 9)

2:30pm  Dr. Jan Meyer (South Africa) – Past, Present and Future Silicon Research in the South African Sugar Industry (p. 10)

3:00pm  Dr. Kiyoshi Ishiguro (Japan) – Review of Research in Japan on the Roles of Silicon in Conferring Resistance against Blast Disease in Rice (p. 11)

3:30pm  Refreshment Break (Fountainview Lobby)

4:00pm  Dr. Anne S. Prahub (Brazil) – Silicon from Rice Disease Control Perspective in Brazil (p. 11)

6:00pm-8:00pm  Poster Session and Social (Oceanview North and Oceanview South)

**Wednesday, September 29, 1999**

7:30am  Continental Breakfast (Fountainview Lobby)

8:00am  General Session (Lakeview)

8:00am-5:00pm  Buses depart for Big Cypress Reservation (lunch provided)

6:30pm  Beach Party Cookout (Outside Ocean Grill)

**Thursday, September 30, 1999**

7:30am  Continental Breakfast, Fountainview Lobby

8:00am  Dr. Fernando Correa (Colombia) – Effects of Silicon Fertilization on Disease Development and Yields of Rice in Colombia (p. 12)

8:30am  Dr. James Menzies (Canada) – Plant Related Silicon Research in Canada (p. 12)

9:00am  Dr. Hailong Wang (New Zealand) – Agricultural Utilization of Silicon in China (p. 13)

9:30am  Dr. Chon-Suh Park (Korea) – Silicon’s Influence on Plants (p. 13)

10:00am  Refreshment Break

10:30am  Formulation of an International Collaborative Agenda for Silicon in Agriculture

12:00pm  Conference Concludes
Oral Abstracts

- Presenting authors appear in **bold**.
- Abstracts are listed by order of presentation.
Silicon in Plants: Facts vs. Concepts

Emanuel Epstein

University of California, Davis, CA, USA

The facts of Si in plant life are one thing; the concepts regarding Si in plant physiology are another thing altogether. Most terrestrial plants grow in media dominated by silicates, and the soil solution bathing roots contains Si at concentrations exceeding those of P by roughly a factor of 100. Plants absorb the element and their Si content is of the same order of magnitude as that of the macronutrient elements. The general plant physiological literature, however, is nearly devoid of Si. The reason for this marked discrepancy is the conclusion that Si is not an "essential" element because most plants can grow in nutrient solutions lacking Si in their formulation. Such Si-deprived plants are, however, experimental artifacts. They may differ from Si-replete plants in (i) chemical composition; (ii) structural features; (iii) mechanical strength; (iv) various aspects of growth including yield; (v) enzyme activities; (vi) surface characteristics; (vii) disease resistance; (viii) pest resistance; (ix) metal toxicity resistance; (x) salt tolerance; (xi) water relations; (xii) cold hardiness; and probably additional features. The gap between plant physiological facts and plant physiological concepts must be closed. The facts of Si in plant life will not change; hence it is the concepts regarding the element that need revising.

Silicon as a Beneficial Element for Crop Plants

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Silicon (Si) has not been proven as an essential element for higher plants, but its beneficial effects on growth are reported in wide variety of crops, including rice, wheat, barley, cucumber, tomato. Si fertilizers are applied to crops in several countries for increased productivity and sustainable production. Plants take up Si in the form of silicic acid. After silicic acid is transported to the shoot, it is concentrated through loss of water and is polymerized as silica gel on the surface of leaves and stems. Evidence is lacking concerning the physiological role of Si in plant metabolism, and the beneficial effects of this element are only observed in plants that accumulate Si. Thus, the silica gel deposited on the plant surface is thought to contribute to the beneficial effects of Si. Beneficial effects of Si are small under conditions of optimal growth, but become obvious when plants are stressed. In this review, the effects of Si under mineral stresses (Al toxicity, P deficiency and excess, Na, Mn and N excess), climatic stresses (low temperature, typhoon, low light), and biotic stresses (diseases) will be discussed.
Silicon Transport at the Cell and Tissue Level

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The predominant Si compound in the soil solution is silicic acid, and the baseline condition for Si transport into and within a plant with no membrane channels or transporters which can move Si compounds is the movement of silicic acid across membranes by dissolving in the lipid phase of the membrane (‘lipid solution’ transport). Based on the best current estimates of ‘lipid solution’ permeability of membranes to silicic acid ($\sim 10^{-10} \text{ m s}^{-1}$), even the lowest Si contents in plants cannot be explained in terms of the soil solution silicic acid concentration and the lipid solution mechanism, and a component of silicic acid entry coupled to transpiratory water uptake is required. For *Oryza* and, under some conditions, *Hordeum* and *Phaseolus*, active influx of silicic acid is needed to account for the observed silica content. Further work is needed as to the mechanism of active transport of silicic acid following the lead of the characterization of Na$^+$-coupled transport in a diatom, and on how silicic acid is coupled to water transport (involving aquaporins?), and on the phloem mobility of silicic acid.

Silicon Deposition in Higher Plants

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Silica deposits, commonly called phytoliths, occur in cell walls, cell lumens or in intercellular spaces and external layers. These deposits frequently possess a characteristic morphology, which reveals their tissue and taxonomic origin. Silicification occurs in roots and the shoot including leaves, culms and, in grasses, most heavily in the inflorescence. Deposits occur in epidermal, strengthening, storage and vascular tissues.

Silicification is reported in the Pteridophyta and the Spermatophyta, including gymnosperms and angiosperms. Dicotyledon families containing Si accumulators of considerable agricultural significance include the Fabaceae, Cucurbitaceae and Asteraceae. Among the monocotyledons, the Cyperaceae and Poaceae (Gramineae) are pre-eminent.

Biogenic silica structure is affected by ambient physico-chemical conditions mediated by tissue maturation, pH, ionic concentrations and cell wall structure. This will be illustrated by reference to work we have conducted on the development of silicification in wheat seedlings.

Silicified tissues may have several functions including support and protection against pathogens and predators. Phytoliths may also sequester toxic metals, and we will give examples principally from our recent work on the codeposition of aluminum and silicon in
cereals and conifers. Some phytoliths have been implicated as carcinogens. Phytoliths are being increasingly used in archaeology as they often retain their morphology in sediments long after the plant has died and the organic matter has broken down.

**Silicon in the Nutrient Solution for Soilless Grown Horticultural Crops**

*W. Voogt* and *C. Sonneveld*


With the change over to soilless growing media in the glasshouse industry in the Netherlands, a lack of knowledge about the role of Si in crops became manifest. It was found that in these systems the Si uptake was dramatically reduced in comparison with soil grown crops. Investigations were carried out on the effects of Si application in soilless culture. With cucumber, melon, courgette, strawberry, bean, rose and Aster ericoides, the Si contents were increased as result of the Si supply in the root environment, whilst with tomato, sweet pepper, lettuce, gerbera, and carnation the uptake was almost negligible. Results showed that cucumber, rose and strawberry could benefit from enhanced Si concentration in the root environment, since total yield was increased and powdery mildew was suppressed. Despite the minor uptake of Si in lettuce and bean, it was found to affect the Mn distribution in the plant.

Initially severe problems with blocking of the irrigation system occurred, because of instability of Si sources. These were solved by the introduction of potassium metaasilicate. The use of polysilicates was found to be less effective.

**Effect of Silicon on Yield**

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Integrated management of 13 physiologically essential nutrients, namely six macronutrients: nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium and seven micronutrients iron, manganese, zinc, boron, copper, molybdenum, and chloride are generally considered by agronomists for increasing and sustaining crop yields. However, there are non-essential elements that under certain agroclimatic conditions enhance crop yield by promoting several physiological processes.

The past and current literature on the effect of silicon (Si) fertilization on crop yield and its potential benefits in increasing and sustaining crop production will be discussed. Rice and
sugarcane grown in rotation on organic and sandy soils in south Florida have shown positive agronomic responses to pre-plant applications of calcium silicate slag.

The recognition of proper Si management to increase and/or sustain crop productivity appears to be greater in temperate countries than in tropical countries. However, due to desilification in which soils (minerals) lose Si as a result of leaching, subtropical and tropical soils are generally low in plant-available Si and may benefit from Si fertilization. Silicon content in some regions might be limiting to sustainable crop production. In addition, Si depletion can occur as a result of intensive cultivation practices and continuous monoculture of high-yielding cultivars.

Plant Genotype, Silicon Concentration, and Silicon-Related Responses

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Silicon concentration in plants influences many responses including insect, nematode, and disease resistance, nutrient status, transpiration and possibly some aspects of photosynthetic efficiency. In many crops, cultivars (genotypes) vary for these same traits. The association of genotypic variation for Si concentration with several plant responses has been the subject of studies that investigated the possibility of breeding or selecting cultivars for Si-limiting environments. This paper briefly reviews research on genotypic variability of sugarcane and rice for silicon concentration, and describes research in Florida on silicon-related responses of cultivars such as disease response, photosynthesis and N and P concentration.

The Mode of Action of Silicon as a Disease Preventing Agent in Cucumber

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Silicon has been exploited for its prophylactic properties against plant diseases for hundreds of years. Its role as a disease-preventing product has been well documented but the mechanisms by which it exerts its beneficial properties in planta remains poorly understood. For a long time, the observation of a systematic accumulation of silica in cell walls and appositions occurring at pathogen penetration sites led to the conclusion that this parietal strengthening was responsible for the increased resistance of plants to diseases. However, recent evidence suggests that silicon would also play an active role in reinforcing plant disease resistance by stimulating the expression of its natural defense reactions. Incidentally,
in the cucumber-powdery mildew system, this latter mechanism appears to be predominant,
if not exclusive. A better understanding of this rather unique property of silicon could be
exploited to optimize its use in agriculture and to help decipher how plants can be naturally
stimulated to protect themselves against pathogens.

Use of Silicon to Reduce Fungicides and Enhance Host Plant
Resistance

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Silicon can control several important diseases of rice, including blast (*Magnaportha grisea*),
brown spot (*Cochliobolus miyabeanus*), sheath blight (*Thanatephorus cucumeris*), leaf scald
(*Monographella albedens*) and grain discoloration (species of *Fusarium*, *Bipolaris*, and
others). Control of several of these diseases such as blast and brown spot equals that
achieved by fungicides. Hence, the number of fungicide applications and rates could be
reduced significantly. Residual activity of silicon was effective for disease control in the
second year crop and was comparable to a first year silicon application or a full rate of a
fungicide. Research revealed that silicon could enhance control of partially-resistant
cultivars to the same general level as completely-resistant cultivars to both blast and sheath
blight. These findings suggest that silicon could be employed in a IPM program for reducing
fungicide use and enhancing host plant resistance in controlling important rice diseases
worldwide.

Methods for Silicon Analysis of Plant Tissue, Soil, and Fertilizer

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The classical method for determining total Si content of various materials has been
conversion of insoluble silicates into sodium silicate through high temperature fusion with
sodium hydroxide, or other sodic bases. The Si then can be determined by a variety of
methods, including gravimetric, colorimetric, and absorption/emission spectrometry. Silicon
also has been determined gravimetrically in plant tissue as the residue after acid digestion.
We have developed a simple, inexpensive, and rapid method for solubilizing Si in plant
tissue that facilitates analysis of a large number of samples. When analyzing soils and
fertilizers, a method for gauging the plant available Si, rather than total Si, generally is
desired. A number of soil-test methods have been developed. Some require extended
incubation periods, field-moist soil, or other procedures that inhibit adoption by routine soil-testing laboratories. Silicon extracted by acetic acid has been correlated to Si uptake by rice and rice grain yield. Using this method, the Everglades Soil Testing Laboratory analyses nearly five thousand samples annually. Since Si fertilizer sources differ in Si content and Si solubility, analytical methods have been developed for predicting their relative ability to provide plant-available Si. We use a column leaching method based on Si elution in Tris buffer (pH 7) for the evaluation of potential silicon soil amendments. However, greenhouse and field evaluations are essential for making final determinations.

Silicon Sources for Agriculture

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Characteristics of an acceptable Si source are: a high content of soluble-Si, physical properties conducive to mechanized application, ready availability, and low cost. Since Si is the second most abundant element in the earth’s crust, finding sources of Si is easy. But, Si is always combined with other elements and most sources are insoluble. Responses of crops to soluble-Si applications in sands (largely SiO$_2$) provide an example of the insolubility of one source. A few sources are soluble, but too costly for general use. Potassium silicate is used as a foliar spray for disease control in some high value crops and sodium silicate has been used to supply Si in research. Calcium silicates have emerged as the most important sources for soil applications. Of those, calcium meta-silicate (wollastonite, CaSiO$_3$) has been the most effective source in many locations with low concentrations of soluble-Si in soils. Such a material, supplied as a slag byproduct from the high temperature electric furnace production of elemental P, is applied extensively to Everglades mucks and associated sands planted to sugarcane and rice. Thermo-phosphate, a commercial fertilizer used in Brazil to supply P, Ca, and Mg, also supplies soluble-Si due to high temperature manufacturing process effects on its magnesium silicate ingredient.

The Relationship of Silicon to Soil Physical and Chemical Properties

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Soil minerals control physical and chemical soil properties. Silicon is a basic mineral formatting element. The aim of our investigation was to obtain information about the effect of silicon fertilization on physical and chemical soil properties. Silicon fertilization has been reported to result in increased soil exchange capacity, improved water and air regimes, transformation of P-containing minerals, formation of aluminosilicates and heavy metal
silicates. All these effects are caused by the change in soil mineral composition as a result of silicates addition (silicon fertilizers) and/or formation of new clay minerals. Both types of minerals are characterized by high biogeochemical activity. They have large surface area and are able to adsorb water, phosphates, K, N, Al, and heavy metals. Absorption may occur as chemosorption or physical sorption. Cations (Al, heavy metals) usually are chemosorbed on silicon-rich surface and lose their mobility. Phosphates and N are weakly adsorbed and remain in plant-available form. Amorphous silica, montmorillonite, and vermiculite represent the newly-formed minerals. These minerals effect the soil solution composition, and physical and chemical properties. The amounts of amorphous silica, monosilicic acids and polysilicic acids in the soil are closely related to each other. Monosilicic acids regulate chemical properties of soil solution. Polysilicic acids have an effect on soil physical properties. Numerous microorganisms present in the soil influence the clay formation process.

Economics of Silicon

Jose Alvarez and Lawrence Datnoff

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Despite the prolific research conducted in crop production and other aspects of silicon application, little is known about the potential economic benefits of its use in agriculture. Although some physical benefits obtained are impressive, the relative high cost of the material could make silicon application unprofitable in some areas of the world.

The purpose of this presentation is to show an economic analysis of two crops and one rotation: rice, sugarcane, and rice-sugarcane rotation. The first case demonstrates the potential economic benefits taking into account the research conducted and the areas where rice is grown or could be grown. The second case does the same for sugarcane. The last case pertains to a specific rice-sugarcane rotation in the Everglades Agricultural Area of south Florida. The three cases seem to indicate that silicon has a tremendous potential for increasing farm revenue. This advantage is especially useful in times of decreasing farm product prices.

Silicon Research Down Under: Past, Present and Future

Suzanne Berthelsen and Andrew Noble

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Ninety-five percent of Australia’s sugarcane is grown on the narrow coastal plain that stretches along northeastern coast of Queensland. The most northern area, from Tully to Mossman, has a unique combination of landforms and climate that gives rise to a range of soils that are not always comparable to those in the southern sugarcane growing regions. In general, these soils have been under sugarcane production for up to 130 years, and apart from
low levels of soluble soil silicon (Si) resulting from natural weathering and leaching processes, there is evidence of declining Si levels following long-term sugarcane production.

Early research into silicate materials in the 1970’s was confounded by the influence of the associated cations (e.g. Ca) accompanying the Si source, and the inability to predict responsive soils. Recent field applications of silicate materials have resulted in substantial yield increases on certain soil types. Consequently, current research has concentrated on delineating the areas and soil types with sub-optimal soil Si levels. Future work involves extending soil surveys to develop Si risk assessment maps for the wet tropics of north Queensland, and with the establishment of field trials to assess the efficacy of selected Si based amendments and develop optimal rates and response functions.

Past, Present and Future Silicon Research in the South African Sugar Industry

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The relative efficiencies of calcium metasilicate slag and calcium carbonate are summarized from the results of a number of glasshouse and field experiments conducted in the South African Sugar Industry since 1970. In four out of the five field trials, significant yield responses ranging from 9 to 24 tons cane/ha were obtained from both the calcium silicate slag and lime treatments. On average, the silicon based treatments were 5% better than the lime treatments. In one trial where the ameliorants were incorporated to a depth of 65cm, calcium silicate increased yield significantly (P>0.01), whilst the response to lime did not attain a level of statistical significance. All ameliorants caused a reduction in exchangeable Al in the soil and a reduction in manganese uptake. With treatments containing silicon the increased yields were associated with an increase in the silicon concentration in the plant.

Current research is focused on the association between silicon assimilation and host-plant resistance to the stalk borer Eldana saccharina Walker (Hymenoptera:Vespidae). Recent evidence from a large scale pot trial in which sugarcane was treated with calcium silicate and artificially infested with E. saccharina at 9.5 months, showed a significant reduction of 33.7% in borer damage and 19.8% in borer mass. Scanning of leaf samples by Near Infra Red Spectrometry suggests that up to 60% of the variation in Eldana resistance can be accounted for by the leaf silicon content.
Review of Research in Japan on the Roles of Silicon in Conferring Resistance against Blast Disease in Rice

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In 1917, I. Onodera showed that rice plants affected by blast disease tended to contain less silicon than those that remained healthy. This was probably the first report that suggested an effect of silicon on blast resistance. Since then, many researchers have demonstrated that applying silicon to the soil causes higher silicon levels in rice and, as a consequence, an increase in blast resistance. Several hypotheses were proposed up to the 1950’s to explain this phenomenon. Most importantly, the fact that silicon is mainly localized in the leaf surface supports the hypothesis that the silicon layer may act as a physical barrier against penetration by the blast fungus. However, this cause-effect relationship has not yet been fully accepted. Application of silicon to commercial rice paddy fields became popular, after the effectiveness of readily available silicate slag on blast disease was demonstrated in 1952. The use of silicate slag reached a peak in the early 1970’s. However, the amount of research has declined since the 1960’s. This is probably because the interests of most blast researchers have changed to investigating more clear-cut blast disease countermeasures such as the use of fungicides and highly resistant genetic resources.

Silicon from Rice Disease Control Perspective in Brazil

Anne S. Prabhu\textsuperscript{1}, Morel P. Barbosa Filho\textsuperscript{1}, Marta C. Filippi\textsuperscript{1}, Lawrence E. Datnoff\textsuperscript{2} and George H. Snyder\textsuperscript{2}

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Rice blast and grain discoloration are mainly responsible for significant losses in grain yield and quality both in upland and irrigated ecosystems in Brazil. Rice planting in rotation with soybean in extensive, contiguous areas and high input technology provided a conducive environment to diseases which were hitherto unimportant such as sheath blight in irrigated rice and take-all in upland rice. Even though varietal resistance constitutes a major component in rice disease management, it should be integrated with long-term benefits of silicon fertilization. A field study conducted with genotypes showing wide variability for grain discoloration and different rates of SiO\textsubscript{2} showed promising results. Initial greenhouse inoculation tests are encouraging in controlling leaf blast at the vegetative phase with silicon. The logical extension of firmly established existing concepts on silicon and rice disease management should rely on multidisciplinary approach and inter-institutional collaboration. Extensive on farm trials at hot spot locations for diseases will compliment the experimental results and increase the speed and efficacy in accomplishing the desired goals.
Effects of Silicon Fertilization on Disease Development and Yields of Rice in Colombia

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The savannas of Colombia contain soils (Oxisols) constrained by silicon (Si) deficiency. Since upland rice production is expanding into this region, field experiments were conducted over two years on three representative soils to determine the extent to which Si deficiency may constrain rice yields and favor disease development. The experiments were complete factorials and included different levels of Si, P and varieties. Sources of Si tested included both calcium metasilicate and calcium silicate slag. Lime was applied to equalize lime value and Ca levels across treatments.

Silicon significantly reduced all observed rice diseases. Leaf blast severity and neck blast incidence were reduced from about 26\% and 53\% in non-amended plots to 15\% in Si-amended plots. Leaf scald severity was reduced from 42\% to 6\% in Si-amended plots, while grain discoloration was reduced from 4.2 to 1.0 in Si-amended plots. Si application increased rice yields by about 40\% on all three soils. A residual effect was also noted for reducing disease development and increasing yields. By amending these soils with Si, a very effective and potentially sustainable method for upland rice production and management of rice diseases appears available.

Plant-Related Silicon Research in Canada

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Silicon is a common but generally minor element found in the majority of living organisms as amorphous silica (SiO\textsubscript{2}nH\textsubscript{2}O) and soluble silicic acid (Si(OH)\textsubscript{4}). Its physiological essentiality is recognized in several protists and vertebrates, but in higher plants, its biological role is not well understood. In Canada, research into the significance of silicon to higher plants has focused on the importance of silicon in plant growth and development, and how this element can be utilized in agriculture. Three main areas of research conducted in Canada will be discussed; 1) the deposition of Si in organs and cells of higher plants, 2) the ability of silicon to help control plant diseases and 3) the use of silicon as an inert dust to control insects in post-harvest products.
Agricultural Utilization of Silicon in China

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\textsuperscript{3}College of Resources & Environmental Sciences, Nanjing Agricultural University, Nanjing, China

The first research on potential uses of Si-containing industrial by-products as fertilizer and soil amendments in China was carried out in late 1950's. Si fertilizer production and utilization has increased steadily since 1970s, and most Si fertilizers have primarily been used to improve rice production by enhancing resistance of rice plants to diseases and lodging. Field trial results conducted in recent years demonstrated that not only rice but many other crops had positive responses to Si. The increased yield by Si fertilization has mainly been attributed to enhanced crop resistance to diseases, lodging, drought and other environmental stresses such as salt and heavy metal toxicity, and optimized crop nutrient balance. It has also been found that applying Si together with other nutrients such as Zn and Mn as well as N, P, and K, can significantly increase the beneficial effect of Si.

This paper provides an overview of the soil Si fertility and history of Si fertilization research and practices in China, highlights the research effort to understand the interactions between Si and other nutrients, and to improve the efficiency of Si fertilization. This is followed by recommendations for future research on Si in China.

Silicon's Influence on Plants

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The first field trial of sodium silicate for rice grown in marine deposit soils in mid 1950's showed no effects. However, furnace slags provided some effects for most of the paddy soils. Ground wollastonite has been found to be more effective, improving growth of rice under the balanced supply of N, P and K in more than 90% of Korean paddy soils containing less than 130 mg kg\textsuperscript{-1} of available SiO\textsubscript{2} in top soils since 1960.

Intensive studies on the paddy soil fertility Basement models based on the soil test results, including available silica, have been started for the sustainable production of rice since 1970s. They may also be used for various upland crops of grass species such as maize, wheat and barley.
In the future, the use of those models may also be tested for the protection from environmental hazards due to the emission of green house gases such as nitrous oxide or methane either from the soil or through the plants.
Poster Abstracts

- Presenting authors appear in bold.
- Abstracts are listed alphabetically by country and last name of presenting author.
- Poster numbers are indicated in parenthesis at the end of abstract titles.
- Posters will be organized by poster number at the Tuesday evening poster session.
AUSTRALIA

Silicon Is Involved in Cane Yield Response to Sugar Mill Waste Products ..............................................(25)

Graham Kingston

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Sugar mills produce nutrient rich waste products (filter mud and furnace ash). In Australia, these materials are returned to cane fields in nutrient management or soil amelioration plans. Generally, yield responses are attributed to N, P, K and Ca constituents of the wastes. However, yield responses have also been reported where the above nutrients have been adequately supplied from fertilizer sources. Thus sugar mill wastes have earned a reputation for "mysterious capacity" to ameliorate soils with low natural fertility. How might we explain such responses?

This field experiment, on a gleyed podzolic soil (redoxic hydrosol) involved comparison of sugar mill ash alone and a sugar mill filter mud /ash mixture with supply of nutrients equivalent to the latter, from fertilizers. Data were acquired over two years, for first and second ratoon crops. The following conclusions were obtained: There was a good cane yield response to both sugar mill wastes in first and second ratoon crops; phosphorus, potassium, calcium and trace elements in the wastes did not improve yield; yield benefits of the sugar mill wastes were attributed to reduced bulk density and better nitrogen and silicon nutrition; sugar mill wastes resulted in higher levels of soil and leaf silicon than other treatments; and filter mud/ash increased soil nitrogen supply - ash alone did not. So silicon in ash may have improved nitrogen use efficiency. Silicon may be part of the mysterious benefits of sugar mill wastes.

Soil Analysis for Predicting Sugarcane Yield Response to Silicon .............................................................(26)

Michael B Haysom and Graham Kingston

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Silicon (Si) is emerging as an important nutrient for sugarcane in Australia and overseas. Large yield responses to Si were recorded in field experiments in north Queensland and Si is involved in response to sugar mill wastes containing ash. Advice for use of Si based amendments is likely to be based on soil analysis.

The following methods were used: Crushed cement building board waste was applied to three soils (euchrozem [volcanic], yellow podzolic & sand [sedimentary]); sugar mill wastes
(filter mud / ash mixture and ash) were applied to a gleyed podzolic soil; soil samples from 0 - 25cm zone were assayed for extractable Si in: 0.005M H₂SO₄, 0.01M CaCl₂ and 0.5M Acetic acid at pH 2.5 and also buffered to pH 4.8; leaf samples were assayed for Si; and relative cane yield was calculated for the gleyed podzolic site. The conclusions were as follows: Soil Si extracted in sulfuric acid and calcium chloride provided useful indices of plant available Si across soil types. Sulfuric acid and pH 2.5 acetic acid extractable Si were most closely related to the yield response on a gleyed podzolic soil. Therefore, 0.005M sulfuric acid holds promise as the basis of a Si soil test.

Some Effects of Silicon in Potting Mixes on Growth and Protection of Plants against Fungal Diseases ............... (13)

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Cucumbers, snapdragons and paper daisies were grown in an organic and sand based Control Mix (CON), +Si Mix (SIM = CON + Silicate) and Rice hull Ash Mix (RAM). Molybdate reactive Si in 1:1.5 DTPA extracts of mixes was 2.25-2.55mg/L for CON, 14.1-15.0mg/L for SIM and 11.4-13.6mg/L for RAM. Growth of cucumbers and paper daisies in RAM and SIM was significantly (P≤0.05) greater than for those grown in CON. Plants grown in RAM accumulated more Si than those grown in SIM, which contained more Si than those from CON. Snapdragons grown in SIM and CON were larger and flowered earlier and than those in RAM. Only bases of snapdragons grown in RAM contained more Si than plants from other mixes, at P=0.06.

Incidence and severity of an incidental infection of powdery mildew (Sphaerotheca fuliginea) was less for cucumbers grown in RAM at 6 and 10 weeks and SIM at 6 weeks than those grown in CON. Severity of infection of paper daisies by black mould (Colletotrichum gloeosporioides) was least when grown in RAM. Commonly used horticultural substrates contain less Si compared with the trial mixes and may contribute to reduced growth and increased susceptibility of potted plants to fungal diseases.
BRAZIL

Response of Upland Rice to Calcium Silicate Applications .................................................. (24)

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In Brazil, upland rice is cultivated mainly in Oxisols that are low in soil fertility including low Si in relation to Fe and Al oxide. An experiment was conducted, under greenhouse conditions, with the objective of evaluating the response of rice to SiO\(_2\). The treatments consisted of six doses of SiO\(_2\) (0.0, 0.75, 1.50, 2.25, 3.00, 3.75 g pot\(^{-1}\) containing 6 kg of soil) in the form of wollastonite, (Vansil-10, 50% of SiO\(_2\)) and three rice cultivars (Caiapó, Carajas, and Confiança). The relationship between SiO\(_2\) rates and grain yield was linear and significant (\(Y = 3.895 + 0.159x, r^2 = 0.638\)). The highest grain yield increase of 23%, in relation to control was obtained with the application of 3.0 g pot\(^{-1}\) of SiO\(_2\) corresponding to 1 t ha\(^{-1}\). The cultivar Confiança consistently showed the highest tissue concentration of Si followed by Carajas and Caiapó. The application of SiO\(_2\) also increased the pH and soluble Si in soil. Upland rice responded to SiO\(_2\) applications, but the magnitude of response was greater at the highest calcium silicate dose and varied according to the cultivar.

Use of Crushed Basaltic Scoria as a Silicon Source for Rice .............................................. (4)

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\(^2\)Undergraduate student

An experiment has been carried out since June 1999 to study the efficiency of crushed basaltic scoria in supplying available silicon to rice plants. The scoria was mixed to 3 kg samples of a medium-textured Red-Yellow Latosol and a sandy Quartz Sand soil at rates of 0, 70, 140 and 240 t ha\(^{-1}\) and placed in ceramic pots. The soil samples were moistened to 50% of the WHC and incubated for 20 days in the greenhouse. Soluble silicon was extracted from the soil by 0.5 M acetic acid solution and determined by colorimetric method, using ascorbic acid as the reducing agent.

In both soils, the extracted silicon increased linearly with the applied rates of basaltic scoria. For the highest rate applied, silicon content raised from 30 to 58 mg kg\(^{-1}\) (93% increase) in the Red-Yellow Latosol, and from 18 to 35 mg kg\(^{-1}\) (94% increase) in the Quartz Sand.
In continuation, three rice crops will be successively cultivated in the pots. Nutrients will be added in proper amounts, but no extra basalt scoria will be applied. For each crop, both dry matter and grain yields will be evaluated, as well as the amount of silicon absorbed by the plants and the soluble silicon content of the soil.

Evaluation of Soil Extractants for Silicon Availability in Upland Rice............................................................ (5)

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Generally, silicon is not considered an element “essential” for plant growth. However, many workers have shown that Si improves the growth of rice and other Gramineae species. Therefore, quantification of Si in soils and plant tissue would be an important routine analysis performed in agriculture research laboratories. The suitability of four extraction methods (acetic acid 0.5 mol L⁻¹, buffer pH 4.0, calcium chloride 0.0025 mol L⁻¹ and water) for estimating the amount of available Si in soil for upland rice was determined. Four soil types corresponding to the following classes were used: Typic Acrustox - isohyperthermic (LEa), Typic Acrustox - isohyperthermic (LVa), Rhodic Acrustox - isohyperthermic (LRd) and Ustoxic Quertzipsammentic - isohyperthermic (AQa), created in each of the soils by applying calcium silicate. Upland rice was grown to maturity in pots of each soil in the greenhouse. Among the extractants studied, the acetic acid 0.5 mol L⁻¹ gave the best estimate for Si availability in soil. The Si content found in the leaves was highly correlated with extractable Si by the acetic acid 0.5 mol L⁻¹ method.

Characteristics of an In Situ Opalized Vegetative Axis in a Brazilian Oxisol and Possible Plant Pathological Implications........................................... (38)

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Hollow, white siliceous cylinders identified as in situ partially opalized branched vegetative axis have been found in an Oxisol in SW Minas Gerais. The main axis is about 4-5 m long.
and 15cm diameter with a continuous wall of silicified outermost xylem tissues a few millimeters thick. Bark and more internal tissues were decomposed, and are being studied by SEM, X-ray fluorescence and diffraction, micromorphology and soil analysis. Organic matter is not preserved, but cell lumina have been replicated, and some cell walls with bordered pits have been permineralized. SEM locally revealed a relict botryoidal texture suggestive of original opal, now converted to low-trystidomite. Si was dominant but some Zn and Cu also were detected. "Available" Si in the adjacent soil increased with depth (3 to 30 ppm), and morphologic studies suggests *Cecropia sp*. Soil both inside and immediately outside the cylinder contained numerous biopedotubules with opal fragments. Silification evidently occurred recently or subsequently. Some *Cecropia* in the region have symptoms reminiscent of citrus blight, common in the area. The tantalizing possibility that silification may be involved with this disease is currently under study.

**Silica in Biodynamic Agriculture Since 1924.......................... (7)**

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The regular use of silica in Biodynamic Agriculture started in the beginning of the 20th century. Biodynamic Agriculture, a pioneer agroecological movement evolved from eight lectures given in 1924 by R. Steiner. Among the recommendations for agricultural purposes, Steiner suggested the use of certain highly diluted substances.

One of these substances was silica: especially prepared (quartz, pulverized very finely: ≤0.2mm) and highly diluted (4g/60liters H₂O/ha) which constitutes the so-called “preparation 501”, that is sprayed on plants in order to enhance the effects of light. This was recommended for improving longitudinal growth and a finer tissues’ structure; to increase elasticity, flexibility and resistance in cereal’s stems; to intensify the synthesis of chlorophyll and the absorption of light; to promote greater contents of sugars and protein; to increase silicon deposition in roots, stems, leaves and fruit; to enhance food’s storage capacity; to intensify colors and shininess of plants, and the yields of certain crops; to improve ripening and taste and increase the product’s aroma. In fact, higher food quality has always been one of the main purposes of biodynamic agriculture.

KOLISKO was one of the first to research some of these effects, from 1931 to 1934. More recently, other experiments were carried out by KLETT in 1968, WISTINGHAUSEN in 1979, ABELE in 1987 and others, in which the relationship between different light conditions and the use of preparation 501 confirmed its effect.

ABELE in 1973 tested the effects of preparation 501 on sugar beets, potatoes, spring wheat, barley and oats. There was a slight increase in the sugar content of sugar beet and also in the content of crude protein in potatoes and cereals. This suggests an influence of silica on carbohydrates and crude protein synthesis, even when used in very high dilutions. Abele obtained higher yields for sugar beets and cereals, observing a significant positive effect
especially in shadow treatments. This result is a confirmation of those first obtained by KOLISKO in 1939 according to which preparation 501 reproduced light effects even in deficient light conditions. JONES and HANDRECK in 1967 confirmed silica’s importance in the plant’s morphological and structural development, inducing, as a consequence, higher resistance against insects and fungi. The same had been observed by GERMAR in 1934, when he added colloidal silicic acid to cereals.

All these compensation (regulation) effects of silica have been studied in Biodynamic Agriculture research since the beginning of the century. In Brazil, such research is only just starting; the potential effects of preparation 501 and its very low costs may very soon become interesting for important branches of agroecological agribusiness, especially sugarcane, citiculture, soybean and essential oils. This paper intends to show the contribution of the Steiner’s indications about the effects of highly-diluted (preparation 501) on plant development and the quality of agricultural products.

Silicon and *Theobroma cacao* .................................................. (14)

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Witches broom of *Theobroma cacao* is caused by the basidiomycete, *Crinipellis perniciosa*. This disease is endemic to the cocoa producing countries of South and Central America, and the Caribbean Islands. The pathogen infects meristematic tissues, flower cushions and developing pods. The disease now limits cacao expansion and consolidation in Brazil.

The only effective control measure is through phytosanitation and its adoption depends on the world cocoa price. The long-term solution is through use of resistant cocoa genotypes.

There is limited information regarding the relationship between mineral nutrition and disease development by *C. perniciosa* in *T. cacao*. We herein report for the first time the effect of silicon on cocoa seedling growth, and on the biology of *C. perniciosa*. Germ tube length of basidiospores of *C. perniciosa* was reduced by 250 mg/kg of Si. Mycelial growth rates varied by isolate and the most sensitive isolate of *C. perniciosa* to Si was from Altamira, PA, Brazil. The role of silicon on cocoa growth and disease resistance to *C. perniciosa* will be discussed.
Calcium Silicate Slag in Tropical Savanna Soil. 
III-Effect on the Availability of Phosphorus in Soil and Sugar Cane.................................(33)

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The objective was to compare the use of limestone to that of calcium silicate slag (39.9% SiO₂) on the availability of soil phosphorus and in sugar cane on two plantations in two acidic soils in the tropical savanna region. Thus, a pot experiment was performed at the Engineering Faculty of Ilha Solteira/UNESP. Blocks were randomized but each one had a factorial design involving 2 levels of acidic correction (1xNC ; 2xNC), saturation was considered on bases equal to 45% (1xNC); two corrective agents (calcitic limestone and calcium silicate slag); and two soils (Quartzose Sand and Dark-Red Latosol). 200mg/dm³ of P was applied together with the corrective agents at the time of the planting of the sugar cane. The soil was analyzed 225 days after the incorporation of these products.

The calcium silicate slag in the dose 1xNC was better than limestone for increasing available P in the soil. For sugar-cane, the slag had a linear effect whereas limestone had no effect at both locations. Therefore, the silicon in the slag affected indirectly the P increase of the soil.

Effect of Silicon Fertilization on Rice Sheath Blight Development in Brazil..............................................(15)

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Sheath blight (Rhizoctonia solani Kühn) is an important disease in intensified rice production systems worldwide. This study examined the effect of calcium metasilicate (wollastonite) at the rates of 0, 2, 4, 6 and 8 Mg ha⁻¹ on sheath blight development. Six rice cultivars were grown on a typic acrustox (red-yellow latosol, 0-20 cm, Ki = 0.74, Si = 9.2 ppm and pH = 4.8). Linear regression models described the relationship between the assessments by highest relative lesion height (HRLH) and severity (scale ranged from 0 to 9) and silicon rates. The HRLH was reduced relative to the control by 24%, 25%, 33%, 20%, 24%, and 32% for the rice cultivars: ‘Epagri 109’, ‘Rio Formoso’, ‘Javaé’, ‘Cica-8’, ‘BR-Irga 409’, and ‘Metica-1’. Sheath blight severity also decreased by 61%, 57%, 59%, 61%, 62%, and 60% for the rice
cultivars 'Epagri 109', 'Rio Formoso', 'Javae', 'Cica-8', 'BR-Irga 409', and 'Metica-1' in comparison to the control.

Response of Six Gramineae Species to Applications of Calcium Metasilicate ................................. (16)

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Despite its abundance and importance, silicon has received far less study than any other nutrient. Silicon concentration of plant varies by soil and plant species. This experiment evaluated the uptake of Si and Ca by six grasses by applying calcium metasilicate ( wollastonite) at the rates of 0, 200, 400, 600 and 800 kg SiO₂ ha⁻¹. The grasses were grown on a typic acrustox (red-yellow latosol, 0-20 cm, Kᵢ = 0.74, Si = 9.2 ppm and pH = 4.8). Only Si, not Ca, significantly increased with increasing calcium silicate rates. On average, Ca values ranged from 0.16 to 0.40%. Linear regression models described the relationship between plant tissue silicon concentration and silicon rate. Silicon concentration (%) in the six gramineae species increased relative to the control by 251%, 125%, 100%, 47%, 40%, and 12% for rice, oat, sorghum, corn, wheat, and rye, respectively. Although dry weights of shoots and roots were not significantly different from the non-treated control, plant heights increased significantly.

Influence of Silicon Fertilization on Powdery Mildew Development in Cucumber ......................... (19)

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It is long known that silicon enhances the fungal resistance of many plant species. In cucumber, the addition of silicon to hydroponic nutrient solutions has helped to reduced powdery mildew (*Sphaerotheca fuliginea*) development. The effect of silicon on powdery mildew development in cucumber was determined. Silicon was added to a typic acrustox (red-yellow latosol, 0-20 cm, Kᵢ = 0.74, Si = 9.2 ppm and pH = 4.8) as calcium metasilicate ( wollastonite) at the rates of 0, 2, 4, 6 and 8 Mg ha⁻¹. Conidia of *Oidium* sp. were collected from infected cucumber plants from fields never treated with fungicides and brushed onto

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leaves of cucumber plants (‘Hibrido Caipira AG370’) amended and non-amended with silicon. Silicon was able to reduce the severity of powdery mildew and the number of mildew colonies relative to the control by 30.3%, and 36%, respectively, but these treatments were not significantly different from the non-treated control. Dry weight also was not affected but leaf area increased significantly.

CANADA

Proof of Stable Aqueous Silicon-Sugar Complexes..............(37)

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The importance of silicon in plant physiology has been amply demonstrated. Yet, almost nothing is known of the chemistry that plants use to uptake and transport silicon. Indeed, although numerous proteins and naturally occurring ligands have been identified as potential silicon binding substrates, no organosilicon complexes have ever been detected under physiological conditions. Using $^{29}$Si NMR spectroscopy, we have shown that certain aliphatic polyhydroxy molecules (“polyols”) - including a number of simple sugar molecules - display an extraordinary affinity for aqueous silicate anions, forming stable monomeric polyol-silicon complexes.

The silicon in these complexes can exist in either five- or six-fold coordination by oxygen, a phenomenon previously unknown in aqueous Si chemistry. Coordinating polyols require at least four adjacent hydroxy groups, two of which must be in threo configuration, and coordinate to silicon via hydroxy oxygens at chain positions on either side of the threo pair. Such species can reasonably be expected to play a central role in the biochemistry of silicon.


**CHINA**

**Effect of Silicon Fertilization on Crops Grown in the Yellow River Alluvial Plain of China**

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The effect of a silicon fertilizer, which is made from blast furnace slag, was tested on various plants growing in the Yellow River alluvial plain of China. The results indicated that this silicon fertilizer increased grain production 10-26% for rice, 10-15% for wheat and 15-25% for peanut. The mechanism for increased yields was based on the original low silicon content in water from the Yellow River, the lack of available silicon in the soil and the richness of trace elements in the blast-furnace-slag-made silicon fertilizer. Silicon content in water from the Yellow River system was between 0 to 10 mg/L. The concentration of available silicon in the soil ranged from 100 to 300 mg/g. Moreover, the relatively high pH value and richness of Ca and Mg observed in the Yellow River alluvial soil probably negatively influenced silicon absorption.

In rural areas of China, agriculture and the farmer are always the pivotal problems in supporting China’s economic development and social stability. It is estimated that five million tons of silicon fertilizer would be required per year for agricultural production in the Yellow River alluvial plain. These data suggest that the application and popularization of silicon fertilizer in the area should be enhanced.

**Yield Response to Si and Combined Use of SiZnMn Fertilizer in China**

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Beneficial effects of Si application on yield and quality of rice as well as other crops have been achieved in the major grain production areas in China in the past two decades. Generally, critical soil available SiO\(_2\) content is 95 mg/kg, but good responses to Si in rice were found in soils with available content as high as 180 mg/kg. In North China critical value for winter wheat was 220 mg/kg and the same yield increase effect was achieved in summer.
corn. In Northeast China, significant yield increases were achieved in light chernozem and brown soils in which soil available SiO₂ content ranged 70–140 mg/kg. Field trials demonstrated that, compared with N, P, Zn, Mn fertilizer use alone or these fertilizers combined with each other, a combined application of SiZnMn could more efficiently increase absorption of N, Zn, Mn and P by crops, improve water use efficiency and resistance to lodging. Since two or three nutrients often appears deficient in one soil in China, the combined use of SiZnMn proved best. The proper doses of Si fertilizer (calculated as Na₂SiO₃) were not higher than 90 kg/ha in South and North China.

**Silicon Induced Cadmium Tolerance of Rice (Oryza sativa L.) Seedlings** ................................................. (29)

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Cadmium (Cd²⁺) toxicity and the effects of silicon (Si) on the cellular and intracellular accumulations and distributions of cadmium were investigated by conventional electron microscopy and EDX analysis. The Si-deprived rice plants (-Si) differed greatly in cadmium distribution in the cell walls and vacuoles of the leaves and roots in comparison to Si-amended treatments. Energy dispersive X-ray microanalysis revealed that considerable amounts of Cd could be detected in the cytoplasm, vacuole or cellular organelles in -Si rice plants, while very little was found in +Si ones. From the microchemical and microbiological point of view, cell wall templates mediated the formation of colloidal silica with a high specific adsorption property and this helped to prevent the uptake of cadmium into the cell.

**Effects of Silicon on the Seedling Growth of Creeping Bentgrass and Zoysiagrass** ......................................... (30)

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The effects of silicon (Si) on the seedling growth of creeping bentgrass and zoysiagrass grown in a nutrient solution with three concentrations of Si (0, 1.7mM and 5.0mM) were studied in a greenhouse chamber. Silicon promotes
turfgrass quality development including rigidity, elasticity, and traffic resistance. It also improves significantly the ability of creeping bentgrass to tolerate heat stress exceeding 45°C during the day and 35°C at night. The Si-treated seedlings produced more fresh matter over the untreated seedlings. Silicon at 5.0mM in the solution increased root length, fresh weight of roots and leaves of creeping bentgrass and zoysia grass. The effects of Si at 1.7mM on the root growth of zoysia grass were not significant. In contrast, Si at 1.7mM and 5.0mM significantly increased growth effects on bentgrass. The treated seedlings increased the uptake of phosphorus and Si by shoots in comparison to the untreated seedlings as determined by quantitative EDX analysis. Thus, Si application to turfgrasses seems to be an efficient maintenance practice for improving stress resistance while enhancing agronomic and environmental benefits.

**Plant Cell Wall Template-mediated Cooperative Synthesis of Micrometer-sized Colloidal Silica** ........................................... (31)

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Zoysiagrass (*Zoysia japonica* L.) is widely used in sports turf and golf courses because of its excellent functional qualities, including rigidity, elasticity, resiliency, and disease tolerance as well. In addition, this turfgrass contains considerable silica deposited in the cell wall and micrometer-sized intercellular spaces of leaf epidermal cells. Thus Si figures is a major mineral constituent of this turfgrass. Such a deposition would increase the mechanical strength of the plant cell wall, so Si acts as a compression-resistant element. That in turn may improve the ability of grass to resist traffic and lodging. It is surprising to find a pronounced difference in the roughness of leaf surface physical properties. Si deprivation usually results in diminished biological performance. We examined whether different Si chemical forms affect the morphological characteristics and the cooperative synthesis of hybrid inorganic-organic silicon materials in the turfgrass cell wall template, and we describe intriguing biological strategies to self-assemble colloidal silica through oligosaccharide of zoysiagrass cell wall template and the silica sol-based nanoparticles for the fabrication of the highly ordered silica superlattices.

The biomineral analysis of the intercellular spaces of zoysia showed continuous silica superlattice arrays of organized hexagonal close packed (h.c.p.) which were preferentially deposited on the cell wall templates when applied as the silica sol-based nanoparticles rather than monosilicic acid molecular species. Biomineralized rods are rhombic in outline and virtually of constant size with major axes averaging 0.6μm. We find that the Si-chemical forms of applications for plant absorption and primary building block of mineralization do
affect significantly the formation of the superlattice arrays comparable to the random arrays that form without nanoparticles as a control. The composition was estimated by energy dispersive X-ray (EDX) spectra on a scanning electron microscope. The resulting intact rod showed carbon, oxygen, and silicon peaks. The variations of secondary electron peaks in the elemental contents with scanning organic-inorganic interfaces were reflected in commensurate changes. High-resolution image of an individual siliceous domain revealed irregular incoherent fringes in all selected microareas.

INDIA

Recycling of Rice Plant Silicon and Potassium for Blast Management in Rice

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Eco-friendly, low-cost input and agronomically efficient management practices for small resource-poor rice farmers are required in the future. A field trial was conducted during the 1996-97 wet season (southwest monsoon season, June-October) in the warm subhumid tropical region of the Maharashtra State, India. The objective was to evaluate the effect of rice hull ash (RHA) (as a source of Si) integrated with rice straw (RS) (as source of K & Si) on incidence of blast disease incited by Pyricularia oryzae Cav., plant growth and yield of rainfed transplanted rice (Oryza sativa L., cv. Chimansal-39). The field trial was a split plot design with three replications. The two main treatments were basal incorporation of RS at 0 and 2.0 t ha\(^{-1}\) at transplanting, and five sub-treatments were 0, 0.5, 1.0, 1.5 and 2.0 kg RHA m\(^{-2}\) added to the seedbed prior to sowing. Fertilizers in the form of urea briquettes containing diammonium phosphate were applied immediately after controlled transplanting, suppling 56 kg N and 14 kg P ha\(^{-1}\).

The integrated use of RHA at 2.0 kg m\(^{-2}\) and RS at 2 t ha\(^{-1}\) significantly reduced the severity of leaf blast (24.9%) and incidence of neck blast (29.7%) in comparison to the non-treated control. Grain yield (17.8 q ha\(^{-1}\)) also increased over the nontreated control (13.3 q ha\(^{-1}\)). Thus, the use of RHA at 1 kg m\(^{-2}\) of seedbed combined with RS at 2 t ha\(^{-1}\) may be helpful to farmers for reducing blast incidence while increasing the rice yields without the use of fungicides.
Recycling of Rice Plant Silicon and Potassium for Leaf Scald Management in Rice ........................................ (12)

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Eco-friendly, low-cost input and agronomically efficient management practices for small resource-poor rice farmers are required in the future. Three field trials were conducted during the 1995, 1996 and 1997 wet seasons (southwest monsoon seasons, June-October) in the warm subhumid tropical region of the Maharashtra State, India. The objective was to evaluate the effects of rice hull ash (RHA) (as a source of Si) integrated with rice straw (RS) (as source of K & Si) on incidence of leaf scald disease incited by Monographella albecens (Thum) (Rhynchosporium oryzae Hashioka and Yokogi), plant growth and yield of rainfed transplanted rice (Oryza sativa L., cv. Indrayani). The field trials were a split plot design with three replications. The two main treatments were basal incorporation of RS at 0 and 2.0 t ha⁻¹ at transplanting, and the five subtrtreatments were 0, 0.5, 1.0, 1.5 and 2.0 kg RHA m⁻² added to the seedbed prior to sowing. Fertilizers in the form of urea briquettes containing diammonium phosphate were applied immediately after controlled transplanting, supplying 56 kg N and 14 kg P ha⁻¹.

The integrated use of RHA at 2.0 kg m⁻² and RS at 2 t ha⁻¹ significantly reduced the incidence (34.9,%) and severity (29.6%) of the leaf scald compared to control. The reduction in the incidence and severity of this disease was 29.5% and 25.6%, respectively, over the control. Grain yield (51.2 q ha⁻¹) also increased over the nontreated control (39.1 q ha⁻¹). Thus, the use of RHA at 1 kg m⁻² of seedbed combined with RS at 2 t ha⁻¹ may be helpful to farmers for reducing leaf scald incidence and severity while increasing the rice yields without the use of fungicides.

Calcium Silicate Slag Applied to Soil Increased Yield of Rice on Inceptisol of Maharashtra State, India ............... (27)

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Efficient fertilizer management practices are required for farmers to improve low yields of transplanted rice (Oryza sativa L.) grown on Inceptisols. A field trial was conducted on an Inceptisol during the 1996-97 Rabi season (December to May) in the warm sub-humid tropical region on the west coast of the Maharashtra State, India. The objective was to evaluate the effects of calcium silicate slag (CSS) on plant growth, nutrient uptake and yield of irrigated transplanted rice (var. RTN-24). The CSS containing 45.0% SiO₂ supplied by
Calcium Silicate Corporation, USA was applied at the rate of 0, 2, 4 and 6 t/ha to soil before transplanting. Fertilizers were applied at 60 kg N/ha and 13 kg P/ha either as basal broadcast and incorporated prilled urea and single superphosphate (PU+SSP) or deep placed 2.7 g urea briquettes containing diammonium phosphate (UB-DAP) for every four hills after transplanting with modified 20X20 cm spacing.

For both methods of fertilizers applied, the CSS improved plant growth, nutrient uptake and yield of rice. However, the CSS applied along with the deep placement of UB-DAP immediately after transplanting increased more plant growth, nutrient (N, P, K, Ca, Mg and Si) uptake and resulted in additional yield increases (1.3 to 1.4 t/ha) than in comparison to the split application of PU+basal SSP. The CSS seemed to reduce the incidence of stem borer in the rice crop. These results suggest the potential use of CSS and deep placed UB-DAP in enhancing yields of transplanted rice on Inceptisols of Maharashtra State, India.

Effect of Calcium Silicate Slag on Plant Growth, Nutrient Uptake and Yield of Sugarcane on Two Soils of Maharashtra State, India

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Attempts were made to investigate decreasing or stagnant yields of sugarcane (Saccharum officinarum L.) on soils of Maharashtra State, India. Two field trials on a Vertisol (Padegaon, Dist. Pune) and one field trial on Inceptisol (Dapoli, Dist. Ratnapuri) were conducted during 1997-98 to evaluate the effect of calcium silicate slag (CSS) on plant growth, nutrient uptake, yield and juice quality of two plant sugarcane varieties (CO-86032 and CO-92013). The CCS containing 45.0% SiO₂ was basal applied to soil at 0, 2, 4, 6, 8 and/or 10 t/ha. Recommended levels of farmyard manure (FYM) and/or NPK fertilizers were also applied to the soils.

In all three field trials, the application of CSS in graded levels resulted in significant increases in plant growth, cane yield and commercial cane sugar. There was improvement in brix, % sucrose and % purity of juice quality due to the CSS applications on the Vertisol at Padegaon only. The total nutrient (N, P, K, Ca, Mg and Si) uptake (kg/ha) was increased due to the application of CSS. These results suggest that considering the plant growth, yield and juice quality, the application of about 6 t/ha CSS to the sugarcane varieties was found beneficial under the given agro-climatic conditions. However, more multi-locational trials in different seasons are required to assess need of calcium silicate fertilizers for improving sugarcane yield in Maharashtra State.
JAPAN

New Silicon Source for Rice Cultivation:
3. Growth and Yield of Wetland Rice
with Reference to Silica Gel Application.......................... (1)

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It is a well-known fact that dry matter production and yield of rice are affected by its silicon (Si) content when grown under solution culture. It is difficult to identify the effect of Si on growth and yield of rice grown under field conditions, because the amount of mineralized N increases when a Si source is applied to the field. The objectives of this study were to evaluate the dry matter production and yield of rice grown under field conditions as affected by a new Si fertilizer, silica gel. Results obtained were as follows: 1) Increased rate of Si application enhanced dry weight, amount of N/leaf area (LA), and chlorophyll/LA of rice. 2) Moisture content of the leaf blade and light transmission ratio was greater in Si treated plots in comparison to the non-treated control in the afternoon. These facts suggest that the net assimilation rate of Si treated plots was greater than the non-treated controls. 3) A greater number of grains per unit area, percentage of mature grains and yield of rice were obtained in Si treated plots in comparison to the non-treated control.

New Silicon Source for Rice Cultivation: 2. Rooting Ability and Early Growth of Wetland Rice as Affected by Silica gel Application to the Nursery Bed............................... (2)

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The early growth of rice is affected by variability among rice seedlings in a temperate region. One of the factors that relates to the variability is silicon (Si) content of rice seedlings. The application of Si to nursery bed of rice is difficult because of its high pH status. The object of this study was to estimate the rooting ability and early growth of rice plant using silica gel. The results obtained were as follows: 1) seedlings treated with Si had a higher dry weight, a
higher dry weight to plant height ratio and increased content of silica compared to the control, 2) the photosynthetic rates of individual leaves and of the plant canopy of rice seedlings were higher in the Si treatments. A greater amount of TAC was observed in the seedlings treated with Si compared to the untreated control, and 3) a greater number of roots and heavier dry weight were found in the Si treated plots than in the control.

New Silicon Source for Rice Cultivation:  
4. How Does Silicon Influence Host Resistance to Rice Blast Disease? .....................................................(3)

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While many researchers have demonstrated that silicon in rice plants plays an important role in the resistance against blast disease, the mechanism is not clearly defined. Based on the work of earlier researchers, we put forward several hypotheses to explain how silicon confers this resistance. One hypothesis was that the absorption of silicon in rice reduces nitrogen uptake, consequently reducing the susceptibility to rice blast. However, our experiments did not support this hypothesis, since applying silica gel to rice did not reduce nitrogen uptake. Another hypothesis was that at least one process of pathogenesis was inhibited in rice plants with higher silicon content. Our results showed no significant differences between high and low silicon concentration on spore germination rates, appressorium formation rates, the size of lesions, and sporulation capacity. Therefore, it is unlikely that these mechanisms are the primary factors of resistance. The remaining possible explanations are that silicon acts as a physical barrier against fungal penetration on the surface of leaves or that silicon promotes some physiological resistance mechanisms within the plant. Consequently, we will test these hypothesis during the early infection phase.
New Silicon Source for Rice Cultivation: 1. Characteristic of New Silicon Source, Silica Gel

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Silicon is known to be one of the most important elements for growing rice. Many researchers have been studying the effect of silicon on plant growth and development for many years. The effect of silicon on growth and yield of plants grown under field condition may be difficult to determine because silicon fertilizers contain some alkali that may increase soil pH. Furthermore, plant diseases are often observed to be reduced when a silicon fertilizer is applied. These facts indicate that a new silicon source for crop production should be considered. We have developed a new silicon source, silica gel that could substituted for the existing silicon fertilizers used by farmers. The characteristics of this fertilizer are as follows: 1) silica gel is amorphous and has a large surface area, consequently, it is highly soluble in water, 2) milling and sieving can control the particle size of the silica gel, and the pH can range between 3 and 9, and 3) no significant difference in amount of mineralized NH₄-N occurred between the treatments with and without silica gel applied to the soil.

Available Silicon in Soils Extracted with Phosphate Buffer

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Acetate buffer has been widely used in Japan to evaluate the plant available Si status of soils. However, it is known that silicon is extracted in excess when the soil has received silicate slag. We proposed a new method to estimate availability by extraction with 0.02M-phosphate buffer, pH6.95 (PB). The procedure is: Si is extracted from 1g soil with 10ml PB in a tube at 40°C for 5 hours, while stirring 5 times during extraction. The Si extracted with PB consisted of water-soluble and phosphate extractable fractions; the average ratios of water-soluble Si of 12 Andosols and 11 non-Andosols were 38% and 53%, respectively.

The result at 4 prefectural agriculture research stations showed that the Si extracted with PB correlated well with the Si content of rice plants except for a few soil types. The correlation
was not found for the acetate buffer method. The Si in Andosols tended to be higher than the amount taken up by rice plant and the overestimation was supposed to be due to the difference in the water-soluble ratios.

We concluded the PB method is useful to evaluate the available Si in soils and is better than the acetate buffer method.

**Effects of Porous Hydrated Calcium Silicate on Silicon Nutrition of Paddy Rice** ...........................................(8)

*Masahiko Saigusa, Akiko Yamamoto and Kyoichi Shibuya*

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Large amounts of porous hydrated calcium silicate (PS) fragment is produced as a industrial waste in the manufacturing process of autoclaved light weight concrete. Silicon is one of the most important elements for rice production, and thus we investigated the effect of PS as a silicate fertilizer on silicon nutrition of paddy rice. The results obtained are: (1) PS is more effective for supplying silicon to rice plant than most commercial slags that were originally used as silicate fertilizers, (2) PS supplies silicon to rice plants continually from time of transplanting to harvest. (3) Tobermorite, main component of PS, was dissolved by 53 days after rice transplanting under paddy condition, but a silica skeleton remained till harvest time. (4) Application of PS reinforced plant resistance against rice blast disease, and also increased rice grain yield. From the foregoing, PS was determined to be a superior material for silicate fertilization of rice. This work was supported in part by Program of Research for the Future from the Japan Society for Promotion of Science (JSPS-RFTF96LOO604)

**KOREA**

**Influences of Silicon on the Control of Temperature and Induction of Electronic Voltages in Rice Plant Tissues** .......(36)

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Jap. x Ind. hybrid rice variety “Dasanbyeo” was grown in a water culture with silicon and without silicon to investigate the influences of silicon on the control of temperature and induction of electronic voltages in rice plant tissues.

Leaf temperatures of silicon treated rice measured by infrared imaging radiometer were 22.7° C in 25° C ambient temperature and 30.7° C in 32° C, respectively, which was 1.7° C and 3.1°
C higher than those of silicon-free plants, respectively. Leaf temperatures of silicon treated plants measured by a potometer were 30.8-32.5°C in 30-38°C ambient temperatures, which were 0.7-0.9°C higher than those of silicon-free plant. However, under conditions of high temperature with 43-48°C leaf temperature of silicon-absorbed plant was 0.2-0.4°C lower than that in silicon-free plant.

The difference in electronic voltages between silicon-free and silicon-treated plants was near 6.5 mV. There was a relatively higher difference in unit and electronic induction pattern was also different from each other.

The change in electronic voltages in silicon treated plants was stable, while it was unstable in silicon-free plants. The induction of electronic voltage in leaf blade of rice plants stimulated by hand showed a sensitive response in the silicon-free plant.

**RUSSIA**

A Proposed History of Silicon Fertilization................................. (39)

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Early agriculturists first used plant ash as a silicon (Si) fertilizer. Over two thousand years ago, the Emperor in China mandated the use of barley or rice with manure as a fertilizer by farmers. Vergilian, 70-19 BC, suggested the use of plant ash for improving the fertility of degraded soils of Rome. The first experiment ever conducted using Si as a fertilizer was by J. Liebig in 1840. His early work helped to promote Si research in Germany, Great Britain, Japan, Russia and USA. The classic field experiment with Si was started at the Rothamsted Experiment Station in 1856. Maxwell in 1898 conducted the first soil tests on the content of plant-available (mobile) Si on the Hawaiian Islands. German scientists, Kreuzhage and Wolf (1884) and Grob (1896), explored Si’s effect on plant disease resistance. Japanese scientists such as Odonera (1917) and Miyake and Adachi (1922) continued with this idea with rice that resulted in many outstanding discoveries. The Russian chemist D.I. Mendeleev suggested the use of Si fertilizers such as SiO₂ and CaSiO₃ in 1870. The first patent for using Si-rich slag as fertilizer was obtained in the USA in 1881. The first field experiments using Si as a by product from the metal industry were conducted by Cowles in 1917. In 1927, V.I. Vernadsky, an academic from Russia, declared that Si is an important element for all living organisms. Based on past and current scientific research with Si, these reviews demonstrate the possibility of developing an adequate theoretical base for silicon fertilization and its practical implementation in agriculture.
USA

Silicon Use in Louisiana Rice: Potential Improvements in Disease Management and Grain Yields

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Sheath blight (\textit{Rhizoctonia solani}) and blast (\textit{Pyricularia grisea}) are major rice diseases in Louisiana, both causing significant losses in grain yield and quality. Field studies were conducted on a Crowley silt loam (1995-1997) and on a Rita muck soil (1995-1996) to determine the effectiveness of silicon soil amendments in reducing the incidence of disease and increasing grain yield of rice. Calcium silicate slag was preplant incorporated at rates of 0, 1120, 2240, 3360, 4480, and 5600 kg/ha. The cultivars Bengal and Cypress were grown in a water-seeded, pinpoint flood cultural system. Grain yield, silicon accumulation in the y-leaf, whole plant, and in the mature rice straw were determined. Disease ratings for sheath blight, blast, and brown spot (\textit{Bipolaris oryzae}) were determined when significant disease was present.

On the Crowley silt loam soil in 1995 and 1996, grain yield increased 14 and 6\%, respectively. Approximately 3360 kg/ha of calcium silicate slag were required to maximize grain yields. The average increase in silicon content over years of the y-leaf, whole plant, and mature rice straw was 30, 34, and 26\%, respectively. The incidence of sheath blight was decreased in 1996-1997. Blast was decreased by calcium silicate slag applications in 1995, although the incidence of blast was very low. On the Rita muck in 1995 and 1996, grain yield increased 24 and 9\%, respectively. This soil required a higher application rate of calcium silicate slag to maximize grain yields, approximately 4480 kg/ha. The average increase in silicon content over years of the y-leaf and mature rice straw was 46 and 21\%, respectively. Whole plant silicon content on the Rita muck was increased 53\%. Sheath blight was not affected by increasing rate of calcium silicate slag in 1996, but the incidence of brown spot was significantly reduced.

Applications of calcium silicate slag to a Crowley silt loam and Rita muck soil resulted in rice yield increases and higher accumulation of silicon in the y-leaf, whole plant, and mature rice straw. Grain yield and silicon accumulation responses were higher on the Rita muck. Calcium silicate slag applications had a positive effect on the incidence of blast, sheath blight, and brown spot on both soils. These field studies indicate that silicon soil amendments offer the potential to reduce disease incidence and increase rice grain yield in Louisiana. More research is needed to determine the economic feasibility of calcium silicate slag applications to Louisiana rice soils.
Beneficial Effects of Silicon on Container-Grown Ornamental Plants ......................................................... (22)

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Silicon (Si) has been reported as a beneficial element for promoting the growth of monocots, particularly rice and sugarcane. However, limited research has addressed the effects of Si on container-grown ornamentals. Since most ornamental crops are grown in soilless media where the Si concentration is minimal, this study was undertaken to determine if Si could be beneficial to ornamental plant growth. Thirty-seven cultivars from 35 genera of ornamental plants were grown in a soilless medium supplemented with K₂SiO₃. Afterwards, plant growth and Si concentration were measured. General results indicated that all of the plants were capable of absorbing Si through their roots with large amounts found to have been translocated to the shoots, indicating that Si may play certain roles in plant metabolism. More specifically, the addition of Si: (1) significantly increased the dry weight of 16 cultivars, and (2) mitigated manganese (Mn) toxicity. Therefore, Si could be used as a fertilizer additive for improving the growth and quality of Si-responsive ornamental plants.

Influence of Silicon and Host Plant Resistance on Gray Leaf Spot Development in St. Augustinegrass .................. (10)

Lawrence E. Datnoff and Russell T. Nagata

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This study investigated the effect of silicon on gray leaf spot, caused by Pyricularia grisea, in St. Augustinegrass. The experiment was a factorial with 10 replications arranged in a RCB in the greenhouse. Main effects were silicon (14 g/m CaSiO₃ / 500 cc soil) and a non-amended control, and sub-effects were four St. Augustinegrass cultivars; Bitterblue, Floratam, FX-10 and Seville. Plants were periodically misted to provide optimum leaf wetness that promoted natural infection by P. grisea. Disease severity was rated over a 4 week period by estimating % gray leaf spot on individual leaflets using a Horsfall-Barratt rating scale. Silicon significantly reduced area under the disease progress curves for gray leaf spot between 44% to 78% among all the St. Augustinegrass cultivars. This element also significantly reduced the final disease severity between 2.0% to 38.8%, and final whole plant infection between 2.5% and 50.5%. Plant silicon content in Si-amended treatments for all cultivars increased between 2.2X to 3.5X over the non-amended controls. Silicon appears to be a good method for reducing gray leaf spot development in St. Augustinegrass.
Plant Available Silicon in Selected Alfisols and Ultisols of Florida

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Plant available silicon was measured in soils from 70 locations in Florida. Forty of these were Ultisols including five soil series and thirty were Alfisols including three soil series. The average soil silicon content in Ultisols ranged from 7 ug/g in the Bonifay soil series to 15 ug/g in the Orangetburg soil series. The average soil silicon content in the Alfisols ranged from 6 ug/g in the Pineda soil series to 15 ug/g in the Winder soil series. One critical minimum concentration of silicon in the soil mentioned in the literature is 19 ug/g. Based on that concentration, corn, Bahia grass, Bermuda grass, pangola grass, chufa and cucumbers will probably respond to silicon added to the soil.

Effects of Fertilization with Silicon on the Components of Resistance to Rice Blast

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The addition of silicon (Si) to Si-deficient soils is known to reduce the epidemic rate of blast, caused by Magnaporthe grisea, in blast-susceptible and partially resistant cultivars of rice. Four cultivars of rice with differential susceptibilities to race IB-49 of M. grisea were fertilized with three rates of calcium silicate and inoculated with the pathogen to test the effects of Si on the components of resistance that influence epidemic rate. The following components of resistance to blast were examined: incubation and latent period, infection efficiency, lesion size, rate of lesion expansion, sporulation per lesion, and diseased leaf area. For each cultivar, the incubation period was significantly lengthened by increased rates of Si, and the numbers of sporulating lesions, lesion size and rate of expansion, diseased leaf area, and number of spores per lesion were reduced. At the highest rate of Si, 1000 kg ha⁻¹, lesion size and sporulation per lesion were 30-45% lower than for cultivars not treated with Si. Thus, Si acts to slow the epidemic rate of blast via reductions in lesion size and spore production per lesion.
Root Application of Potassium Silicate
Reduce Feeding Damage to Sargent Crabapple
Leaf Tissues by Adult Japanese Beetles...................................................................... (18)

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Two-year-old Sargent Crabapple ‘Malus sargentii’ seedlings were subjected to 4 continuous
days of 100 ml root application of potassium silicate at the rate of 0, 100, 200, and 400 ppm
in August, 1998. After three days of post-treatment applications, 3 detached leaves were
placed in each of 3 petri dishes along with one adult female Japanese Beetle (Popilla
japonica) (n=3/concentrations) for 7 days. Root, stem and leaf tissue Ca, K, Mg, Na and Si
were analyzed using a Coupled Plasma Spectrometer. Potassium silicate at 100 ppm
concentration significantly reduced percent leaf tissue eaten by adult Japanese Beetles. The
ion leakage of stem tissues of 100 and 200 ppm treated plants were significantly lower than
the control and 400 ppm. These lower ion leakage effects were also observed with red-osier
dogwood stem tissues at 100 ppm. The results of the tissue analysis indicate that Si and Ca
levels were significantly higher in root tissues for 100 ppm treated plants compared to stems
and leaves. The K and Mg levels in root tissues were higher for the control and slightly
higher for 100 ppm treatments compared to stems and leaves. The Na levels in root tissues
were the same for control, 100 and 200 ppm, and significantly lower in 400 ppm treatment.
In a companion study, fall webworm larvae were also exposed to the same above
concentrations and treatments, however, since there was not a significant effect of potassium
silicate on percent leaf tissue eaten by fall webworm larvae (Palaearctica vernata), this
suggests there may be differences between major groups of leaf-feeding insects.

Lime Effect on Silicon Release from Silica Fume Dust........ (35)

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The objective of this study was to evaluate lime’s effect on silicon (Si) release from fume
dust, a byproduct dominated by silica from an electric arc furnace. Fume dust was pelletized
with 10% Ca(OH)$_2$ and 10% CaCO$_3$, respectively. The releases of Si from lime-pelletized
fume dusts were compared with those of pelletized fume dust via a 20-day continuous
column leaching, using 10 g sample per column with 1 ml per minute of de-ionized water
buffered to pH 7.0. We calculated leachate Si ion species using a geochemical model
MINTEQA2/PRODEFA2, Version 3.0. We found that leachate Si concentration of lime-
pelletized fume dust varied with leaching time and lime sources. The Ca(OH)$_2$ has more
significant influence than CaCO$_3$ on Si release from fume dust; but CaCO$_3$ has longer
residual effect than Ca(OH)$_2$. The Ca(OH)$_2$ initially (first 48 hours) reduced Si release in
spite of high leachate pH due to high-soluble Ca level (>100 mg L⁻¹). Maximum Si concentration occurred when leachate pH ranged from 7.5 to 9 and leachate Ca concentration was lower than 100 mg L⁻¹. Lime affects Si release from fume dust through its free radicals: Ca²⁺ and OH⁻. The former decreases Si release by precipitating the free silicate ions from the solution, while the later increases Si release from fume dust by forming silicate ions.

**VENEZUELA**

**Silicon Applications for Blast Control of Rice on Two Soils Types from Portuguesa, Venezuela.........................(20)**

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Blast, caused by *Magnaporthe grisea* (Barr) *Pyricularia grisea* (Cooke)Sacc., is an important rice disease in Venezuela. During the 1997 rainy season, a study was done to evaluate the effect of different doses (0, 5, 10, 15 and 20 t/ha) of silica sand (99.64 % SiO₂, granulometry 51 %< 0.075 mm) to control blast in the variety Cimarron. The experiment was a completely randomized factorial (2x5) design with 9 replications conducted on two soils from the state of Portuguesa. The plants were sown in pots and maintained in tubs with water. Leaf blast was reduced using silicon by 81.6; 69.4; 46.9 and 83.7 % in comparison to the control. The injury decreased from grade 7 to 4, 4, 3 and 2. The reduction of blast incidence on the panicle using silicon was 36.5; 42.3; 42.3 and 65.7 % in comparison to the control. The magnitude of the response to silicon was better with the soil from Guanare in comparison to Acarigua. These results demonstrate that blast was controlled with the application of silica sand. Although the residual using silicon needs to be evaluated, the results indicate the possibility of using this material in an integrated blast control program.
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