Silicon Research Summaries on Dicotyledonous Crops

by Dr. Mary Provance-Bowley, Ph.D.

Although the bulk of silicon research has been dedicated to monocot species (categorized as "silicon accumulators"), the beneficial effects of silicon, lists of crops benefiting from silicon supplements, and isolation of silicon's mode-of-action continues to expand.

Introduction

Silicon (Si) has been recognized as being an essential nutrient for the *Equisetaceae* (Chen and Lewin, 1969; Hoffman and Hillson, 1979); *Bacillariophyceae* (Raven, 2003), wetland *Poaceae* (Pilon-Smits et al., 2009), and *Cyperaceae*; evidenced as being essential for beets (Raleigh, 1939) an "agronomically essential' (improving fitness and agricultural productivity) element for others such as rice and sugarcane (Cheng, 1982, Fox and Silva, 1978; Haysom and Ostatek-Boczynski, 2006; Kamenidou et al., 2008; Kamenidou et al., 2010; Ma, 2004; Savant et al., 1997; Savant et al., 1999); and a "quasi-essential" element (deficiency causing growth, development and reproductive abnormalities; Epstein, 1999) or "beneficial substance" (official in 2013; AAPFCO, 2014. However, essentiality has not been established for all plant species based on the guidelines established by Arnon and Stout (1939).

True grains and pasture grasses are all monocot species and "for most of the world's population, grain is the primary source of nutrition" (Kendall and Pimentel, 1994). So, one could assume that when conducting research on a newly suspected plant nutrient, that the first crops to be studied would be the most agronomically important ones. This has proved to be the case with initial and extensive research focused on monocot grain species such as rice (*Oryza sativa* L.). Rice is categorized as a "silicon accumulator" (Ma et al., 2001). However, when plant species were initially separated into classes as accumulating, intermediate or non-accumulating, researchers analyzed only shoot silicon content, which ranged from 0.1 to 10%, and not root concentrations. And, even with the grain driven focus being mainly on the shoots of monocot species, eight species of *Cucurbitales*, dicots, were determined to be intermediate. Tomatoes (*Solanaceae*), initially classified as "silicon excluders", have shown Si deficiency symptoms during reproduction; after the first bud flowering stage (Miyake and Takahashi, 1978). These observations revealed that tomato plants may bloom, but can fail to pollinate and often either bear no fruit at all, or the fruit that forms is malformed under Si-free conditions.

Dicots can accumulate as much or even higher levels of Si in their roots as their shoot tissues [e.g. tomato (*Solanum lycopersicum* L.), radish (*Raphanus sativus*), and Chinese cabbage (*Brassica rapa*)]; Lewin and Reimann, 1969). Crimson/Italian clover (*Trifolium incarnatum* L.) has been reported to have eight x the concentrations of Si in its roots as compared with its shoots.

Although the list of crops benefiting from Si supplements and elucidation of Si's modes of action in affecting both abiotic and biotic stresses has continued to expand for both monocot and dicot species, tissue sampling for analysis of root or shoot Si uptake levels can be difficult as it is imperative that plant tissue samples are free of all soil particles to avoid the potential confounding of results, since silicon is ubiquitous in nature and present in soils, air, and water. Cleaning of samples has therefore proven both tedious and time consuming. So, in order to control for soil contamination, many dicot trials have been conducted using nutrient solution with liquid Si sources rather than in field or potted greenhouse trials using native soils with non-liquid soil amendments as the Si source. This however, does not mean that only liquid Si products are capable of supplying soluble Si for dicot growth, any more so than has been determined using monocots. By limiting silicon supplements to only hydroponic production, and liquid Si sources for dicots, field producers of dicot crops are at a clear disadvantage, not having access to lower cost fertilizer and soil amendment Si sources to meet their production needs. There is also not a currently approved method by AAPFCO for determining and guaranteeing the Si content of liquid Si sources for the United States.

Silicon's Effects on Soils

An aspect of Si's positive effects in crop production that is often not considered is Si's beneficial effects on soils, and these benefits are not monocot specific. As stated by Meena et al. (2014), "Soil treatment with biogeochemically active silicon substances optimizes soil fertility through improved water, physical and chemical soil properties, and maintenance of nutrients in plant-available forms." Silicate additions to soils increase the cation exchange capacity (CEC; Smyth and Sanchez, 1980). A positive correlation was exhibited between CEC and soluble silicon levels in native soils (acetic acid-extractable soil silicon test), where no silicate, lime, or nutrient additions had been made (Figure 1).

Other benefits of Si to soils include substitution for phosphate at soil binding sites, releasing tied-up phosphate, and increasing phosphorus (P) availability for plant uptake (Matichenkov and Bocharnikova, 2001). Silicate complexes are also known to hold excess soil phosphate in a plant available form for future plant uptake, thus, increasing P use efficiency. Silicon can also decrease P uptake under excess conditions (Ma et al., 2001). However, the plant benefits from Si's soil effects are not limited to phosphate and CEC alone. Silicon also reduces aluminum (Al) toxicity.

The affinity of Si for aluminum occurs both in soil solution (formation of hydroxyaluminosilicate precipitate species; Baylis et al., 1994) and in plant roots (Hodson and Sangster, 1993; Hodson and Evans, 1995; Kidd et al., 2001), reducing toxic root and shoot Al uptake. Silicon is well known as a part of soil structure and binds with Al in solution to form hydroxyaluminosilicates (Cocker et al., 1998, Wada and Wada, 1980), and the binding of monomeric Al in solution in the presence of Si reduces soluble Al concentrations (Barcelo et al., 1993).

Silicon also affects other nutrient and metal toxicities and deficiencies, decreasing Mn uptake and shoot transport and increasing plant partitioning under toxic Mn levels (Li et al., 2012; Maksimović et al., 2012; Iwasaki et al., 2002). Under deficient iron (Fe) conditions, Si has been shown to enhance Fe acquisition and increase the apoplastic pool of Fe by/in cucumber roots (Pavlovic et al., 2013). Plant influx of sodium (Na) under high salt conditions is reduced by Si (Ma et al., 2001), while Na, boron (B) and Chloride (Cl) soil to plant translocation is reduced by Si in toxic sodic-B soils (Gunes et al., 2007a), and B under toxic B levels alone (Gunes et al., 2007b). As for other nutrients, macro- and micro- (K, Mg, K, Cu and Zn), Si has been shown to have moderating effects on plant uptake (Chen et al., 2000). Silicon can also affect positive changes in soil microorganism ratios and soil enzyme activity (Wang et al., 2013). Concentrations of Si are increased in the roots of mycorrhizal soybean plants under toxic Mn levels (Nogueira, 2001). So, silicon provides a multitude of benefits to soils and the plants grown in them.

Crop Removal of Silicon from Soils

Although Si is ubiquitous in nature, unfortunately, this does not mean that all forms of Si in soils are soluble (McKeague and Cline, 1963ab) or available for plant uptake (Richmond and Sussman, 2003). In order for plant uptake to occur, Si must be soluble and in the soil solution (Jones and Handreck, 1967), and the form of Si in soil solution is monosilicic acid (H_4SiO_4).

An estimate of annual global crop removal of Si from soils amounted to between 210 and 224 million Tons based on FAO crop figures from 1998 (Matichenkov and Bocharnikova, 2001), and with an increase in global grain production from 1998-2013 of 16.87% (Earth Policy Institute, 2014), this figure could be revised upward to a minimum of 245 million Tons. And, although our monocot grasses and grains remove higher quantities of Si than our dicot crop species, dicots do uptake and remove Si. Two important dicot crops with high global production levels have been shown to benefit from silicon supplements (see section Pepper, Potato, Tomato, Tobacco (*Solanaceae*) below for a summation of some of the research results for both tomatoes and potatoes). In potato tubers, taste has been positively correlated with Si content with tubers consisting of 209-479 ppm Si (Jitsuyama et al., 2009).

The purpose of soil fertility is to replace soil nutrients removed during cropping and to provide for the current seasons plant uptake needs. Otherwise, we are in essence, mining the soil of its mineral nutrients. And, regardless of where or not we fully understand why plants uptake Si and all of Si's plant beneficial effects and modes of action for all crops, if you are not replacing the Si removed from cropping, you are mining the soil of Si. It is therefore not surprising that issues of soil quality, destruction of global soils and sustainable crop production issues have now come to the forefront of agricultural production. Ma and Yamaji (2006) have stated "repeated cropping and the constant application of chemical fertilizers such as nitrogen, phosphorus and potassium have depleted the amount of Si that is available to plants in the soil. An awareness of Si deficiency in soil is now recognized as being a limiting factor for crop production". Meena et al. (2006), also suggest that depletion of plant available silicon from soils is the limiting factor contributing to declining yields (Meena et al., 2014).

Summation

In summation, Si can provide benefits to crops by affecting soils, roots, and shoots in ways not solely confined to monocots. Considering the increased demand for dicot fruits and vegetables to meet the nutrient demands of an ever increasing global population, it is essential that field producers have access to fertilizers and soil amendments containing the beneficial substance silicon.

Below you will find short summations of research targeting Si's beneficial effects to non-monocot (dicot) plant species and soils when subjected to abiotic stresses. The research extends as far back as 1921 for beets and to horticultural crops such as Magnolia trees. Rather than providing the references for that section at the end, each reference is provided immediately following the short article summation.

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Baylis, A.D., C. Gragopoulou, K.J. Davidson, and J.D. Birchall. 1994. Effects of silicon on the toxicity of aluminium to soybean. Commun. Soil Sci. Plant Anal., 25(5-6):537-546.

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Cheng, B. T. 1982. Some significant functions of silicon to higher plants. J. Plant Nutr., 5(12):1345-1353.

Cocker, K.M., D.E. Evans, and M.J. Hodson. 1998. The amelioration of aluminium toxicity by silicon in higher plants: Solution chemistry or an in planta mechanism?. Physiol. Plant., 104(4):608-614.

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Iwasaki, K., P. Maier, M. Fecht, and W.J. Horst. 2002. Effects of silicon supply on apoplastic manganese concentrations in leaves and their relation to manganese tolerance in cowpea [*Vigna unguiculata* (L.) Walp.]. Plant Soil, 238(2):281-288.

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Kamenidou, S., T.J. Cavins, and S. Marek. 2010. Silicon supplements affect floricultural quality traits and elemental nutrient concentrations of greenhouse produced gerbera. Sci. Hortic-Amsterdam, 123(3):390-394.

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Ma, J. F. 2004. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Sci. Plant Nutr., 50(1):11-18.

Ma, J.F., Y. Miyake, and E. Takahashi. 2001. Silicon as a beneficial element for crop plants. pp. 17–39, In L.E. Datnoff, G.H. Snyder and G.H. Korndörfer (eds.) Silicon in agriculture: Studies in plant science, 8. Elsevier Science B.V.D, Amsterdam, The Netherlands.

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Pilon-Smits, E.A., C.F. Quinn, W. Tapken, M. Malagoli, and M. Schiavon. 2009. Physiological functions of beneficial elements. Current Opinion in Plant Biol. 12(3):267-274.

Raleigh, G.J. 1939. Evidence for the essentiality of silicon for growth of the beet plant. Plant Physiol., 14(4):823-828.

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Wada, S., and K. Wada. 1980. Formation, composition and structure of hydroxy-aluminosilicate ions. Eur. J. Soil Sci., 31:457–467.

Wang, L., K. Cai, Y. Chen, and G. Wang. 2013. Silicon-mediated tomato resistance against Ralstonia solanacearum is associated with modification of soil microbial community structure and activity. Biol. Trace Elem. Res., 152(2):275-283.

Silicon and Abiotic Stress

Beans, Peas-Legumes: (*Fabaceae*)

As solution pH decreases below 6.0, soybean [*Glycine max* (L.) Merr. cv. Hark] root growth reductions due to aluminum (Al) toxicity become increasingly more severe (**Baylis et al., 1994**). Higher concentrations of Si are needed at lower pH to alleviate Al toxicity, as Si's affinity for Al is pH dependent. The formation of sub-colloidal inert hydroxyaluminosilicates is the method of silicon alleviated aluminum toxicity.

Baylis, A.D., C. Gragopoulou, K.J. Davidson, and J.D. Birchall. 1994. Effects of silicon on the toxicity of aluminum to soybean. Commun. Soil Sci. Plant Anal., 25(5&6): 537–546.

A one Ton/acre application rate of calcium silicate to plots of soybean [*Glycine max* (L.) Merr.] -millet (*Echinochloa spp*.) hay increased yields by 21% when compared with a lime, potash and phosphate treatment (**Conner, 1921**). This effect of calcium silicate was attributed to a more complete precipitation of toxic aluminum salts with calcium silicate having more of an effect than just "furnishing plant food".

Conner, S.D. 1921. Liming in its relation to injurious inorganic compounds in the soil. J. Am. Soc. Agron., 13(3):113–124.

Foliar applications of stabilized silicic acid resulted in increased pod numbers and seed yields of 14% for soybean (*Glycine max* L) Merr.), 15% for common bean (*Phaseolus vulgaris* L.), and 9.6% for peanuts (*Arachis hypogaea*; **Crusciol et al., 2013**).

Crusciol, C.A.C., R.P. Soratto, G.S.A. Castro, C.H.M.D. Costa, and J. Ferrari Neto. 2013. Foliar application of stabilized silicic acid on soybean, common bean, and peanut. Rev. Ciênc. Agron., 44(2):404–410.

Silicon mediated cowpea (*Vigna unguiculata* L. Walp) tolerance to Mn toxicity results from reduced Mn concentration in the apoplast and increased Mn adsorption in the cell walls (**Fecht-Christoffers et al., 2007**).

Fecht-Christoffers, M.M., P. Maier, K. Iwasaki, H.P. Braun, W.J. Horst. 2007. The Role of the Leaf Apoplast in Manganese Toxicity and Tolerance in Cowpea (*Vigna Unguiculata* L. Walp). pp 307–321. In Burkhard Sattelmacher and Walter Johannes Horst (eds.), The Apoplast of Higher Plants: Compartment of Storage, Transport and Reactions. The significance of the apoplast for the mineral nutrition of higher plants. Springer. Dordrecht, The Netherlands.

Increased leaf fresh weight (16.4%), leaf dry weight (24.1%) and inflorescence weight of alfalfa (*Medicago sativa*) with silicon fertilizer, with no effect on stem weight, although Si additions at mature stage increased stem dry weight and root number (**Fuping et al., 2005**). No effect on seed yield seen in year 1, but thousand seed weight increased by 29%.

Fuping, T., Z. Zihe, C. Zixuan, and W. Suomin. 2005. Effect of Si fertilizer on yield of alfalfa. Gansu Nongye Daxue Xuebao, 40(1):42–47.

The effects of silicon on alleviation of iron deficiency of soybean (*Glycine max* L. cv. Klaxon), an iron inefficient and chlorosis susceptible plant and cucumber (*Cucumis sativus* L. cv. Ashley), an iron efficient plant were evaluated in hydroponic solution using sodium silicate hydrate as the silicon source (**Gonzalo et al., 2006**). Silicon additions prevented chlorophyll degradation, decelerated growth reductions, and maintained leaf iron content of the iron inefficient soybean variety under iron deficiency conditions. In cucumber, silicon additions delayed reductions in stem dry weight, stem length, number of nodes, and root and shoot iron content, with no effect seen in alleviation of leaf chlorosis. The different iron deficiency responses observed after addition of silicon were suggested to be due to plant-specific iron efficiency strategies.

Gonzalo, M.J., Lucena, J.J., & Hernández-Apaolaza, L. 2013. Effect of silicon addition on soybean (*Glycine max*) and cucumber (*Cucumis sativus*) plants grown under iron deficiency. Plant Physiol. Biochem., 70:455-461.

Increased alfalfa (*Medicago sativa*) shoot and root growth with silicon Used Si deficient top soil in pots with silicon addition rates of (0, 0.025, 0.05, 0.10, 0.20, 0.30 g/kg) growing alfalfa. Silicon content of roots and shoots increased with increasing Si rates, and Si content of roots > shoots (**Guo et al., 2006**). Silicon increased leaf area, height, forage yields, & shoots per plant during reproductive period. Silicon also increased root volume, # of secondary roots & root biomass. The effects of Si application roots > shoots. Shoot to root dry weight ratios were <1.62 +Si and 1.91 –Si.

Guo, Z.G., H.X. Liu, F.P. Tian, Z.H. Zhang, and S.M. Wang. 2006. Effect of silicon on the morphology of shoots and roots of alfalfa (*Medicago sativa*). Aust. J. Exp. Agric., 46(9):1161–1166.

Silicon improved salt and drought induced physio-hormonal changes, including shoot length, plant fresh weight and dry weight, of soybean (*Glycine max* L. Merr. cv. Daewonkong) which were reduced under NaCl (a salt stress inducer) and polyethylene glycol (PEG; a drought stress inducer) additions (**Hamayun et al., 2010**). The adverse effects of NaCl and PEG were alleviated at silicon addition rates of 100 and 200 mg L-1. The effects of silicon were more pronounced under salt induced than drought induced stress. Silicon affected the gibberellic acid biosynthesis pathway, increasing GA1 and GA4 content of soybean leaves with or without stress (salt, drought). Jasmonic acid concentrations in leaves increased under both salt and drought stress but declined with silicon additions. Free salicylic acid also increased under both salt and drought, but the increase was greater with silicon under salt stress, and decreased under drought with silicon.

Hamayun, M., E.Y. Sohn, S.A. Khan, Z. Shinwari, A.L. Khan, and I.J. Lee. 2010. Silicon alleviates the adverse effects of salinity and drought stress on growth and endogenous plant growth hormones of soybean (*Glycine max* L. Merr.). Pak. J. Bot., 42(3):1713–1722.

Kidney bean (*Phaseolus vulgaris* L. var. 'Red Kidney'), grown hydroponically at different levels of manganese showed growth reduction and toxicity symptoms at manganese (Mn) nutrient solution concentrations of 5×10^{-4} mM (**Horst and Marschner 1978**). When silicon was supplied at 0.75 ppm Si, the 5×10^{-3} mM Mn concentrations were tolerated and higher silicon application rates (40 ppm) resulted in kidney bean plant tolerance of 10^{-2} mM Mn when no growth suppression was observed. Manganese tolerance was attributed to increased leaf tissue tolerance of high Mn concentrations as opposed to reduced uptake and transport. Without silicon additions, 100 ppm Mn was the critical level for toxicity in leaf tissue. This critical level was increased to >1000 ppm when plants were supplied with 40 ppm Si. A molar ratio of Si/Mn of 6 in plant tissue was determined to be sufficient to prevent toxicity at lower Mn levels, but at >1000ppm Mn, silicon was unable to prevent Mn toxicity symptoms even at ratios >20. When silicon was not supplied at optimal Mn supply levels (10−4 mM), leaf blade Mn distribution showed gatherings in uneven spots as opposed to even distribution with silicon at lower concentrations and a somewhat even distribution even at high Mn concentrations. At the cellular level, a greater amount of leaf Mn was transported into vacuoles with silicon additions. This suggests that silicon affects bean leaf Mn tolerance primarily by preventing Mn accumulation in areas of leaf tissue where metabolism and growth could be affected.

Horst, W.J. and H. Marschner. 1978. Effect of silicon on manganese tolerance of bean plants (*Phaseolus vulgaris* L.). Plant Soil, 50(1-3):287–303.

Silicon solution culture supplements decreased manganese (Mn) toxicity symptoms in a Mn-sensitive cowpea (*Vigna unguiculata* L. Walp. cv. TVu 91) cultivar by inducing enhanced adsorption of Mn in the cells walls, thus decreasing soluble Mn in the apoplast (**Iwasaki et al., 2002**). Within the apoplast silicon mediated detoxification of Mn was also indicated.

Iwasaki, K., P. Maier, M. Fecht, and W.J. Horst. 2002. Effects of silicon supply on apoplastic manganese concentrations in leaves and their relation to manganese tolerance in cowpea (*Vigna unguiculata* (L.) Walp.). Plant Soil, 238:281–288.

Calcium carbonate, dolomitic lime and calcium silicate (from phosphate slag) are all excellent liming materials, increasing soil pH and base saturation similarly (**Jones and Edwards, 1954**). When comparing 2-year averages at four locations, white clover fields receiving 4,000 pounds of calcium silicate (1.0-1.5% P) in the first year showed white clover (*Trifolium repens* L.) forage yields to be increased by 4 to 38% when compared to calcium limestone plus 50 pounds phosphate.

Jones, U.S. and W.D. Edwards. 1954. Limestone, dolomite, and calcium silicate slag for white clover pastures on red and yellow soils. Soil Sci. Soc. Am. J. Proc., 18(4):412–417.

The effects of silicon on manganese (Mn) nutrition of soybean were evaluated using nutrient solutions for a 43 day period ending prior to flowering (**Kluthcouski & Nelson, 1980**). The form of silicon (Si) used was not disclosed and the nutrient solutions were maintained at a very acidic pH of 5.3. Si reduced the severity symptoms under no Mn inputs, and no symptoms were displayed when silicon was added under deficient (low) levels of Mn. Under toxic levels of Mn, Si delayed onset of toxicity symptoms and reduced their severity, however at extremely high Mn levels no effect of Si was seen. Silicon did not affect Mn concentrations in roots, stems, or older leaves, total uptake and distribution of Mn, shoot and root weight, plant height, or root to shoot ratios. A Mn x Si interaction affected Mn concentrations in the youngest mature leaves only. It was noted that since the experiment was terminated prior to flowering that Si additions could affect soybean plants under no, low, or toxic levels of Mn during reproduction growth. Note: The pH range suggested for normal soybean growth is 6.5-7.5, while the recommended pH range for soybean production is slightly acidic to neutral, 6.6-7.0, (**Ketterings et al., 2005**).

Kluthcouski, J., and L.E. Nelson. 1980. The effect of silicon on the manganese nutrition of soybeans (*Glycine max* (L.) Merrill). Plant Soil, 56(1):157-160.

Ketterings, Q.M., G. Albrecht, and J. Beckman. 2005. Soil pH for Field Crops. Agron. Fact Sheet Series. FS No. 5. Cornell Univ. Coop. Ext. available online at <www.nnyagdev.org/PDF/SoilpH.pdf>: accessed 8 Aug. 2014.

The effects of soil available silicon (Si) on soybean (*Glycine max* L. Merr.) seed germination, growth, development and physiological functions was evaluated **(Li et al., 2004**). At soil available Si content between 55.1-202.8 mg kg-1, protease and lipase activities in germinating seeds increased with increasing soil Si levels. Amylase activity and germination rate was unaffected, but bioactivity of seeds and seedling respiration rate was increased. These Si levels also increased the rate of seedling photosynthesis, root activity, and nitrate reductase activity, but chlorophyll content in leaves was unaffected. Transpiration rate of seedlings decreased while water use efficiency and leaf water content increased, promoting drought resistance. Positive linear relationships between Si concentrations of soybean seedlings and soil available Si content (r2 = 0.994). The authors concluded that soil supplied Si to soybean germinating seeds and seedlings improved their physiological functions. This resulted in enhancement of seed germination and seedling growth rate.

Li, Q., C. Ma, H. Li, Y. Xiao, and X. Liu. 2004. Effects of soil available silicon on growth, development and physiological functions of soybean. Ying Yong Sheng Tai Xue Bao, 15(1): 73–76. (In Chinese with English abstract).

Effects of root applied silicon (Si) to susceptible cowpea (asparagus bean; V*igna unguiculata* ssp. sesquipedalis Wight.) plants inoculated with *Uromyces vignae* (rust pathogen) resulted in increased activity of antioxidant stress parameter enzymes, decreased malonyldialdehyde, delayed and inhibited reductions in physiological photosynthetic stress parameters including chlorophyll fluorescence ratio, photosynthetic electron transport rate, and active photosystem II reaction centers (**Li et al, 2007**). Additionally, higher total respiration and alternative pathway capacity in leaves was maintained with increased Si content. Non-inoculated, susceptible plants had increases in peroxidase and catalase activities. A resistant variety showed Si to increase the antioxidant defense system (peroxidase, catalase, and superoxide dismutase) considerably while reducing malonyldialdehyde in inoculated leaves. For the susceptible variety, improved resistance to rust was visually apparent as reduced disease index.

Li, G.J., Y.H. Liu, Z.J. Zhu, X.H. Wu, and B.G. Wang. 2007. Effect of exogenous silicon on resistance of asparagus bean rust and its physiological mechanism. J. Zhejiang Univ. Agric. Life Sci., 33(3):302–310.

Silicon (Si) additions improved alfalfa (Medicago sativa) water use efficiency under light and moderate water stress (**Liu et al., 2009**). Silicon improved water use efficiency of alfalfa under light, 65% field capacity (FC), & moderate, 50% FC, water stress attributed to decreasing transpiration rate. No response from Si was seen under wet (80% FC) or extreme drought (35% FC). Increased forage biomass (increased shoot development and plant height) under moderate water stress and increased shoot development under light water stress were attributed to Si additions.

Liu, H.X, Z.G. Guo, X.H. Guo, X.R. Zhou, W.S. Hui, and K.Y. Wang. 2009. Effect of addition of silicon on water use efficiency and yield components of alfalfa under the different soil moisture. Acta Ecol. Sinica, 29(6):3075–3080. (In Chinese with English Abstract).

Silicon (Si) improves seed vitality and seedling biomass (**Liu et al., 2011**). Effects of Si on alfalfa (*Medicago sativa*) seed germination and seedling growth using hydroponic culture were evaluated. No Si effects were seen on initial time of seed germination or final germination rate, but seeds germinated faster with enhanced germination index, vigor index and germination energy. Silicon did not improve seed quality, but improved seed vitality. Silicon increased shoot length of alfalfa seedlings, but had no effect on root length. Silicon increased biomass of alfalfa seedlings. Silicon solution concentration was not related to germination index, germination energy, length of shoot and root, or biomass of seedlings.

Liu, H.X. X.R. Shen, and Z.G. Guo. 2011. Effects of silicon on seed germination and seedling growth of alfalfa. J. Acta Prataculturae Sinica, 1:023.

Silicon (Si) additions to potted alfalfa (*Medicago sativa*) increased shoot phosphorus (P) and potassium (K) levels while increasing P and decreasing K in the soil (**Liu and Guo, 2011**). Silicon had no effect on alfalfa biomass at moisture levels of 35% or 80% field capacity (FC), but increased biomass when soil moisture was 50% or 65% FC. Silicon increased total alfalfa shoot K and P but had no effect on total nitrogen (N). No effects were seen on total soil N, available N, total P or total K. However, soil available P was increased and available K was decreased.

Liu, J., and Z. Guo. 2011. Effects of supplementary silicon on nitrogen, phosphorus and potassium contents in the shoots of *Medicago sativa* plants and in the soil under different soil moisture conditions. Chinese J. Appl. Environ. Biol. 17(6):809–813. (In Chinese with English Abstract).

Aflatoxins can infect peanuts, rapeseed, nuts, legumes, chocolate as well as other agriculture products affecting food quality and animal and human health (**Lizárraga-Paulín et al., 2013**). They have been recognized globally as a significant agricultural and food production problem since 1960. Silicates are capable of adsorbing aflotoxins through hydrogen bonds. Vegetable fibers, clays and synthetic silicates are known to sequester mycotoxins. Silicates are the most widely used as they don't create waste problems, don't destroy vitamins and proteins in foods, don't generate partial reactions, and don't produce toxic metabolites. Both naturally occurring aluminum silicates and hydrated sodium calcium aluminosilicates are used with the later having a greater adsorption capacity, even in liquid products such as milk. Bioavailability of aflatoxins to poultry and young animals is therefore reduced.

Lizárraga-Paulín, E.G., S.P. Miranda-Castro, E. Moreno-Martínez, I. Torres-Pacheco, and A.V. Lara-Sagahón. 2013. Chap. 5. pp. 93–128. Novel methods for preventing and controlling Aflatoxins in food: A worldwide daily challenge. In M. Razzaghi-Abyaneh (ed.) Aflatoxins-Recent Advances and Future Prospects. InTech publ. Rijeka, Croatia.

Silicon (Si) addition to Potassium (K)-deficient soybean (*Glycine max* L. Merr.) seedling growing media enhanced K use efficiency (**Miao, Han and Zhang, 2010**). Physiological reductions in shoot and root biomass under K-deficiency were ameliorated with silicon additions. Leaf, stem and root K concentrations were increased with Si additions to K-deficient seedling growth medium. Under K-deficiency, hydrogen peroxide and malondialdehyde tissue content increased, but was reduced to non-stressed levels with Si. K deficiency-induced increases in superoxide dismutase, catalase and peroxidase were also reduced with Si.

Miao, B.H., X.G. Han, and W.H. Zhang. 2010. The ameliorative effect of silicon on soybean seedlings grown in potassium deficient medium. Annals Bot., 105:967–973.

Soybean (*Glycine max* L. Merr.) plants were grown in culture medium with and without silicon (Si; **Miyake and Takashi, 1985**). At early growth stages, evidence of Si deficiency was not evident as plants grew normally with or without Si. However, at flowering stage malformations, evidenced as leaf curling and curving to the outside, and in severe cases necrotic spots, were visually apparent on the 7th and 8th leaves of Si deficient plants. Growth of Si deprived plants was markedly inferior and pollen fertility rate was reduced. Soybean plants freely translocated Si from roots to shoots suggesting that soybean Si uptake is to cucumber (*Cucumis sativus* L.).

Miyake, Y., and E. Takahashi. 1985. Effect of silicon on the growth of soybean plants in a solution culture. Soil Sci. Plant. Nutr., 31(4):625–636.

Salt stressed cowpea (*Vigna unguiculata* L. Walp.), and kidney bean (*Phaseolus vulgaris* L.) plants grown hydroponically with calcium silicate showed reversal of salt related stress symptoms (**Murillo-Amador et al., 2007**). Beneficial effects from silicate additions included improved growth and physiological parameters (membrane permeability, net photosynthesis, chlorophyll content, stomatal conductance and transpiration), in addition to improved nutrient balance.

Murillo-Amador, B., S. Yamada, T. Yamaguchi, E. Rueda-Puente, N. Ávila-Serrano, J.L. García-Hernández, R. López-Aguilar, E. Troyo-Diéguez, and A. Nieto-Garibay. 2007. Influence of calcium silicate on growth, physiological parameters and mineral nutrition in two legume species under salt stress. J. Agron. Crop Sci., 193(6):413–421.

Calcium silicate, but not calcium carbonate applied at rates of 1500, 3000, 6000, or 12,000 kg ha-1 was effective in reducing downy mildew (*Peronospora manshurica*) of soybean (*Glycine max* L. Merr.), 7 and 66 days after seeding (**Nolla, Korndörfer, and Coelho, 2006**). Frog's eye patch (*Cercospora sojina*) disease incidence was reduced throughout the evaluation period, 120 days. Asian rust (*Phakopsora pachyrhizi*) was only observed on one trial date and was not suppressed by silicate on that particular date. Calcium silicate increased soybean leaf silicon (Si) content 1.70 fold. Soybean leaf tissue Si content ranged from 0.34% to 0.55% Si.

Nolla, A. G.H. Korndörfer, and L. Coelho. 2006. Efficiency of calcium silicate and carbonate in soybean disease control. J. Plant. Nutr., 29:2049–2061.

Peanuts provide 4.7-5.8 mg Si per 100 g which is slightly lower than wheat (6.3 mg per 100 g; **Pennington, 1991**).

Pennington, J.A.T. 1991. Silicon in foods and diets. Food Addit. Contamin., (A:8:1):97–118.

Soybean (*Glycine max* L. Merr.) seedling relative leaf water content, a main factor influencing growth reductions under drought conditions, increased 19.0% with supplemental silicon (Si), and 30.0% under combined drought + Ultraviolet-B radiation (UV-B) stress (**Shen et al., 2010**). Under UV-B stress reductions in Anthocyanin (91.5%) and phenol (10.0%) production were attributed to Si. Extensive membrane damage resulting from drought + UV-B stress, measured as lipid peroxidation and osmolyte leakage, was also reduced with Si. Silicon had a + effect on photosynthesis under stress, increasing photosynthesis 21.0% under UV-B, 18.3% under drought, and 21.5% under drought + UV-B. Although UV-B light proved to be more stressful than drought, Si additions ameliorated the biological and physiological damages caused by these environmental stresses.

Shen, X., Y. Zhou, L. Duan, Z. Li, A.E. Eneji, and J. Li. 2010. Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet-B radiation. J. Plant Physiol., 167(15):1248–1252.

In general the best rate of calcium silicate for maximum yield of 22 plant species grown in two different soils was 0.98 tons Si acre-1 (**Thiagalingam, 1971**). Overall, nutrient status of plant tissue when supplied with calcium silicate showed increases in calcium (Ca) along with decreases in magnesium (Mg), manganese (Mn), aluminum (Al), and iron (Fe). Silicon concentrations in plant tissue were in the order of grains ≥ grasses ≥ vegetables and fruits ≥ legumes, except for two species of legumes in the Desmodium genus which had levels of Si similar to grasses. Papaya (*Carica* L.) and pineapple (*Ananas comosus*) leaves and sugarcane (*Saccharum officinarum* L.) sheaths accumulated the highest levels of Si, while stems were the lowest.

Corn (*Zea mays* L.) yields were similar (98%) at 280 kg P ha-1 with Si when compared to an 1120 kg P ha-1 rate without Si. Corn leaf Si levels at silking were 0.5 and 0.6% which were adequate. It was determined that Si, P and Fe concentrations in leaf tissue are important for stover development, while levels of P, Ca, K, Al and Fe affect ear production.

Silicon transport in five different plant species studies was not increased with increased transpiration rate suggesting that Si transport to shoots is not related to transpiration. In the dark all plants but sugarcane accumulated Si in their roots only, with sugarcane continuing to transport silicon to leaf tissue. Tick-trefoil (*D. intortum*), corn and sugarcane xylem exudate Si when compared with external solution Si levels revealed active transport uptake in these species rather than mass flow. For tomato (*Solanum lycopersicum* L.) and alfalfa (*Medicago sativa*), which had lower exudate concentrations it was determine that their Si selectivity mechanism resides in the roots. It was concluded that metabolic energy is required for both Si and P transport. The mechanism for silicon selectivity is in the roots of alfalfa plants.

Thiagalingam, K. 1971. Effects of calcium silicate on yield and nutrient uptake and mechanism of silicon transport in plants. Issue 385, 454 pp. Ph.D. Dissertation, Dept. Agron. Soil Sci. Univ. Hawaii, Honolulu.

Si affects Na^+ distribution in roots, shoots and leaves improving salt tolerance (**Wang and Han, 2007**). Potassium silicate supplemented hydroponic solution increased dry shoot weight of both a salt and non-salt tolerant alfalfa (*Medicago sativa*) cultivar under salt stress. Silicon inhibited Na uptake by roots and affected the uptake and transport of other nutrients in shoots and leaves affected by salt.

Wang, X.S., and J.G. Han. 2007. Effects of NaCl and silicon on ion distribution in the roots, shoots and leaves of two alfalfa cultivars with different salt tolerance. Soil Sci. Plant Nutr., 53:278–285.

Si alters antioxidant activity in roots, shoots & leaves improving salt tolerance (**Wang et al., 2011**). Effects of exogenous NaCl and Si in hydroponic culture on antioxidative enzymes in roots, shoots and leaves of two alfalfa (*Medicago sativa*) cultivars: high salt tolerant (Zhongmu No. 1) and low salt tolerant (Defor). NaCl -Si affected root and shoot antioxidative enzyme activity to different extents in both cultivars. NaCl +Si increased ascorbate peroxidase (APX) activity in root, shoot and leaves, and catalase (CAT) activity in leaves, and peroxidase (POD) activity in shoots of both cultivars. For the salt tolerant (Zhongmu No.1) cultivar NaCl +Si resulted in decreased superoxide dismutase (SOD) activity in shoots and in roots of both cultivars. Changes in antioxidative enzyme activity of alfalfa vary by organ after salt stress, but silicon can alter the activity of antioxidative enzymes in one or several organs improving salt tolerance.

Wang, X., Z. Wel, D. Liu, and G. Zhao. 2011. Effects of NaCl and silicon on activities of antioxidative enzymes in roots, shoots and leaves of alfalfa. Afric. J. Biotech., 10(4):545–549.

Under stress caused by additions of decomposed cowpea (asparagus bean) stub extract, silicon improved cowpea (*Vigna unguiculata* W.) seed germination, seedling growth, and photosynthetic activity (**Wang et al., 2008**). However, when not subjected to stress only root activities were increased.

Wang, B.G., Y.H. Liu, X.H. Wu, Z.F. Lu, and G.J. Li. 2008. Effects of silicon and liquid of decomposed asparagus bean stubs on ATPase activity and photosynthetic system of *Vigna unguiculata* W. ssp. *sesquipedlis*. Acta Agric. Shanghai, 24(4):92–96.

Silicon (Si) enhanced growth under salt stress of greenhouse grown common bean (*Phaseolus vulgaris* L.) receiving irrigation water containing two levels of NaCl (30 & 60 mM: **Zuccarini, 2008**). Silicon additions reduced plant Na concentrations (especially in leaves) and ameliorated the negative effects of NaCl on gas exchange. A more pronounced effect from Si was seen at the 30 mM salt concentration. However, Si was not shown to affect shoot and root concentrations of Cl. Salinity induced reduction in K content was partially ameliorated by Si, especially in the roots

Zuccarini, P. 2008. Effects of silicon on photosynthesis, water relations and nutrient uptake of *Phaseolus vulgaris* under NaCl stress. Biolog. Plant., 52(1):157–160.

Beet (*Beta vulgaris* L.)

Beet (*Beta vulgaris* L.) yields with calcium silicate increased 44% when compared to calcium hydroxide when used as a liming agent calcium silicate can give better results than lime in beet production, particularly in acid soils with high aluminum salts, as beets are sensitive to aluminum (**Conner, 1921**).

Conner, S.D. 1921. Liming in its relation to injurious inorganic compounds in the soil. J. Am. Soc. Agron., 13(3):113–124.

Use of a synthetic calcium silicate seed treatment as a solid carrier was more effective than shale or vermiculate in increasing stand growth and reducing table beet (*Beta vulgaris* L.) seed mortality associated with Rhizoctonia solani and *Pythium ultimum* (**Khan et al., 1992**). A synergistic effect in reducing root disease incidence was seen when calcium silicate was combined with the fungicides metalaxyl and thiram.

Khan, A.A., G.S. Abawi, and J.D. Macguire. 1992 Integrating matriconditioning and fungicidal treatment of table beet seed to improve stand establishment and yield. Crop Sci., 32(1):231–237.

Phosphate slag can contain trace levels of radium and uranium contaminants present during geological phosphate rock formation, in addition to calcium silicate (**Montvedt, 1986**). However, dry forage yields of Swiss chard (*Beta vulgaris* L.) were increased with phosphate slag additions at a soil pH of 5.8. It was determined that radionuclides are negligible from phosphate slag when applied at the recommended liming rate even at the high rates recommended for sugarcane (*Saccharum officinarum* L.) production.

Mortvedt, J.J. 1986. Effects of calcium silicate slag application on radium-226 concentrations in plant tissues. Commun. Soil Sci. Plant. Anal., 17(1):75–84.

Raw beets (*Beta vulgaris* L.) contain higher silicon concentrations (25.4 mg 100g-1) than peanuts, but lower than whole grain rice (40.9 mg 100g-1; **Pennington, 1991**).

Pennington, J.A.T. 1991. Silicon in foods and diets. Food Addit. Contam., (A:8:1) 97–118.

Experiments with multiple nutrient additions resulted in evidence of the essentiality of silicon for the growth of beet (*Beta vulgaris* c.v. Detroit Red; **Raleigh, 1939**).

Raleigh, G. J. 1939. Evidence for the essentiality of silicon for growth of the beet plant. Plant Physiol., 14(4):823-828.

Coffee (Coffea arabica)

Coffee (*Coffea arabica*) seedling morphological growth response (total dry weight, root dry weight, shoot dry weight and stem diameter, silicon (Si) uptake and soil silicon levels were measured in response to pre-plant soil granulated silicon fertilizer additions (0, 3, 6, & 9 g SiO2 to 90% kg-1 fertilizer mixture) with or without diammonium phosphate (DAP; **Caicedo and Chavarriaga, 2007**). DAP with silicon (Si) resulted in increased growth and development of sprouts, number of leaves and total dry weight with the best results at the two highest Si rates + DAP, and at six months increased root growth, shoot growth, and stem diameter.

Caicedo, L.M., and W. Chavarriaga Montoya. 2007. Effect of application of silicon dose on the seedbed development of small coffee plants Colombia variety. Agro.Castarric., 15(1):27–37.

The effects of nutrient solutions of Sili-K®, 12.2% SiO_2, on plant growth, water, and macro and micronutrient uptake of coffee (*Coffea arabica* L.) seedlings was evaluated for 33 days (**Cunha et al., 2012**). Water consumption, potassium (K) uptake and biomass accumulation were lower with silicon (Si) additions, while solution OH^- and Si uptake was increased. The Si uptake was greater in leaves than in the stems and roots. Plant tissue phosphorus (P), calcium (Ca), zinc (Zn), copper (Cu), and iron (Fe) were also reduced with the Sili-K®. Note: The pH of the solution is not disclosed, rather, only an increase in OH^- nutrient solution concentrations was noted. Therefore, this would suggest an increase in solution pH which likely resulted in some of the changes noted in nutrient uptake.

da Cunha, A.C.M.C.M., M.L. de Oliveira, E.C. Caballero, H.E.P. Martinez, P.C.R. Fontes, and P.R.G. Pereira. 2012. Growth and nutrient uptake of coffee seedlings cultivated in nutrient solution with and without silicon addition. Rev. Ceres Viçosa, 59(3):392-398.

Cotton (*Gossypium hirsutum* L.)

Silicon (Si) concentration is high in cotton (*Gossypium hirsutum* L.) fibers during the elongation phase of development, but decreases as the fiber matures (**Boylston, 1988**). Thus, suggesting that Si plays a role during cotton fiber development.

Boylston, E.K. 1988. Presence of silicon in developing cotton fibers. J. Plant Nutr., 11(12):1739–1747.

Silicon (Si) may serve in several important metabolic roles during cotton (*Gossypium hirsutum* L.) fiber growth and development (**Boylston et al., 1990**). Fiber Si concentrations increase during elongation and reach their peak when secondary wall development is initiated, suggesting age-related functions for Si during cotton fiber development. During fiber development Si concentration is high from day 1-21 post-anthesis during the elongation phase. The highest mass ratio of Si fiber-1 mass occurs at the initiation of secondary wall growth.

Boylston, E.K., J.J. Hebert, T.P. Hensarling, J.M. Bradow, and D.P. Thibodeaux. 1990. Role of silicon in developing cotton fibers. J. Plant Nutr., 13(1):131–148.

Although the chemical composition of different parts of the cotton plant are known to vary, analysis of 28 cotton plants from different soil types at the time of oldest boll opening had silicon concentrations varying from 0.053 to 0.218% with a mean value of 0.093 (**Cooper and Mitchell, 1946**).

Cooper, H. P., & Mitchell, J. H. (1946). Chemical composition of the cotton plant grown on different soil types. In Soil Sci. Soc. Am. Proc. 2(374):377.

At low aluminum concentrations in solution culture sodium silicate application had negligible effects on reactive aluminum (Al) in solution (**Li et al., 1989**). However, at higher Al rates, reactive Al decreased 6-15% with increasing silicon rates. Select cotton (*Gossypium hirsutum* L.) cultivars showed improved root growth when silicon was added in the absence of Al, and at low Al concentration levels.

Li, Y.C., A.K. Alva, and M.E. Sumner. 1989. Response of cotton cultivars to aluminum in solutions with varying silicon concentrations. J. Plant Nutr., 12(7):881–892.

Cucumber, Melon, Squash (*Cucurbitaceae*)

Silicon supplied via nutrient solution ameliorated iron (Fe) deficiency symptoms of cucumber (*Cucumis sativus* L. cv. Semkross), and partially mitigated Zn or Mn deficiency symptoms (**Bityutskii et al., 2014**). Physiological effects of silicon under Fe deficiency included increases in leaf Fe content and tissue accumulation of organic acids and phenolic compounds. The benefits of silicon were attributed to increased distribution of Fe toward apical shoot portions and accumulation of Fe-mobilizing compounds (e.g. citrate in leaves and roots or cathechin in roots). However, silicon did not appear to affect mobility and tissue distribution of either Zn or Mn under deficiency conditions.

Bityutskii N., J. Pavlovic, K. Yakkonen, V. Maksimovic, and M. Nikolic. 2014. Contrasting effect of silicon on iron, zinc and manganese status and accumulation of metal-mobilizing compounds in micronutrient-deficient cucumber. Plant Physiol. Biochem., 74:205-211.

Potted cucumber (*Cucumis sativus* L.) seedlings receiving various concentrations of potassium silicate in soil drench were evaluated for passive and active silicon (Si) uptake (**Faisal et al., 2012**). At higher transpiration rates leaf Si accumulation increased. However, Si uptake levels exceeded concentrations that could be attributed to passive (transpirational) uptake alone at lower Si treatment rates, but were correlated with passive transport at the highest Si treatment rate. It was concluded that both active and passive uptake are involved in cucumber Si uptake and that transpiration rates, soil Si availability and the plant's Si needs determine Si uptake and deposition in cucumber leaves.

Faisal, S., K.L. Callis, M. Slot, and K. Kitajima. 2012. Transpiration-dependent passive silica accumulation in cucumber (*Cucumis sativus*) under varying soil silicon availability. Botany, 90(10):1058-1064.

An iron (Fe) inefficient and chlorosis susceptible soybean (*Glycine max* L. cv. Klaxon) plant, and an iron efficient cucumber (*Cucumis sativus* L. cv. Ashley) plant were evaluated as to the effects of silicon (Si) on the alleviation of Fe deficiency when grown hydroponically using sodium silicate hydrate (**Gonzalo et al., 2006**). Silicon prevented chlorophyll degradation, decelerated growth reductions, and maintained leaf Fe content of the Fe inefficient soybean variety under Fe deficiency conditions. For cucumber, Si delayed reductions in root and shoot Fe content, stem dry weight, stem length, and number of nodes, with no effects seen on leaf chlorosis. The different Fe deficiency responses observed after addition of Si suggest plant-specific Fe efficiency strategies.

Gonzalo, M.J., J.J. Lucena, and L. Hernández-Apaolaza. 2013. Effect of silicon addition on soybean (*Glycine max*) and cucumber (*Cucumis sativus*) plants grown under iron deficiency. Plant Physiol. Biochem., 70:455-461.

When comparing calcium silicate to calcium carbonate soil amendment applications to field grown pumpkin (*Cucurbita pepo* L.), both were equally effective in neutralizing soil acidity (**Heckman 2002**). However, calcium silicate increased pumpkin yields regardless of fungicide treatment for powdery mildew control in the year of application. A residual effect of calcium silicate was seen in year two when a synergistic effect with the fungicide resulted in disease reductions.

Heckman, J. 2002. Silicon fertilization of pumpkins. Proc. Penn. Veg. Conf. pp. 101–102. Mid-Atlantic Fruit & Veg. Convention. 29-31 Jan. 2002. Hershey, PA.

Bloom-type (*Cucurbita moschata* Duch cv. Shintosa) pumpkin grafting stock was suppressed in growth when supplied with toxic levels of manganese (Mn) in the absence of silicon (Si) additions to the nutrient solution (**Iwasaki and Matsumura, 1999**). Silicon alleviated these symptoms and the effects were heightened as silicon concentrations increased. This alleviation of growth depression was not due to reduced plant Mn concentrations. Without Si, Mn deposits were located surrounding necrotic leaf lesions and at the base of trichomes. With silicon, Mn was located at the base of trichomes only in conjunction with Si deposits. Localized accumulation of metabolically inactive forms of Mn with Si at the base of leaf trichomes is a suggested mechanism of alleviating Mn toxicity with Si supplements.

Iwasaki, K., and A. Matsumura. 1999. Effect of silicon on alleviation of manganese toxicity in pumpkin (*Cucurbita moschata* Duch cv. Shintosa). Soil Sci. Plant Nutr., (Jap. Soc.), 45(4):909–920.

Cucumber (*Cucumis sativus)*, known to accumulate high levels of silicon (Si) in its shoots, was compared to fava bean (*Vicia faba*) for their uptake and xylem loading of Si (**Liang, et al., 2005**). The shoot Si uptake of cucumber was > 2 x the calculated rate from transpiration alone, while fava bean uptake was lower than predicted from the transpiration rate. Xylem exudate Si concentrations were much higher in cucumber than fava bean regardless of external solution concentrations. Uptake of Si was inhibited at low temperatures and by 2,4-D,a metabolic inhibitor. However, these effects on fava bean Si uptake were not exhibited. It was concluded that in cucumbers, Si uptake and transport is active and not dependent on external Si concentrations. This is in contrast to fava bean where the uptake appears to be passive, via the transpiration stream.

Liang, Y., J. Si, and V. Römheld. 2005. Silicon uptake and transport is an active process in *Cucumis sativus*. New Phytol., 167(3):797-804.

Hydroponically grown two-leaf stage cucumber (*Cucumis sativus* cv. Jinchun 4) plants received different concentrations of silicon (0,0.1 and 1 mM/L) added to the solution culture and were subjected to chilling stress (15/8°C) for six days (**Liu et al., 2009a**). Silicon additions reduced leaf withering, increased plant silicon content, increased antioxidant activity (SOD, GSH-Px, APX, MIDHAR, GR, GSH and AsA) and decreased levels of MDA, hydrogen peroxide, and superoxide radical under chilling stress.

Liu, J.J., S.H. Lin, P.L. Xu, X.J. Wang and J.G. Bai. 2009a. Effects of exogenous silicon on the activities of antioxidant enzymes and lipid peroxidation in chilling-stressed cucumber leaves. Agric. Sci. China, 8(9):1075–1086.

The effects of silicon supply on drought resistance of pot grown cucumber (*Cucumis sativus* cv. Jinchun 4), 2 month old seedlings, was evaluated. In the absence of stress, only slight increases in net photosynthetic rate (NPR) were seen (**Ma et al., 2004**). However, under drought stress Si greatly improved NPR, while under non-stressed and stressed conditions significant decreases in transpiration rate and stomatal conductance were exhibited with Si. Decreased stomatal conductance, along with enhanced water holding capacity and maintenance of a relatively stable transpiration rate were considered the main reasons for sustained photosynthesis with silicon during drought stress. Additional effects of silicon under drought stress included increased biomass accumulation, higher leaf tissue water content, decreased breakdown of chlorophyll, reduced plasma membrane permeability, reduced leaf malondialdehyde content, alleviated peroxidase induced physiological response, modulated superoxide dismutase activity, and increased catalase activity. As stress severity was increased these drought stress parameters positively correlated with silicon application rate. It was determined that under drought stress, the number one reason for silicon's positive effects on biomass maintenance was due to increased photosynthesis and the second reason was increased water holding capacity.

The conclusions drawn from this study were that silicon's involvement in plant metabolism enhanced cucumber resistance to drought stress.

Ma, C.C., Q.F. Li, Y.B Gao, and T.R. Xin. 2004. Effects of silicon application on drought resistance of cucumber plants. Soil Sci. Plant Nutr. (Jap.), 50(5):623-632.

Different transporters mediate silicon transport from soil to above ground organs (**Ma et al., 2011**). Lsi1 (NIP group: aquaporin family), is responsible for soil uptake of Si into root cells in both dicots and monocots differing in expression patterns and cellular localization by plant species. A homolog of the rice (*Oryza saliva* L.) Si transporter, Lsi1, is CmLsi in pumpkin (*Cucurbita pepo* L.), which is localized in all root cells. Lsi2 an active efflux transporter mediates transport of Si from root cells toward the stele. Polar localization is at the distal (Lsi1) and proximal (Lsi2) sides of both the exodermis and endodermis in rice. Xylem sap Si, in the form of monosilicic acid, is unloaded by Lsi6, a homolog of Lsi1. Lsi6 also affects inter-vascular transfer at the node, which determines distribution of silicon within the panicles. Lsi6 differs from Lsi1 and Lsi2 as it is expressed in leaf sheaths and blades in addition to root tips. In leaf sheaths and blades Lsi6 is localized in the adaxial side of the xylem parenchyma cells. Knockout of Lsi6 does not affect root uptake, but does affect the deposition pattern in leaf blades and sheaths. Within leaf blades, two types of silicified cells are found, silica cells, and silica bodies (otherwise known as silicified motor cells). Loss of function following knockout of Lsi6 results in an altered Si pathway. Lsi6 is required in Si delivery to specific cells, and this cell-type specificity is dependent on a symplastic pathway delivery by Lsi6.

Ma, J.F., N. Yamaji, and N. Mitani-Ueno. 2011. Review: Transport of silicon from roots to panicles in plants. Proc. Jap. Acad. Ser. B, 87(7):377–385.

Symptoms of manganese (Mn) toxicity were not apparent in leaves of cucumber (*Cucumis sativus* L.) supplied with excess Mn (100 µM) when also supplied with silicon (Si), although leaf Mn concentrations were extremely high (**Maksimović et al., 2012**). Leaf apoplast, free Mn+2 and hydrogen peroxide, of Si treated plants under high levels of Mn, was decreased. Silicon contributed indirectly to reductions in hydroxyl radical in leaf apoplasts by reducing free apoplastic Mn and regulating the Fenton reaction. Direct inhibitory effects of Si on guaiacol-peroxidase activity may also be contributing to reductions in peroxidase-mediated hydroxyl radical production.

Maksimović, J.D., M. Mojović, V. Maksimović, V. Römheld, and M. Nikolic. 2012. Silicon ameliorates manganese toxicity in cucumber by decreasing hydroxyl radical accumulation in the leaf apoplast. J. Exp. Bot., 63(7):2411–2420.

Cucumber (*Cucumis sativus* L.) yields were increased 46% with foliar silicon (Si) treatments (10 kg ha-1) at the 3rd leaf stage and subsequent bi-weekly applications during the season (**Matichenkov and Bocharnikova, 2008**). Soil Si applications (40 kg ha-1) also increased yields. Additional benefits of Si included stimulation of fruit formation and accelerated fruit maturation.

Matichenkov, V.V., and E.A. Bocharnikova. 2008. New generation of silicon fertilizers. pp. 71. In Malcolm Keeping (ed.) Silicon in Agriculture Conference South Africa 2008, 4th International Conference Abstracts. University of Kwazulu-Natal, Wild Coast Sun, Port Edward, KwaZulu-Natal, South Africa.

Differential accumulation of silicon (Si) by species and cultivar is due to plant-root uptake ability (**Mitani-Ueno et al., 2011**). In pumpkin (*Cucurbita moschata* Duch.), two Si efflux transporters were identified, CmLsi2-1 from bloom-type and CmLsi2-2 from bloomless-type cultivars that were expressed in both roots and shoots. They differ from the Si influx transporter CmLsi1. A mutation in the influx transporter CmLsi1 is responsible for the bloomless phenotype which results in low Si uptake.

Mitani-Ueno, N., N. Yamaji, and J.F. Ma. 2011. Silicon efflux transporters isolated from two pumpkin cultivars contrasting in Si uptake. Plant Signal. Behav., 6(7):991–994.

Silicon supplements to cucumber (*Cucumis sativus*) nutrient solution increased root apoplastic iron (Fe) pools and enhanced Fe acquisition by regulation of gene expression levels of proteins, resulting in increased Fe mobilizing compounds under Fe deficiency (**Pavlovic et al., 2013**).

Pavlovic, J., J. Samardzic, V. Maksimović, G. Timotijevic, N. Stevic, K.H. Laursen, T.H. Hansen, S. Husted, J.K. Schjoerring, Y. Liang, and M. Nikolic. 2013 Silicon alleviates iron deficiency in cucumber by promoting mobilization of iron in the root apoplast. New Phytol., 198(4):1096–107.

Solid SiO_2 phytolith formation in cucumber (*Cucumis sativus*) fruit rinds is under genetic control by a single locus (Hr) gene that previously was known to control lignin formation and be associated with plant defense against herbivory (**Piperno et al., 2002**). Phytolith's slow degradation, and uniqueness of phytoliths by species has been used in archeological sites for dating, determining and validating plant species evolutionary relationships, and in determining diets of pre-historic humans. Phytolith formation is believed to have had an evolutionary fitness advantage, although human selection has moved toward less silicification and softer rind varieties with increased rate of postharvest rot.

Piperno, D.R., I. Holst, L. Wessel-Beaver, and T.C. Andres. 2002. Evidence for the control of phytolith formation in Cucurbita fruits by the hard rind (Hr) genetic locus: Archaeol. Ecol. Implic. PNAS, 99(16):10923–10928.

Potassium silicate supplements increased K(+) transport, decreasing chloroplast absorption of Na(+), while increasing active oxygen scavenging in chloroplasts resulting in alleviation of salt stress injury to chloroplast membranes of cucumber (*Cucumis sativus* L.) seedlings (**Qian et al., 2006**).

Qian, Q.Q., W.S. Zai, Z.J. Zhu, and J.Q. Yu. 2006. Effects of exogenous silicon on active oxygen scavenging systems in chloroplasts of cucumber (*Cucumis sativus* L.) seedlings under salt stress. J. Plant Physiol. Mol. Biol., 32(1):107–112.

Sodium silicate supplements to nutrient solution at a rate of 1.8 mM reduced manganese (Mn) toxicity symptoms in cucumber (*Cucumis sativus* L. cv. Chinesische Schlange) under low to high Mn concentrations (0.5–1000 µm: (**Rogalla and Römheld, 2002**). Manganese content in the leaves was similar, but without silicon (Si) higher Mn concentrations were found in the intercellular washing fluid and more so in the leaf apoplast. The Mn concentration of the intercellular washing fluid increased with increasing severity of Mn-toxicity symptoms, but correlated negatively with Si supplementation. In plants receiving Si, less Mn was located in the symplast and more found bound to the cell wall. Silicon supplements resulted in less available and less toxic Mn in the plants. Silicon mediated Mn tolerance of cucumber is due to enhanced Mn binding to the cell wall and lowering of symplastic Mn concentration.

Rogalla, H., V. Römheld. 2002. Role of leaf apoplast in silicon-mediated manganese tolerance of *Cucumis sativus* L. Plant Cell Environ., 25:549–555.

Trichome morphology on the surface of cucumber (*Cucumis sativus* L.) fruit changed following silicon (Si) supplementation (**Samuels et al., 1993**). Changes included a duller and coarser outer covering appearance, and high Si content in trichomes but not in surrounding epidermis or fleshy mesocarp and endocarp tissues. Within the epidermal layer Si is restricted to the trichomes and is mainly deposited in the epicuticular wax of cucumber.

Samuels, A.L., A.D.M. Glass, D.L. Ehret, and J.G. Menzies. 1993. The effects of silicon supplementation on cucumber fruit: Changes in surface characteristics. Annal. Bot., 72: 433–440.

Silicon supplied in nutrient solutions to zucchini squash (*Cucurbita pepo* L., cv. Rival) grown in perlite under high salinity had increased fruit ascorbic acid content but no effect on fruit quality during storage regardless of salt levels was seen (**Savvas et al., 2009**).

Savvas, D., I. Karapanos, A. Tagaris, and H.C. Passam. 2009. Effects of NaCl and silicon on the quality and storage ability of zucchini squash fruit. J. Hort. Sci. Biotech., 84(4):381–386.

Exogenous applications of silicon to cucumber (*Cucumis sativus* L.) decreased lipid peroxidation resulting from toxic levels of Mn, inhibited Mn toxicity symptoms, and improved plant growth (**Shi et al., 2005**). Alleviation of Mn toxicity by Si was attributed to significant increases in the activities of metabolic antioxidant enzymes.

Shi, Q.H., Z.Y. Bao, Z.J. Zhu, Y. He, Q.Q. Qian, and J.Q. Yu. 2005. Silicon mediated alleviation of Mn toxicity in *Cucumis sativus* in relation to activities of superoxide dismutase and ascorbate peroxidase. Phytochem., 66:1551–1559.

Applications of a 2.5% monosilicic acid solution supplied through drip irrigation to triploid watermelon (*Citrullus lanatus* Thunb. cv. Queen of Hearts grafted onto a squash hybrid (*Cucurbita maxima* x *Cucurbita moschata* cv. Strongtosa) increased fruit quality (10% increase in pulp consistency and rind width) but did not affect overall yields (harvest weights and fruit number (**Toresano-Sánchez et al., 2010**).

Toresano-Sánchez, F., M. Díaz-Pérez, F. Diánez-Martínez, and F. Camacho-Ferre. 2010. Effect of the application of monosilicic acid on the production and quality of triploid watermelon. J. Plant Nutr., 33(10):1411–1421.

Bitter gourd (*Momordica charantia*) seeds subjected to salt stress (NaCl) had reductions in germination rate, germination index and vitality index (**Wang et al., 2010**). However, exogenous silicon applications increased germination rate, germination index and vitality index, while decreasing malondialdehyde content and increasing antioxidant enzyme (superoxide dismutase, peroxidase, and catalase) activities under NaCl stress.

Wang, X.D., O.Y. Chao, Z.R. Fan, S. Gao, F. Chen, and L. Tang. 2010. Effects of exogenous silicon on seed germination and antioxidant enzyme activities of Momordica charantia under salt stress. J. Animal Plant Sci., 6(3):700–708.

Silicon may be involved in metabolic or physiological activity when cucumber (*Cucumis sativus* L.) plants are subjected to salt stress (NaCl: (**Zhu et al., 2004**). This was exhibited as increases in activity of superoxide dismutase, guaiacol peroxidase, ascorbate peroxidase, dehydroascorbate reductase, and glutathione reductase; and decreases in levels of lipid peroxidation, hydrogen peroxide, and electrolytic leakage in leaves of salt stressed cucumber plants when potassium silicate was added to the nutrient solution.

Toxicity was mitigated with improved growth under salt stress.

Zhu, Z.J., G.Q. Wei, J. Li, Q.Q. Qian, and J.Q. Yu. 2004. Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (*Cucumis sativus* L.). Plant Sci., 167:527–533.

Crucifers (*Brassicaceae*)

Silicon (Si) had a direct effect in decreasing plant chromium (Cr) uptake and stabilizing Cr in Cr contaminated soil (**Ding et al., 2013**). Silicon soil supplements to pakchoi (*Brassica chinensis* L.) grown in low Cr soil showed improved growth. And, although shoot dry weight decreased with Si supplements under high soil Cr, the activity of the antioxidants POD (peroxidase), SOD (superoxide dismutase), and CAT (catalase) increased. Shoot Cr decreased and root Cr was increased due to soil formation of organic matter bound Cr and reduction in exchangeable-bound Cr. Rhizosphere pH increases with Si mediated detoxification of Cr.

Ding, X., S. Zhang, S. Li, X. Liao, and R. Wang. 2013. Silicon mediated the detoxification of Cr on pakchoi (*Brassica chinensis* L.) in Cr-contaminated soil. International Symposium on Environmental Science and Technology (2013 ISEST), Procedia Environ. Sci.,.18:58–67.

Sodium (Na) silicate added to hydroponically grown canola (*Brassica napus* L.; aka rape seed) under salinity stress increased plant growth chlorophyll content while reducing shoot lignin and Na accumulation and lipid peroxidation in roots (**Hashemi et al., 2010**). Reactive oxygen species (ROS) scavenging capacity during salt stress was increased with Si, exhibited as increased catalase and cell wall peroxidase activity. Ameliorative effects on salinity stress attributed to Si supplements included reductions in tissue Na content, maintenance of root cell membrane integrity, reductions in lipid peroxidation and lignification, and increases in ROS scavenging capacity. Root Si concentrations were higher than shoot after Si additions.

Hashemi, A., A. Abdolzadeh, and H.R. Sadeghipour. 2010. Beneficial effects of silicon nutrition in alleviating salinity stress in hydroponically grown canola, *Brassica napus* L., plants. Soil Sci. Plant Nutr., (Tokyo) 56:244–253.

Silicon additions to solution culture increased oilseed rape (*Brassica napus* L.) shoot and root dry matter yields and net photosynthetic rate and maintained plant phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) content under boron (B) deficiency (**Liang and Shen, 1994**). Enhanced B uptake and accumulation under B deficiency were exhibited while B uptake was reduced under toxic levels.

Liang, Y.C., and Z.G. Shen. 1994. Interaction of silicon and boron in oilseed rape plants. J. Plant Nutr., 17(2-3):415–425.

Silicon additions increased shoot and root biomass at both low and high cadmium (Cd) levels and decreased Cd uptake and root-to-shoot transport with enhanced antioxidant defense activity in two pakchoi (*Brassica chinensis* L.) cultivars Shanghaiqing (Cd-sensitive) and Hangyoudong (Cd-tolerant; **Song et al., 2009a**). Silicon reversed reductions in superoxide dismutase, catalase and ascorbate peroxidase activities and increases in malondialdehyde and H_2O_2 at the high Cd rate. Silicon heightened increases in ascorbic acid, glutathione and non-protein thiols resulting from the high Cd level. Silicon was more effective in enhancing Cd tolerance in the Cd-tolerant cultivar than in the Cd-sensitive cultivar. Si-enhanced Cd tolerance in pakchoi was mainly due to suppression of Cd uptake and root to shoot transfer along with enhancement of antioxidant defenses.

Song, A., L. Zhaojun, J. Zhang, G. Xue, F. Fan, and Y. Liang. 2009a. Silicon-enhanced resistance to cadmium toxicity in *Brassica chinensis* L. is attributed to Si-suppressed cadmium uptake and transport and Si-enhanced antioxidant defense capacity. J. Hazard. Mater., 172:74–83.

The role of silicon (Si) in alleviating Cd-induced oxidative stress in roots of pakchoi (*Brassica chinensis* L.) of two cultivars, Shanghaiqing (Cd-sensitive), and Hangyoudong (Cd-tolerant), under low or high Cd stress with or without Si additions was evaluated (**Song et al., 2009b**). Silicon-mediated alleviation of cadmium (Cd) toxicity is attributed to enhanced root length, antioxidant defense capacity, and membrane integrity along with reduced oxidative damage. Cadmium caused reductions in root length, more so for Cd-sensitive cultivar, and additions of Si increased root length under both low and high Cd regardless of cultivar Cd sensitivity. Both low and high Cd additions resulted in reductions in superoxide dismutase, catalase, ascorbate peroxidase(s) activity and increases in the concentration of malondialdehyde. Silicon additions nullified these effects with the beneficial effects of Si additions being more pronounced in the Cd-tolerant cultivar.

Song, A., Z. Li, and Y. Liang. 2009b. Silicon-mediated alleviation of cadmium toxicity in roots of *Brassica chinensis* is mainly attributable to silicon-enhanced antioxidant defense capacity and silicon-suppressed oxidative damage. pp.1-7, In Proc. Int. Plant Nutr. Colloq. XVI., Paper 1043. Univ. Calif. Davis, CA.

Grapes (*Vitis vinifera* L.)

The deposition of silicon (Si) in grape organs is dependent on age, intensity of transpiration and Si content of the nutrient solution and/or Si solubility in the soil (**Blaich and Grunhofer, 1997**). The majority of Si is located within the margin of older leaves and can reach 2%.

Blaich, R., and H. Grundhöfer. 1997. Uptake of silica by grapevines from soil and recirculating nutrient solutions. Vitis, 36(4):161–166.

Silicates have been used in Australian viticulture for 20 years with outstanding results in yield, fruit quality and soil health (**Lynch, 2008**). These results have been seen under multiple climatic conditions irrespective of soil type, texture, or pH. Superior grapes (both table and wine) have resulted from Si supplements with enhanced skin quality, higher Brix, more uniform bunch size, and near absence of fungal diseases. Sustainability is increased with increases of beneficial insects apparent.

Lynch, M. 2008. Silicates in contemporary Australian farming: A 20-year review. p. 68.
In Malcolm Keeping (ed.) Silicon in Agriculture Conference South Africa, 26-31 October, 2008, 4th International Conference Abstracts. Univ. Kwazulu-Natal, Wild Coast Sun, Port Edward, KwaZulu-Natal, South Africa.

Silicon's effects on salt and boron (B) toxicity were evaluated on two grape (*Vitis vinifera* L.) variety rootstocks (**Soylemezoglu et al., 2009**). Silicon additions reversed salt and B toxicity effects by decreasing rootstock accumulation of sodium (Na) in *V. Berlandieri* x *V. Rupestris* and both B and chloride (Cl) in (*V. vinifera* x *V. Berlandieri*) and (*V. Berlandieri* x *V. Rupestris*). Silicon reversed the effects of increased stomatal resistance, lipid peroxidation, H_2O_2, and proline (caused by B toxicity), salinity, and the combined effects salt and B. Superoxide disumutase and catalase levels were lowered while ascorbate peroxidase levels were increased with Si for varieties under combined stress. It was concluded that Si alleviates salt and B toxicity and their combined negative effects in multiple ways; by preventing oxidative membrane damage, by preventing translocation of Na and B root-to-shoot and/or soil-to-plant, and by decreasing Na and B plant tissue phytotoxic effects. However, one rootstock variety was more responsive to Si additions than the other.

Soylemezoglu G., K. Demir, A. Inal, and A. Gunes. 2009. Effect of silicon on antioxidant and stomatal response of two grapevine (*Vitis vinifera* L.) rootstocks grown in boron toxic, saline and boron toxic-saline soil. Sci. Hortic., (Amsterdam) 123:240-246.

Greenhouse Crops

The potential benefits from silicon in greenhouse production could be substantial considering that standard soilless media is devoid of silicon (**Frantz et al., 2004**).

Frantz, J.M., D.S. Pitchay, J.C. Locke, and C. Krause. 2004. Evaluating silica uptake in bedding plants. # 375 Poster Sessions 17- Mineral Nutrition. In Abstracts: 101st Annu. Int. Conf. Am. Soc. Hort. Sci. 18 July 2004. Austin, Texas. HortSci., 39(4):776.

The first documented case of silicon (Si) uptake and deposition in New Guinea impatien (*Impatiens hawkeri* W. Bull.), a Balsaminaceae species is documented (**Frantz et al., 2005**). Scanning electron microscopy and energy dispersive X-ray analysis revealed Si deposits in unique silica filled cells of leaf margins located mainly near hydathodes, but no silica was found in the xylem. These results are contrary to earlier phylogenetic studies suggesting that Si uptake and deposition is confined to monocot species. The potential use of silicon in greenhouse ornamental crop production should be considered as most greenhouse production uses soilless media devoid of Si.

Frantz, J.M., D.D.S. Pitchay, J.C. Locke, L.E. Horst, and C.R. Krause. 2005. Silicon is deposited in leaves of New Guinea impatiens. Plant Health Prog., Plant Manage. Netw. 17 Feb. 2005. Available online at: <doi:10.1094/PHP-2005-0217-01-RS> accessed: 20 Oct. 2014.

When comparing three methods of analysis for measuring plant tissue silicon (Si) content, electron beam analysis (EBA) was reliable, but expensive, and could locate, but not quantify Si deposits at high concentrations only localized to specific areas (**Frantz et al., 2008**). Colorimetric analysis was inexpensive and mostly, but not always obtained similar results to inductively coupled plasma–optical emission spectroscopy (ICP-OES). Although ICP-OES previously required the use of hazardous [(Hydrofluoric acid (HF)] and equipment damaging [sodium hydroxide (NaOH)], requiring replacement, by substituting either reagent with potassium hydroxide (KOH) costs were reduced (although not to the level of colorimetric analysis), and data analysis was less variable with improved automation. Silicon deposition in 14 floriculture species was mostly around trichome bases and along the leaf margins using EBA. The three methods achieved similar results for Si in most cases, but the EBA method had lower detection limits ~ 300 mg kg−1 dry wt. Si. This enabled the identification of additional species (zinnia, impatiens, verbena, and calibrachoa) having significant Si deposition.

Frantz, J.M., J.C. Locke, L. Datnoff, M. Omer, A. Widrig, D. Sturtz, L. Horst, and C.R. Krause. 2008. Detection, distribution, and quantification of silicon in floricultural crops utilizing three distinct analytical methods. Comm. Soil Sci. Plant Anal., 39:2734-2751.

Several ornamental flower crops have clearly benefited from silicon (Si) supplements (**Frantz et al., 2010a**). The benefits could prove to be even more important where high electrical conductivity (EC) reduces water quality during production, and under high copper (Cu), due to pesticide application or injectors, which negatively affect growth. A list of ornamental crops and benefits seen from Si supplements includes:

1. Poinsettia: reduced bract edge burn, improved shelf-life
2. Zinnia, sunflower, phlox: reductions in powdery mildew disease
3. Gerbera: increased flower size
4. Zinnia: increased resistance to metal toxicity, decreased growth of aphid populations
5. New Guinea Impatiens: improved salt-tolerance.

Frantz, J.M., J.C. Locke, and N. Mattson. 2010a. Research Update: Does silicon have a role in ornamental crop production? OFA Bull. Nov-Dec. 924:17–18.

Silicon uptake in 46 crops grown hydroponically showed a general pattern of silicon deposition along leaf margins and in leaf trichomes (**Frantz et al., 2010bc**). Minimal silicon was found in roots and stems. Of the dicot ornamental plant species tested, nearly 50% had leaf dry weight silicon concentrations >0.1%. This is considered to be the nutrient content threshold used to differentiate macro from micro plant nutrients. Common pesticides and fertilizer can also contain silicon and some do not list silicon as an ingredient on their labels or MSDS sheets. Water sources can also vary in dissolved silicon content. Products that contain high levels of silicon may not release more silicon at higher rates and some products can act more as a slow release silicon product. Fertigation with silicon is an effective delivery method but some silicon products can be expensive requiring mixing and pH management. Comparable amounts of silicon can be supplied to plants via slag, rice hulls and biofuel crops.

Frantz, J.M., J.C. Locke, D. Sturtz, C. Ranger, and S. Leisner. 2010b. Silicon in ornamental crops: Detection, delivery, and function. Indo-US Workshop on Silicon in Agriculture. Abstract #5, 25-27 February 2010. Bangalore. India.

Frantz, J.M., J.C. Locke, D. Sturtz, and S. Leisner. 2010c. Silicon in ornamental crops: Detection, delivery, and function. In F.A. Rodrigues (ed.) Anais do V Simpósio Brasileiro Sobre Silício na Agricultura. Chap 6. pp. 111–134. Univerisdade Federal de Viçosa, Brazil.

Silicon alleviated copper (Cu) toxicity symptoms in Arabidopsis thaliana while decreasing the RNA levels of genes involved in Cu transport and heavy metal ATPase production (**Frantz and Leisner, 2010**). Leaf tissue Cu was similar with or without silicon but with silicon internal Cu pools were better managed. Similar alleviation of Cu toxicity symptoms in Zinnia (*Zinnia elegans*) was also seen with silicon additions, but in this case copper uptake was reduced suggesting that both physiological changes and gene expression can be affected by silicon in mediating Cu toxicity.

Frantz, J.M., and S. Leisner. 2010. Silicon mediates copper toxicity in Arabidopsis thaliana and *Zinnia elegans*. Indo-US Workshop on Silicon in Agriculture. Abstract #6, 25–27 February 2010. Bangalore. India.

Silicon (Si) concentrations in Zinnia (*Zinnia elegans*; considered to be a Si accumulator), increased in leaf, stem, and root when supplemented with Si in the growth media under toxic levels of copper (Cu), and Cu toxicity symptoms decreased. Snapdragon (*Antirrhinum* spp.), considered a Si non-accumulator, leaf Si concentrations increased with increasing Si rates and also with increasing Cu supply but did not result in reductions in Cu toxicity symptoms. Both Zinnia and Snapdragon accumulated less Cu when supplied with Si and Cu induced stress activity (PAL & POD) was reduced by Si. Although both species benefited from Si supplements, it is likely that different mechanisms are reducing metals toxicity in Si accumulator and non-accumulator species (**Frantz et al., 2011**).

Frantz, J.M., S. Khandahar, and S. Leisner. 2011. Silicon differentially influences copper toxicity response in silicon-accumulator and non-accumulator species. J. Am. Soc. Hort. Sci., 136:329–338.

Silicon (Si) is an integral part of the soil-plant system in nature and agricultural production systems (**Hou et al., 2006**). Horticultural crops benefiting from Si supplements have included apple (*Malus* spp.), grape (*Vitus* spp.), strawberry (*Fragaria* spp.), melon, gherkin, cucumber (*Cucumis* spp.), eggplant (*Solanum melongena*), bean (*Phaseolus vulgaris*), and rose (*Rosa* spp.). Both plant health and soil productivity can benefit from Si, especially under abiotic or biotic stress conditions. Some of the benefits of Si include: enhanced soil fertility, improved disease and pest resistance, increased photosynthesis and yield, improved fruit quality, improved plant architecture, regulation of transpiration, increased tolerance to toxic levels of aluminum (Al), manganese (Mn) and iron (Fe), and reduced frost damage. Silicon deficiency has been demonstrated as reduced pollen fertility, which affects fruit yields. Large quantities of soluble Si removed from soils annually during crop production can affect phosphorus (P), Al, heavy metals, Fe, and Mn availability, increase soil erosion, decrease microbial populations, and decrease plant Si nutrition. With ongoing global environmental changes, Si will become more and more important in sustainable production of horticultural crops.

Hou, L., E. Szwonek, and S. Xing. 2006. Advances in silicon research of horticultural crops. pp. 5–17. In A. Dobrzanski, F. Adamicki, R. Kosson, J. Szwejda, K. Górecka, and B. Nowak (eds.) Veg. Crops Res. Bull. No. 64, Res. Inst. Veg. Crops, Skierniewice, Poland.

In Taiwan, a soil amendment mixture containing 60.5% slag was successfully developed to control soil borne crop diseases (**Huang, 1991**). Fusarium wilt (causal agent *Fusarium oxysporum*) of watermelon (*Citrullus lanatus* Thunb.), radish (*Raphanus sativus*), and pea (*Pisum sativum* L.); club root (causal agent (*Plasmodiophora brassicae*) of crucifers (*Brassica* spp.), cucumber (*Cucumis sativus* L.) blight (various causal agents) and pythium (*Pythium* spp.) damping off, and bacterial wilt (causal agent *Pseudomonas viridiflava*) of tomato (*Solanum lycopersicum* L.), were effectively controlled with this amendment.

Huang, J.W. 1991. Control of soilborne crop diseases by soil amendments. Plant Prot. Bull., 33:113–123. (English abstract).

Benefits of silicon (Si) supplements to cut flower production include increased flower and stem diameter and increased stem dry weight (**Kamenidou, 2005**). Plant organ Si concentrations were highest in leaves> flowers > stems, regardless of Si treatment. Soil incorporation of rice hull ash and potassium silicate as either a soil drench or soil incorporated, were all beneficial Si sources.

Kamenidou, S. 2005. Silicon supplementation affects greenhouse produced cut flowers. MS Thesis, Oklahoma State Univ.

Weekly applications of potassium silicate ($KSiO_3$), as a substrate drench, $KSiO_3$ substrate incorporated as hydrous powder, sodium silicate ($NaSiO_3$) as a foliar spray, or rice hull ash substrate incorporated during greenhouse-production of ornamental sunflowers (*Helianthus annuus* L. 'Ring of Fire') resulted in increased silicon content of treated plants when compared with non-amended controls (**Kamenidou et al., 2008**). Improvements in horticultural traits were Si source and application rate dependent. Positive effects on sunflower plants were exhibited as thicker, straighter stems, increased size (diameter) of flowers and stems, increased plant height, and improved sunflower quality. However, abnormalities of stunted growth, deformed flowers, and delayed flowering were observed with liquid Si concentrations of 100 and 200 mg•L−1 Si as $KSiO_3$ substrate drenches. The best Si product formulations, application method, and rates determined from this trial for greenhouse sunflower production were 100 g m–3 Si as rice hull ash substrate incorporation, 140 g m–3 Si as hydrous $KSiO_3$ substrate incorporation, 100 mg L–1 Si as NaSiO3 weekly foliar application, and 50 mg L–1 Si as weekly substrate drenches of $KSiO_3$. Note: As no information was contained in the article's methods section as to preventative measures used to avoid foliar application drips to substrate, the author was contacted via email. On Oct. 1 2014 Sophia Kamenidou-sofia.kamenidou@ucr.edu replied stating, "I was the one that applied the foliar spray treatments. It was applied through a very fine mist (no dripping), in each pot individually and the surface of the pot was covered with plastic until the foliar spray completely dried out. You will notice that we did not perform elemental analysis for these treatments. If you read through the different manuscripts based on my MSc research, the discussion indicates that the foliar application mostly had a "sealant" effect possibly affecting transpiration and the improved horticultural traits were not attributed to Si uptake for the foliar treatments" She reiterated in an email 7 October 2014 "For this study: foliar sprays were applied through a very fine mist (the exact amount applied per plant was not calculated; sprayed each plant just before occurrence of "runoff") in each pot individually and the surface of the pot was covered with plastic sheet until the foliar spray visibly dried out"

Kamenidou, S., T.J. Cavins, and S. Marek. 2008. Silicon supplements affect horticultural traits of greenhouse-produced ornamental sunflowers. HortSci., 43(1):236-239.

Different silicon (Si) sources at different application rates were evaluated for their effects on floricultural quality traits, plant and leaf tissue Si content, and nutrient uptake of greenhouse grown gerbera (*Gerbera* hybrid L. 'Acapella'). Potassium silicate ($KSiO_3$) was applied weekly as a substrate drench, or as hydrous KSiO3 substrate amendment, sodium silicate ($NaSiO_3$) was applied as a foliar spray, and rice hull ash was incorporated into the substrate (**Kamenidou et al., 2010**). Silicon supplements resulted in thicker flower peduncles, increased flower diameters, increased plant height, and earlier flowering. Plants grown in Si-amended media accumulated higher tissue silicon levels in leaves, peduncle and flowers. Leaf macronutrients concentrations of S and K along with the micronutrients boron (B), copper (Cu), iron (Fe), and manganese (Mn) were slightly affected with Si-supplements. At lower application rates of substrate applied formulations leaf tissue aluminum (Al) was reduced. High rates of the foliar Si spray (150 mg Si L-1, $NaSiO_3$) resulted in stem shortening and flower deformation. However, this was likely due to sodium toxicity or leaf antitranspirant effects as the material dried on the leaves. It was determined that greenhouse grown gerberas can benefit from Si supplements, but for optimal growth, the forms and rates of the different products need to be optimized.

Kamenidou, S., T.J. Cavins, and S. Marek. 2010. Silicon supplements affect floricultural quality traits and elemental nutrient concentrations of greenhouse produced gerbera. Sci. Hort., (Amsterdam) 123(3):390-394.

Silicon (Si) increased gerbera (*Gerbera jamesonii*) cut flower water uptake (**Kazemi et al., 2012**). Flower weight was increased while malondialdehyde (MDA), ACC-oxidase (1-aminocyclopropane-1-carboxylate oxidase-last step catalyst in ethylene production) and membrane permeability were decreased with supplemental Si. Senescence and lipid peroxidation were also delayed. One and 2mM Si concentrations increased vase life of cut flowers.

Kazemi, M., M. Gholami, and F. Hassanvand. 2012. Effects of silicon on antioxidative defense system and membrane lipid peroxidation in gerbera cut flower. Asian J. Biochem., 7(3):171–176.

Copper (Cu) toxicity can develop from high doses of Cu containing nutrient additions and pesticides (**Li et al., 2008**). Arabidopsis (*Arabidopsis thaliana* L. Heyn.) plants subjected to high levels of Cu with silicon (Si) supplements exhibited reductions in leaf chlorosis and increased shoot and root biomass along with reductions in stress-induced enzyme (phenylalanine ammonia lyase-PAL) activity in shoots. RNA levels of two Cu transporter genes, induced by high Cu, were also reduced with high Si rates. Under Cu stress the benefits of Si include alleviation of plant physiological stress and altered gene expression.

Li, J., S.M. Leisner, and J. Frantz. 2008. Alleviation of copper toxicity in Arabidopsis thaliana by silicon addition to hydroponic solutions. J. Amer. Soc. Hort. Sci., 133(5):670–677.

Silicon is taken up by New Guinea impatiens (*Impatiens hawkeri* W. Bull.), and localized to unique cells in the hydrathode areas of leaf margins (**Locke et al., 2004**).

Locke, J.C., D. Pitchay, and J.M. Frantz. 2004. Effect of nitrogen, potassium, and silicon nutrition on disease susceptibility of various ornamental crop species. USDA-ARS, Natl. Dig. Lib., Available online at: <http://www.ars.usda.gov/sp2UserFiles/Place/50820500/Posters/Locke167681_2004_Effect.pdf> accessed: 20 Oct. 2014

At least 12 commonly grown floriculture crops have been documented to accumulate silicon (Si) in excess of 0.1% of leaf tissue dry weight (**Locke et al., 2009**). The positive effects from Si have resulted from supplementing either soilless mix growing media or the fertigation solution. Examples of the benefits seen from these Si supplements are: delayed disease onset along with reduced severity of powdery mildew disease of Zinnia (*Zinnia elegans*), and increased tolerance of zinnia to copper toxicity (increased shoot and root biomass and decreased leaf chlorosis).

Locke, J.C., J. Frantz, M.A. Omer, D.S. Sturtz, J. Li, and S. Leisner. 2009. Evaluation of the use of supplemental silicon in floricultural crop production to reduce disease stress and micronutrient (Cu) toxicity and to enhance crop quality. pp. 96 & 144. GreenSys. 2009. 14-19 June 2009. Quebec City, Canada

Bract necrosis of Poinsettia (*Euphorbia pulcherrima*) has been associated with either low Ca or high K concentrations in bract margin tissues (**McAvoy and Bible, 1996**). However, silica sprays reduced the occurrence and severity of bract necrosis without affecting Ca or K concentrations in bract tissues. Silicate sprays were also as effective as $CaCl_2$ in protecting against bract necrosis even at a lower concentration. These treatment results did not differ by poinsettia cultivar (“Supjibi Red’ or ‘Angelika White’).

McAvoy, R.J., and B.B. Bible. Silica sprays reduce the incidence and severity of bract necrosis in poinsettia. HortSci., 31(7):1146–1149.

Strawberry (*Fragaria* x *ananassa Duchesne* cv. ‘Hokowase’) plant dry weight of tops, total fruit number, and total marketable fruit yield (weight), was increased with silicon (Si), demonstrating a positive effect of Si on strawberry plant growth and fruit production (**Miyake and Takahashi, 1986**). Dry leaf Si content was increased from 0.06% (no Si supplement) to 1.22% with Si amendment. Root Si content of treated plants was 0.06% (similar to leaves of the untreated controls), with a calculated root to shoot ratio of 20.3:1. The mode of Si uptake in strawberry is likely similar to that of soybean, freely translocated from root to shoot. Silicon concentration was much higher in the crown at formation than during the beginning or ending of flowering. Pollen fertility was decreased when Si was withheld.

Miyake, Y. and E. Takahashi. 1986. Effect of silicon on the growth and fruit production of strawberry plants in a solution culture. Jap. Soc. Soil Sci. Plant. Nutr., 32(2):321–326.

Addition of silicate at ≥ 200 ppm to 6” potted chrysanthemums (*Dendranthema morifolium*, cv. X) resulted in reductions in leaf miner (*Liriomyza trifolii*) emergence (**Parrella et al., 2007**).

Parrella, M.P., T.P. Costamagna, and R. Kaspi. 2007. The addition of potassium silicate to the fertilizer mix to suppress Liriomyza leafminers attacking chrysanthemums. In VIII International Symposium on Protected Cultivation in Mild Winter Climates: Advances in Soil and Soilless Cultivation. Acta Hort., 747:365–370.

Silicon (Si) supplements to cut rose (*Rosa* x *hybrida* L. cv. ‘Hot Lady’) under salt (NaCl) stress resulted in increased growth, quality and yields (**Reezi et al., 2009**). Rates of 50 and 100 ppm Si were better than 150 ppm with the higher rate adversely affecting solution pH. Some of the benefits attributed to Si were restoration of membrane integrity and function and flower color, and reductions in malondialdehyde content attributed to salt stress.

Reezi, S., M. Babalar, and S. Kalantari. 2009. Silicon alleviates salt stress, decreases malondialdehyde content and affects petal color of slat stressed cut rose (*Rosa xhybrida* L.) “Hot Lady”. Afric. J Biotech., 8(8):1502–1508.

Three chrysanthemum (*Dendranthema grandiflorum*) cultivars ‘Gaya Pink’, ‘Lemmon Tree’ and ‘White Angel’ showed increases, but differed in leaf silicon (Si) content following Si supplements to a coir-based media (**Sivanesan et al., 2013**). Silicon additions resulted in plant height, stem diameter, branch number, and chlorophyll content increases, while flower number and size were increased at different Si rates. Although necrotic lesions were seen on older leaves at the beginning of flowering, they were less severe at the higher Si rate. Other leaf nutrients were seen to either increase or decrease with Si.

Sivanesan, I., M.S. Son, J.Y. Song, and B.R. Jeong. 2013. Silicon supply through the subirrigation system affects growth of three Chrysanthemum cultivars. Hort. Environ. Biotech., 54(1):14–19.

Silicate addition to rose (*Rosa* c.v. “Kardinal”) hydroponic growth solution increased length of harvested stems, but was not shown to affect postharvest life (**Walter, 2004**).

Walter, V. 2004. Effects of silicon additive to the growth and postharvest life of hydroponically grown ‘Kardinal’ roses. 101st Annual International Conference of the American Society for Horticultural Science. Poster Session 39-Floriculture. Abstract #318. 19 July 2004. HortSci., 39(4):824.

Herbs

It was found that at high altitudes above oak and beech forest zones that there are 4 native herbs which have the potential for exploitation (**Dajć, Z. 2002**). Different herb species were found growing in different environments based on their parent rock (limestone vs. silicate). The two important herb species native to the silicate parent material sites were European white ginger (*Asarum europaeum*) and calamint (*Calamintha officinalis*).

Dajć, Z. 2002. Genetic resources of medicinal and aromatic plants of Yugoslavia-current situation and further prospects. pp. 130-142 In D. Bančevič, J. Bemáth, L. Maggioni, and E. Lippman (compilers) Report of a working group on medicinal and aromatic plants. Eur. Coop. Prog. Crop Genetic Res Network. (ECP/GR). 1st Meeting 12-14 Sept. 2002. Gozd Martuljek, Slovenia.

A pot study was conducted to determine the effects of cow manure vs. silicate fertilizer soil additives on cadmium (Cd) concentrations of edible parts of sweet basil (*Ocimum basilicum*) grown in Cd contaminated soil (20 mg kg-1 Cd) for three months (**Putwattana et al., 2010**). Increases in biomass production of 4.7 x for cow manure (20% w/w rate), and 1.7 x for silicate fertilizer (20% w/w rate) were recorded. However, shoot Cd concentrations doubled with cow manure application while a 3-fold decrease in shoot Cd concentrations resulted from silicate fertilizer additions. There is a potential for silicate fertilizer to immobilize Cd in soils although root concentrations were not reduced with silicate fertilizer. It is therefore more likely that the silicate fertilizer reduced root to shoot transport of Cd which resulted in lower Cd accumulation in the edible parts of sweet basil. And, although biomass increases were more substantial with cow manure, the increases in tissue Cd would suggest that cow manure applications to high Cd soils may not be advisable.

Putwattana, N., M. Kruatrachue, P. Pokethitiyook, and R. Chaiyarat. 2010. Immobilization of cadmium in soil by cow manure and silicate fertilizer, and reduced accumulation of cadmium in sweet basil (*Ocimum basilicum*). Sci. Asia, 36(4):349-354.

Starflower (*Borago officinalis* L.) is an annual medicinal herb (plant family-Boraginaceae) containing high concentrations of gamma-linolenic acid, a dietary supplement purported to treat inflammation and auto-immune diseases (**Torabi, Majd and Enteshari, 2012**). Large scale field production is inhibited by low and inconsistent seed germination. Exogenous silicon treatments of sodium silicate (Na_2SiO_3) increased germination rate, germination index, and seedling growth with the benefits increasing with increasing application rate up to ~1.5 mM. Seedling fresh and dry weights were also increased. Improvements in seed germination and seedling establishment resulted from Si additions.

Torabi, F., A. Majd, and S. Enteshari. 2012. Effect of exogenous silicon on germination and seedling establishment in *Borago officinalis* L. J. Medicinal Plant Res. 6(10):1896–1901.

Leafy Vegetables

Salinity increased hydrogen peroxide (H_2O_2), proline concentrations, antioxidant activity, membrane permeability, lipid peroxidation and stomatal resistance of spinach (*Spinacia oleracea* L. cv. Matador), all indicative of stress (**Eraslan et al., 2008**). Exogenous silicon (Si) applications increased tolerance to salinity stress by enhancing antioxidant systems and protecting plants from oxidative damage. Silicon additions resulted in decreased H_2O_2 and lipid peroxidation, increased chlorophyll content, and increased superoxide dismutase and catalase activity. Exogenous salicylic acid application showed less obvious effects in reducing salinity stress affecting increases in superoxide dismutase only.

Eraslan, F., A. Inal, D.J. Pilbeam, and A. Gunes. 2008. Interactive effects of salicylic acid and silicon on oxidative damage and antioxidant activity of spinach (*Spinacia oleracea* L. cv. Matador) grown under boron toxicity and salinity. Plant Growth. Regul., 55:207–219.

In the absence of silicon (Si), stomatal resistance, membrane permeability, lipid peroxidation, hydrogen peroxide, and proline were all higher in spinach (*Spinacia oleracea* L. cv. Matador) plants grown in a naturally sodic-B toxic soil (**Gunes et al., 2007**). Applications of Si at either a 2.5 or 5.0 mM rate increased Si concentrations while reducing sodium (Na), Chlorine (Cl), and Boron (B) accumulation and their toxic effects on root and shoot growth. Silicon increased leaf lipoxygenase and non-enzymatic antioxidant activity while decreasing superoxide dismutase, catalase, and ascorbate peroxidase activity. The higher Si rate was more effective. Silicon ameliorated salt and B toxicity by reducing plant uptake and translocation, preventing oxidative membrane damage, and reducing inplanta phytotoxic effects. Tomato (*Lycopersicon esculentum* Mill. cv. H2274), less salt tolerant than spinach, was even more responsive to Si additions.

Gunes, A., A. Inal, E.G. Bagci, and D.J. Pilbeam. 2007. Silicon-mediated changes of some physiological and enzymatic parameters symptomatic for oxidative stress in spinach and tomato grown in sodic-B toxic soil. Plant Soil, 290:103–114.

Trees

Young Mango (*Mangifera indica* cv. Ewaise) transplants were evaluated for growth and nutritional status when subjected to water deficiency with or without soil silicon (Si) supplements (**Aal and Oraby, 2013**). Drought reduced all growth parameters evaluated, as well as leaf water content, chlorophyll content, carbohydrate assimilation and uptake of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and Si. Silicon at 150 mg kg-1 soil lessened these effects. Drought greatly increased H_2O_2 content while Si reduced these levels. It is recommended that 150 g kg-1 silicon soil amendment be applied for young mango orchards under drought conditions.

Aal, A.M.K.A.A. and M.M.M. Oraby. 2013. Using silicon for increasing the tolerance mango cv. Ewaise transplants to drought. World Rur. Obs., 5(2):36-40.

Mesquite (*Prosopis juliflora*, Swartz) are small leguminous (Fabaceae) trees or shrubs that are often grown in arid and semi-arid regions for forage, food, fuel, charcoal and timber (**Bradbury and Ahmad**, 1990). Mesquite seedlings treated with high salinity (NaCl) and sodium silicate had increased leaf dry matter, suggesting that silicon could be beneficial in growing mesquite trees in high salt soils.

Bradbury, M., and R. Ahmad. 1990. The effect of silicon on the growth of *Prosopis juliflora* growing in saline soil. Plant Soil 125:71–74.

Spherical bodies (35-65 nm) of amorphous silica form in the lumen of terminal tracheids, vein sheath cells, epidermal cells, as a layer exterior to the cell wall of epidermal cells and in the cuticle, and in guard cells of the southern magnolia (*Magnolia grandiflora* L.; (**Postek, 1981**). This leaf silica deposition may function in providing leaf strength, reduce transpiration, and increase pathogen resistance.

Postek, M.T. 1981. The occurrence of silica in the leaves of *Magnolia grandiflora* L. Bot. Gaz., 142(1):124–134.

The beneficial effects of silicon (Si) soil supplements to citrus trees in Florida were determined to be both indirect and direct (**Matichenkov et al., 1999**). Indirect effects we attributed to increasing soil fertility evidenced by reduced nutrient leaching and increased soluble nutrient availability. The direct effects we attributed to increased plant stress tolerance. Grapefruit (*Citrus* × *paradisi*) seedlings showed enhanced seedling growth and improved root system branching with Si-rich supplements. Leaf Si content of both orange (*Citrus* × *sinensis*) and grapefruit increased with age and biotic stress with uptake related to soil Si status. Healthy trees were located in areas of higher soil soluble silicon levels, while unhealthy trees were found growing in low soluble Si soils.

Matichenkov, V., D. Calvert, and G. Snyder. Silicon fertilizers for citrus in Florida. Proc. Fla. State Hort. Soc., 112:5-8.

Soil silicon (Si) levels and leaf Si content of healthy and sick citrus (*Citrus* spp.) trees were evaluated. When subjected to insect attack and infection, Si content of leaves increased (**Matichenkov et al., 2000**). It was determined that the use of Si fertilizers may improve soil properties, provide nutrients to citrus, and protect trees from disease and insect attack stress. Citrus may actively transport monosilicic acid to increase resistance to environmental stress.

Matichenkov, V.V., D.V. Calvert, and G.H. Snyder. 2000. Prospective of silicon fertilization for citrus in Florida. pp. 137-141. In Proc. Soil and Crop Sci. Soc. of FL Vol. 59. Soil Crop Sci. Soc. Fla.

Pepper, Potato, Tomato, Tobacco (*Solanaceae*)

Potato (*Solanum tuberosum* L.) plants receiving no amendment, calcium/magnesium silicate, or dolomitic lime at rates of 284.4 mg/dm3 per pot containing 50 dm3 of a sandy clay loam were subjected to drought stress (**Crusciol et al., 2009**). Stalk lodging was reduced while average tuber weights and tuber yields were increased with silicon (Si) and, to a larger degree, in the absence of drought stress. Under drought stress leaf Si levels were highest with Si additions. Under deficit water and Si, total sugars and soluble proteins were decreased in leaves. Leaf proline concentrations increased under drought and under high Si suggesting that Si is affected plant osmotic adjustment.

Crusciol, C.A., A.L. Pulz, L.B. Lemos, R.P. Soratto, and G.P.P. Lima. 2009. Effects of silicon and drought stress on tuber yield and leaf biochemical characteristics in potato. Crop Sci. 49:949–954.

Potato (*Solanum tuberosum* L.) plantlets grown in tissue culture medium supplemented with silicon (Si) had taller shoots with higher weight and longer roots (**Fang and Ma, 2006**). Optimum results were achieved at the 5 mML-1 silicic acid rate. Silicon affected increases in bound to free water ratio, chlorophyll content, cell wall extraction rate and cellulose content, while decreasing respiration rate and pectin.

Fang, J.Y., and X.L. Ma. 2006. Effect of silicon on the growth of test-tube potato plantlets and the cell wall formation. Acta Agron. Sinica., 32(1):152–154. (In Chinese with English abstract).

In the absence of silicon (Si), stomatal resistance, membrane permeability, lipid peroxidation, hydrogen peroxide, and proline were all higher in tomato (*Lycopersicon esculentum* Mill. cv. H2274) plants grown in a naturally sodic-B toxic soil (**Gunes et al., 2007**). Applications of Si at either a 2.5 or 5.0 mM rate increased Si concentrations while reducing sodium (Na), chloride (Cl) and boron (B) accumulation and their toxic effects on root and shoot growth. Silicon increased leaf lipoxygenase and non-enzymatic antioxidant activity while decreasing the activity of superoxide dismutase, catalase, and ascorbate peroxidase. The higher Si rate was more effective. Silicon ameliorated salt and B toxicity by reducing plant uptake and translocation, preventing oxidative membrane damage, and reducing inplanta phytotoxic effects. Tomato, less salt tolerant than spinach (Spinacia oleracea L. cv. Matador), was more responsive to Si additions

Gunes, A., A. Inal, E.G. Bagci, and D.J. Pilbeam. 2007. Silicon-mediated changes of some physiological and enzymatic parameters symptomatic for oxidative stress in spinach and tomato grown in sodic-B toxic soil. Plant Soil, 290:103–114.

Synthetic calcium silicate, used as a primer for pepper (*Capsicum annuum* L.) seeds, significantly increased final radical area which had a strong positive correlation with final seed germination (a measurement of seed quality) rate (**Hacisalihoglu and White, 2010**).

Hacisalihoglu, G., and J. White. 2010. Determination of vigor differences in pepper seeds by using radical area test. Acta Agric. Scandinavica Sect. B- Soil Plant Sci., 60:355–340.

Silicon (Si) for 13 different potato (*Solanum tuberosum* L.) cultivars ranged from 209 to 479 mg kg-1 Si. Taste of steamed tubers correlated positively with Si content (**Jitsuyama et al., 2009**).

Jitsuyama, Y., A. Tago, C. Mizukami, K. Iwama, and S. Ichikawa. 2009. Endogenous components and tissue cell morphological traits of fresh potato tubers affect the flavor of steamed tubers. Am. J. Pot. Res., 86:430–441.

Tomato (*Lycopersicon esculentum* Mill. cv. 'Momotaro T-93') fruit sucrose and silicon (Si) content was increased with granular silicate supplements to perlite media (**Lee et al., 2002**). Silicate application correlated positively with tomato fruit Si content and activities of sucrose phosphate synthase (SPS) and Sucrose synthase (SS) The activation of SPS and SS due to silicate supplements was concluded to be responsible for the increased fruit sucrose content.

Lee, J.W., Y.C. Kim, K.Y. Kim, H.K. Yun, H. K., and T.C. Seo. 2002. Influence of silicate application on the sucrose synthetic enzyme activity of tomato in perlite media culture. In A.P. Papadopoulos (ed.) XXVI International Horticultural Congress: Protected Cultivation 2002: In Search of Structures, Systems and Plant Materials. Acta Hort., 633:259–262.

Silicon (Si) content is greater near the distal end (further from attachment) and decreases toward the center of potato (*Solanum tuberosum* L.) tubers (**LeRiche et al., 2009**). However, Si content was not correlated with after-cooking darkening although phosphorus (P), calcium (Ca), copper (Cu), sulfur (S), and magnesium (Mg), were.

LeRiche, E.L., G. Wang-Pruski, and V.D. Zheljazkov. 2009. Distribution of elements in potato (*Solanum tuberosum* L.) tubers and their relationship to after-cooking darkening. HortSci., 44(7):1866–1873.

Silicon affects reproductive growth of tomatoes (*Solanum lycopersicum* L.; **Miyake and Takahashi, 1978**). Silicon deficiency symptoms appear after the 1st bud at flowering stage and include: deformation of newly formed leaflets (curving to outside, warping, hardening and possibly thickening), retarded development of apex, leaves slightly yellow with necrotic spots beginning at lower leaves and moving upward, severe silicon deficiency results in plant drying lower leaves to top, failure to pollinate with either no fruit formation or deformed fruit, with symptoms increasing during long days and decreasing during short days.

Miyake, Y., and E. Takahashi. 1978. Silicon deficiency of tomato plant. Soil Sci. Plant. Nutr., 24(2):175–189.

When comparing dolomite and calcium/magnesium silicate applications at 60% targeted calcium (Ca) base saturation rate at two moisture conditions (with or without water stress), calcium /magnesium silicate reduced soil acidity and supplied Ca and Mg similar to dolomite (**Pulz et al., 2008**). However, an additional benefit is increased plant available silicon (Si) and phosphorus (P). With the added Si from calcium/magnesium silicate, potato (*Solanum tuberosum* L.) plants were taller, stem lodging was reduced, and higher marketable tuber yields were obtained.

Pulz, A.L., C.A.C. Crusciol, L.B. Lemos, and R.P. Soratto. 2008. Silicate and limestone effects on potato nutrition yield and quality under drought stress. R. Bras. Ci. Solo., 32:1651–1659. (In Portuguese with English abstract).

Silicic acid additions to rockwool substrate under greenhouse conditions increased the number of fruits per plant of cherry tomato (*Lycopersicon esculentum* var. cerasiforme cv. 'Salomee') and increased overall yield when compared with conventional fertility without silicon fertilizer additions (**Toresano-Sánchez et al., 2012**).

Toresano-Sánchez, F., A. Valverde-García, & F. Camacho-Ferre. 2012. Effect of the application of silicon hydroxide on yield and quality of cherry tomato. J. Plant Nutr., 35(4):567-590.

Soils and CO_2 Sequestration

Various silicon containing materials were evaluated as to their effects on leaching of four inorganic soil contaminates with concentrations ranging from 10,000 to 12,000 ppm: cadmium-Cd (II), lead-Pb (II) nitrates, sodium arsenite and sodium chromate (**Akhter et al., 1990**). Fly ash was not effective, however when slag was used as a binding agent it performed well in any combination tested. And, several slag mixtures were effective in immobilizing Pb. At comparative application rates, Type I Portland cement was the most effective at immobilizing arsenic (As) and chromium (Cr).

Akhter, H., L.G. Butler, S. Branz, F.K. Cartledge, and M.E. Tittlebaum. 1990. Immobilization of As, Cd, Cr and Pb-containing soils by using cement or pozzolanic fixing agents. J. Hazard. Mater., 24(2):145-155.

Initially, three products (silicate iron slag fertilizer, fly ash, and phosphogypsum) were evaluated to determine which if any was best at reducing methane emissions while sustaining crop production from paddy soils (**Ali et al., 2008, 2009**). Silicate iron slag fertilizer, which contains electron acceptors, was determined to be the best product of the three for reducing methane emissions while maintaining crop productivity. Methane emission rates from rice (*Oryza sativa*, cv. Dongjinbyeo) field flood waters decreased ($p < 0.05$) with increasing silicate fertilizer application rate (0, 1, 2 and 4 Mg ha^{-1}). However, soil redox potential was found to increase methane emission rates. Silicate fertilizer application increased dissolved iron concentrations in percolated water, and soil active and free iron oxides. These iron forms acted as oxidizing agents and electron acceptors, which suppressed methane emissions. Decreases in methane emissions were 16–20% at the highest silicate fertilizer rate with additional benefits seen as grain yield increases (13–18%) and increased plant growth (including root biomass, volume and porosity). The plant beneficial effects were attributed to improved rhizosphere oxygen concentrations, which further reduced methane emissions by enhancing methane oxidation. It was determined that the best product for reducing methane emissions while sustaining rice crop production was the silicate fertilizer.

Ali, M.A., J.H. Oh, and P.J. Kim. 2008. Evaluation of silicate iron slag amendment on reducing methane emission from flood water rice farming. Agricult. Ecosyst. Environ., 128(1):21-26.

Ali, M.A., C.H. Lee, S.Y. Kim, and P.J. Kim. 2009. Effect of industrial by-products containing electron acceptors on mitigating methane emission during rice cultivation. Waste Manage., 29(10):2759-2764.

An invention relating to a three step process for long-term carbon dioxide sequestration which begins by reacting a metal silicate with a caustic alkali metal hydroxide resulting in a carbonate of that metal in step three (**Blencoe et al., 2004**).

Blencoe, J., D. Palmer, L. Anovitz, and J.S. Beard. 2004. Carbonation of metal silicates for long-term CO2 sequestration US Patent # 20040213705 A1 Pub. 28 Oct. 2004.

The main sorption sites of glyphosate in soils are on the surfaces of aluminum and iron oxides, poorly ordered alumino silicates and edges of layered silicates (**Borggaard and Gimsing, 2008**). Soils enriched with these minerals are effective in sorbing glyphosate and reducing its mobility in soils and subsequent leaching into ground water.

Borggaard, O.K., and A.L. Gimsing. 2008. Fate of glyphosate in soil and the possibility of leaching to ground and surface waters: A review. Pest Manage. Sci. 64:441–456.

The effects of Si on Cd and Zn contaminated soil was evaluated using amendments of calcium silicate as the silicon source (**Cunha et al., 2008**). Both Cd and Zn were immobilized in the soil and this was not attributed to a change in soil pH. The distribution of Cd and Zn in soil fractions was altered by silicon. The most bioavailable pools within the soil were decreased with metals allocation to the more stable fractions of organic matter and crystalline iron oxides attributed to the addition of silicon.

Cunha, K.P.V., C.W.A Nascimento, and A.J. Silva. 2008. Silicon alleviates the toxicity of cadmium and zinc for maize (*Zea mays* L.) grown on a contaminated soil. J. Plant Soil Sci. 171:849–853.

A geochemical model for carbon sequestration is presented and the potential for industrial carbon sequestration is proposed based on natural carbon sequestration in soils (**Guthrie et al., 2001**). The formation of carbonate rocks is mainly due to the interaction of aqueous fluids with silicate rocks in soils that are enriched with calcium and magnesium. This occurs naturally in the environment from normal weathering, ground water flow, or hydrothermal activities. Fluid–rock interactions lead to the dissolution, leaching or other mineral alteration reactions of silicates which release alkaline-earth metals. The alkaline-earth metals released from silicates to the aqueous solution then react with dissolved CO_2 forming carbonate precipitates. Thus silicates are involved in the natural conversion of carbon dioxide to more stable and immobile forms in soils.

Guthrie, G.D., J.W. Carey, D. Bergfeld, D. Byler, S. Chipera, H.J. Ziock, and K.S. Lackner. 2001. Geochemical aspects of the carbonation of magnesium silicates in an aqueous medium. pp. 1-14 In NETL Conf. on Carbon Sequestration May 2001.

In nature, the chemical weathering processes of silicate rocks provides a major sink for both soil and atmospheric CO_2 (**Hartmann and Kempe, 2008**). The potential use of finely ground silicate rocks to agricultural and forested soils has been suggested as a means of stimulating CO_2 sequestration. However, whether this method of CO_2 sequestration could be practiced on a global scale, under real conditions, remained unknown. By applying estimates using “normal treatment” amounts a theoretical global maximum potential of 65 x 106 metric tons sequestered C/acre from stimulated weathering was determined if all agricultural and forest lands in the world received homogenous applications of finely ground silicate rocks. Additional emissions from application and the fact that some lands may not be conducive to application using current techniques, limits application on a global scale and therefore may overestimate the overall carbon sequestration by using this method. However, this method of carbon sequestration may prove feasible in some cropping systems and climates and provide a cost effective technique for sequestering atmospheric carbon in some areas of the world, especially if increases in crop production are considered.

Hartmann, J., and S. Kempe. 2008. What is the maximum potential for CO_2 sequestration by “stimulated” weathering on the global scale? Naturwissenschaften, 95(12):1159-1164.

An acid soil experimentally contaminated with Cd by adding 20 or 40 mg/kg was treated with 400 mg/kg Si (**Liang et al., 2005**). The silicon addition increased soil pH while decreasing Cd availability. In the silicon amended soil, Cd adsorbed onto Fe-Mn oxide bound fractions increased. At a much lower rate of 50 mg/kg Si these soil effects were not exhibited. The results attributed tolerance to Cd as being partly attributed to immobilization of Cd in soils along with an increase in soil pH from the silicate addition.

Liang, Y., J.W.C. Wong, and L. Wei. 2005. Silicon-mediated enhancement of cadmium tolerance in maize (*Zea mays* L.) grown in cadmium contaminated soil. Chemosphere, 58(4):475-483.

In a recent review it is stated that intensive crop cultivation over long time periods deplete soils of available silicon (Si), and that this depletion of soil Si could be one of the limiting factors contributing to yield declines (**Meena et al., 2014**). Silicon is depleted in soils from heavy and reoccurring erosion, transport of sediments, plant removal of Si, and normal soil desilification processes. Since the form of soil available for plant uptake is also soluble, leaching losses from soils also occurs. Soils in the tropics and subtropics are soils that are commonly low in available Si which have been shown to benefit from silicon fertility. The soil Si content in some regions may also limit sustainable crop production. Thus, by improving Si management of soils it is likely that increased and sustainable crop yields may be achieved for both temperate and tropical countries. In order to manage agriculturally important soils prudently it is necessary to survey these soils for their Si status. By doing so, we may have a key to curbing declining and stagnating yields and be able to develop region-specific Si nutrient management recommendations.

Meena, V. D., Dotaniya, M. L., Coumar, V., Rajendiran, S., Kundu, S., & Rao, A. S. (2013). A Case for Silicon Fertilization to Improve Crop Yields in Tropical Soils. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 1-14.

The dominant ionic forms of arsenic (As) in soils are determined by soil pH, and the release of arsenic from soils is controlled by soil retention mechanisms (**Mehmood et al., 2009**). Within soils As retention occurs by surface adsorption onto iron and aluminum oxides and hydroxides and by ligand exchange. Silicates also play a role in soil As adsorption by As-Silicate coprecipitation from As adsorption by silicate clays such as kaolinite, illite and montmorillonite.

Mehmood, A., Hayat, R., Wasim, M., & Akhtar, M. S. (2009). Mechanisms of arsenic adsorption in calcareous soils. J. Agric. Biol. Sci, 1:59-65.

A heather species, *Erica andevalensis*, known for growing in acidic, metal enriched soils, was tested for a response to silicon (Si) nutrient solution additions under toxic copper (Cu) levels (**Oliva et al., 2011**). Silicon improved plant growth and reduced the water loss associated with plant death from excess Cu. Leaf Cu concentrations were reduced (up to 32%) while root Cu was increased with Si. Leaf phytoliths consisting of silica deposits were associated with not only Cu, but other plant nutrients such as potassium (K), calcium (Ca), and phosphorus (P). The silicon induced Cu tolerance was determined to be as a result of inhibited Cu transport from roots to shoots. It was also suggested that the Si phytoliths in leaves may have contributed to Cu toxicity tolerance by immobilizing or deactivating Cu.

Oliva, S.R., M.D. Mingorance, and E.O. Leidi. 2011. Effects of silicon on copper toxicity in Erica andevalensis Cabezudo and Rivera: a potential species to remediate contaminated soils. J. Envir. Monitor., 13(3):591-596.

Seven soil amendments were evaluated for their effects on rice growth and metal uptake in pots of copper (Cu) and cadmium (Cd) contaminated soils (**Li et al., 2008**). Limestone increased grain yield 12.5–16.5 fold, and decreased Cu and Cd concentrations in grain by 23.0%–50.4%. The Ca-Mg-P fertilizer, silicon fertilizer, pig manure, and peat increased grain yield 0.3–15.3 fold, and reduced grain Cu and Cd concentrations to below the tolerance limits for foods. However, grain and straw Cu and Cd levels were dependent on soil available Cu and Cd concentrations, and, soil availability of these metals was directly affected by soil pH. The highest rate of limestone had the highest soil pH and lowest soil Cu and Cd levels, while the soils with the lowest pH had the highest Cu and Cd levels. Note: Under the trial design, it appears that pH had more of an effect on Cu and Cd levels than the individual treatments. It may be wise to design the trial so that soil pH is similarly adjusted for all treatments in order to discern the effects of the products on Cd and Cu uptake and soil availability.

LI, P., WANG, X., ZHANG, T., ZHOU, D., & HE, Y. (2008). Effects of several amendments on rice growth and uptake of copper and cadmium from a contaminated soil. Journal of Environmental Sciences, 20(4), 449-455.

The mineral carbonation process involves dissolution of silicates containing MgO- or CaO-(e.g. olivine, serpentine, wollastonite), and subsequent precipitation of carbonates (e.g. magnesite, calcite: **Prigiobbe et al., 2009**). The kinetics of olivine dissolution kinetics and magnesite precipitation were studied. It was concluded that two potential mechanisms exist, direct precipitation of magnesite and concurrent precipitation of magnesite and hydromagnesite. After which the latter converts to the former.

Prigiobbe, V., Hänchen, M., Werner, M., Baciocchi, R., & Mazzotti, M. (2009). Mineral carbonation process for CO_2 sequestration. Energy Procedia, 1(1):4885-4890.

During the heating process of spent shales, wollastonite and fosterite are produced (**Reddy et al., 1989**). These two silicate phases control the calcium (Ca) and magnesium (Mg) concentrations in addition to buffering the pH of spent shale extracts. Calcite controls the recarbonated Ca concentrations, while silicate and carbonate phases control the Mg concentrations.

Reddy, K. J., Hasfurther, V. R., & Drever, J. I. (1989). Application of a geochemical model to the prediction of the chemistry of extracts from non-recarbonated and recarbonated spent shales (No. DOE/MC/11076-2887). Western Res. Inst., Laramie, WY (USA).

The influence of silicic acid additions on extractable zinc (Zn), copper (Cu), potassium (K) and sodium (Na) concentrations were evaluated in a sandy calcareous soil (**Saleh et al., 2013**). Waterlogging decreased Zn and Cu concentrations but increased K, with no effects on Na. Salinity decreased Zn and Cu, but increased K and Na levels. Silicon had no effect on soil extractable Cu, K and Na. However, Zn concentrations decreased. The authors concluded that Zn and Cu fertilizers should be recommended under waterlogged and/or saline soil conditions to reduce the incidence of nutrient deficiencies, and that K over-fertilization could occur in waterlogged soils. They also suggested Zn fertilizers be added with silicon to avoid reductions in extractable Zn. Note: The pH of the soil was not monitored, nor listed, and since this was a calcareous soil it is likely that the pH was already near or above neutral pH. It is also likely that the effects in Zn reductions from silicon applications were due to an additional increase in soil pH following the silicon product application. It is widely known and accepted that Zn and Fe availability are reduced in alkaline soils.

Saleh, J., N. Najafi, S. Oustan, N. Aliasgharzad, and K. Ghassemi-Golezani. 2013. Effects of silicon, salinity and waterlogging on the extractable Zn, Cu, K and Na in a sandy loam soil. Int. J. Agric.: Res. Rev., 3(1):56-64.

When comparing three silicon sources (sodium silicate, calcium silicate and silicic acid) applied to the soil, application of calcium silicate was most effective in increasing wheat plant growth and biomass accumulation (**Sattar et al., 2013**).

Sattar, A., M.A. Cheema, S.M.A. Basra, & A. Wahid. 2013. Optimization of source and rate of soil applied silicon for improving the growth of wheat. Pak. J. Agri. Sci., 50(1):63-68.

The key processes controlling atmospheric CO_2 concentrations are weathering, followed by calcium (Ca) and magnesium (Mg) carbonate precipitation (**Schuiling and Krijgsman, 2006**). In order to enhance weathering and reduce CO_2 levels, olivine or calcium silicates can be reacted in autoclaves with captured CO_2. This technology can be applied on a wider scale by applications of fine-powdered olivine to farm and forest lands. It is suggested that adoption of this strategy for CO_2 sequestration requires the method to also serve a broader economic goal.

Schuiling, R. D., & Krijgsman, P. (2006). Enhanced weathering: an effective and cheap tool to sequester CO_2. Climatic Change, 74(1-3):349-354.

The potential to reduce CO_2 emissions from the pulp and paper industry by substituting calcium silicate for mined, crushed calcium carbonate was investigated (**Teir et al., 2005**). It was suggested that this substitution could completely eliminate CO_2 emissions from carbonate calcination and that the estimated amount of reduction in Finland would amount to 200 kt of carbon dioxide emissions/year. A preliminary investigation of the feasibility to produce precipitated calcium carbonate (PCC) from calcium silicates and the potential to replace calcium carbonate as the raw material was made. A method of replacing the current PCC with manufactured silicates was evaluated using modeling software. The results suggested that acetic acid could be used to extract calcium ions and provide the potential for mineral carbonation and sequestration of CO_2. The limited availability and relatively high price of Wollastonite, a mined calcium silicate material, presents an obstacle for use of this method. It was suggested that a more common alternative, basalt rock, could be used instead.

Teir, S., Eloneva, S., & Zevenhoven, R. (2005). Production of precipitated calcium carbonate from calcium silicates and carbon dioxide. Ener. Conver. Manage., 46(18):2954-2979.

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Sunflower: *Helianthus*

The effect of silicon soil amendments on drought stress of 12 sunflower (*Helianthus annuus* L.) cultivars was investigated (**Gunes et al., 2008a**). Silicon alleviated the deleterious drought effects for 6 out of 12 cultivars. Increased stomatal resistance, membrane damage, H_2O_2, proline, lipid peroxidation, superoxide dismutase and ascorbate peroxidase. Decreased relative leaf water content and catalase activity attributed to drought stress were reversed by silicon. Non-enzymatic antioxidant activity was also increased by silicon during drought stress. It was concluded that alleviation of sunflower drought stress by silicon is due to prevention of membrane damage. However, genotypic variations in sunflower cultivars affected their response to silicon fertility.

Gunes, A., D.J. Pilbeam, A. Inal, and S. Coban. 2008a. Influence of silicon on sunflower cultivars under drought stress, I: growth, antioxidant mechanisms, and lipid peroxidation. Commun. Soil Sci. Plant Anal., 39(13-14):1885-1903

Silicon soil amendments were evaluated for their effects on essential and nonessential nutrient uptake of 12 sunflower (*Helianthus annuus* L.) cultivars under drought stress. Under drought conditions, sunflower mineral uptake was reduced regardless of cultivar (**Gunes et al., 2008b**). However, silicon (Si) was shown to improve uptake of Si, potassium (K), sulfur (S), magnesium (Mg), iron (Fe), copper (Cu), manganese (Mn), sodium (Na), chloride (Cl), vanadium (V), aluminum (Al), strontium (Sr), rubidium (Rb), titanium (Ti), and chromium (Cr) under drought stress, but zinc (Zn), molybdenum (Mo), nickel (Ni), and bromide (Br) uptake was unaffected.

Gunes, A. Y.K. Kadioglu, D.J. Pilbeam, A. Inal, S. Coban, & A. Aksu. 2008b. Influence of Silicon on Sunflower Cultivars under Drought Stress, II: Essential and Nonessential Element Uptake determined by Polarized Energy Dispersive X-ray Fluorescence. Commun. Soil Sci. Plant Anal., 39(13-14):1904-1927.

Silicon and Biotic Stress

Beans, Peas-Legumes: (*Fabaceae*)

Silicon applied at a rate 0f 0-1.7 mM Si showed no enhanced silicon uptake or disease resistance in a susceptible soybean (*Glycine max* L. Merr.), cultivar (**Arsenault-Labrecque et al., 2011)**. However, the cultivar with elevated tissue silicon levels following silicon supplements displayed the highest level of resistance to soybean rust (*Phakopsora pachyrizi*, causal agent). There is therefore a potential for Integrated Pest Management (IPM) use of silicon in rust control programs.

Arsenault-Labrecque, G., J. Montpetit, W. Rémus-Borel, and R.R. Bélanger. 2011. Effect of silicon amendment on the enhancement of soybean resistance to *Phakopsora pachyrhizi*. Phytopathol., 101(6):S257.

Acibenzolar-S-methyl (ASM), jasmonic acid (JA), potassium silicate (PS) and calcium silicate were evaluated for their effects on Asian soybean rust, causal agent *Phakopsora pachyrhizian*, resistance (**Cruz et al., 2014**). ASM, JA and PS were applied as foliar sprays while calcium silicate was applied as a soil amendment. The time from inoculation until symptom development was extended for soybean, (*Glycine max* L. Merr.), plants amended with calcium silicate and those receiving ASM sprays. PS sprays resulted in fewer uredia per cm^2 leaf area. ASM and PS were the most effective in reducing rust symptoms while JA increased susceptibility to rust.

Cruz, M.F.A., F.Á. Rodrigues, A.P.C. Diniz, M. Alves Moreira, and E.G. Barros. 2014. Soybean resistance to *Phakopsora pachyrhizi* as affected by Acibenzolar-S-Methyl, jasmonic acid and silicon. J. Phytopathol., 162(2):133-136.

Further studies compared the effects of jasmonic acid (JA), Acibenzolar-S-Methyl (ASM) and calcium silicate, on induction of defense enzymes when soybean, *Glycine max* [(L.) Merr.] was challenged with Asian soybean rust, causal agent *Phakopsora pachyrhizian* (**Cruz et al., 2013**). Rust severity was reduced when plants were either sprayed with ASM or supplied with calcium silicate as a soil amendment. This was not seen with JA sprays. Chitinase activity was affected by ASM 72 hours after inoculation, at 24 and 72 for JA, and at 141 hours for calcium silicate. Effects on β-1,3-glucanase activity were seen 72 hours after inoculation while Phenylalanine ammonia-lyase activity was affected at 72 and 141 hours with ASM sprays. It was concluded that rust symptoms are milder when plants are either sprayed with ASM or soil supplied with calcium silicate, and that these reductions likely involve effects on defense enzymes.

Cruz, M.F.A.D., F. Á. Rodrigues, E.R. Polanco, C.R.D.S. Curvêlo, K.J.T. Nascimento, M.A. Moreira, and E.G. Barros. 2013. Inducers of resistance and silicon on the activity of defense enzymes in the soybean-*Phakopsora pachyrhizi* interaction. Bragantia, (AHEAD), 0-0.

Pea seedlings grown for five weeks in silicate fertilizer amended medium had increased foliar silicon content, increased chitinase and glucanase activity (Pathogenesis-related (PR) proteins), and fewer fungal leaf spot (*Mycosphaerella pinodes*) lesions (**Dann and Muir, 2002**). Suggesting that silicon supplements to growth media increases pea plant silicon accumulation and induces early activation of host defenses increasing fungal pathogen resistance.

Dann, E.K., and S. Muir. 2002. Peas grown in media with elevated plant-available silicon levels have higher activities of chitinase and ß-1,3-glucanase, are less susceptible to a fungal leaf spot pathogen and accumulate more foliar silicon. Australasian Plant Pathol., 31:9–13.

Foliar application of potassium silicate (KSi), pH 5.5 or 10.5, to soybeans (*Glycine max* L. Merr. cv. MG/BR-46 Conquest) did not result in increased leaf Si or K concentrations but did reduce rust disease (*Phakopsora Euvitis pachyrhizi* Syd. & P. Syd.,) regardless of solution pH (**Pereira et al., 2009**). Reductions in rust severity with KSi, pH 5.5, foliar application did not differ from fungicide (acibenzolar-S-methyl) treatment which reduced rust disease by 65%. Although rust disease was controlled with either KSi or fungicide, neither was shown to activate plant disease defense enzymes suggesting a different mode of action.

Pereira, S.C., F.A. Rodrigues, V. Carré-Missio, M.G.A. Oliveira, and L. Zambolim. 2009. Effect of foliar application of silicon on soybean resistance against soybean rust and on the activity of defense enzymes. Trop. Plant Pathol. 34(3):164–170.

Foliar sprays of potassium silicate (KSi), sodium molybdate (NaMo), singly or in combination, with or without azoxystrobin fungicide, were evaluated for their effects in reducing Anthracnose, causal agent *Colletotrichum lindemuthianum*, symptoms of common bean (*Phaseolus vulgaris* L.) while increasing yield (**Polanco et al., 2014**). Mean area under the disease progress curve reductions of 63% for the fungicide, 29% for KSi, 14% for NaMo, and 41% for KSi + NaMo sprays were recorded. This resulted in yield increases of 150% for the fungicide, 13% for KSi, 20% for NaMo, and 47% for KSi + NaMo. It was suggested that foliar sprays of KSi with NaMo could be used to reduce bean anthracnose symptoms and consequently increase yields.

Polanco, L. R., Rodrigues, F.A., Moreira, E.N., Duarte, H.S.S., Cacique, I.S., Valente, L.A., Vieira, R.F., Paula Junior, T.J, and Vale, F.X.R. 2014. Management of anthracnose in common bean by foliar sprays of potassium silicate, sodium molybdate, and fungicide. Plant Dis., 98(1):84-89.

Foliar sprays of KSi in the greenhouse, KSi or KOH (at different pH rates) vs. fungicide spray (epoxiconazole + pyraclostrobin), in the field were evaluated for rust (*Phakopsora pachyrhizi*) disease control when applied pre-inoculation to soybean (*Glycine max* L. Merrill) plants (**Rodrigues et al., 2009**). KSi application rates did not correlate with leaf tissue Si levels but increased leaf concentrations by 67% to 73% when compared to the controls. Rust severity was reduced 70% at the KSi (pH 5.5) application rate. Fungicide, KOH and KSi (pH 5.5) were all effective in reducing rust disease. KSi pH 10.50 and 5.5 reduced rust severity 36% and 43%, respectively. KSi and KOH treatments, regardless of pH, were similar in their disease suppressive effects and both were similar to fungicide. Both field and greenhouse experiments showed reductions in rust intensity with foliar Si applications.

Rodrigues, F.A., H.S.S. Duarte, G.P. Domiciano, C.A. Souza, G.H. Korndörfer, and L. Zambolim. 2009. Foliar application of potassium silicate reduces the intensity of soybean rust. Australasian Plant Pathol., 38:366–372.

Aphanomyces root rot of green beans (*Phaseolus vulgaris* L.) causes browning of roots and stems and can even result in plant death (**Watson, 2013**). The fungal pathogen is soil borne. Potassium silicate reduced disease severity of hypocotyls when used as a potting mix soil drench at 6, 9 and 12% application rates. But the highest rate resulted in some root distortion. These results, however were not seen in the field, but may have been due to the low application rate applied during the field trials or the leaching of material through the profile requiring multiple applications.

Watson, A. 2013. Development of methods to monitor and control Aphanomyces root rot and black root rot of beans. New South Wales Department of Primary Industries. Project # VG08043. Horticulture Australia Ltd. Sydney Australia.

Beet (*Beta vulgaris* L.)

Burned or ground rice straw or husk as silica soil amendments reduced cotton leaf worm (*Spodoptera littoralis* Boisd.) populations and increased leaf silicon content of sugar beets while increasing sugar content and root weight (**Shalaby, 2011**). Plant sprays of magnesium silicate or sodium silicate reduced cotton leaf worm populations and increased leaf silicon content, sugar content, and root yield.

Shalaby, G. 2011. Utilization of silica to suppress populations of the cotton leafworm, *Spodoptera littoralis* Boisd. on sugar beet. J. Agric. Res. Kafer El-Sheikh Univ., 37(4):668–678.

Coffee (*Coffea arabica*)

The effect of silicon on brown eye spot (fungal pathogen *Cercospora coffeicola*) intensity (post inoculation) and mineral nutrition of coffee seedlings (*Coffea arabica* cv. *Catuaí Vermelho* IAC 99) was tested using 6 rates of silicic acid (0, 0.5, 1, 2, 4 and 6 g kg-1 soil), and X-ray microanalysis of two cultivars (C. Arabica cv. Topazio MG1190 and *Icatu Precoce* IAC 3282), treated or untreated with calcium silicate (1 g kg-1 of soil) and inoculated or uninoculated with C. coffeicola (**Botelho et al., 2011**). Reductions in disease severity were seen with increasing silicic acid rates. Foliar concentrations of Mg and P were decreased in a linear fashion while S and Cu were increased. Boron content showed a quadratic correlation, decreasing with increasing silicic acid but increasing at the 4 g kg-1 soil rate. X-ray microanalysis showed inoculated coffee seedlings to have reduced levels of K and Ca regardless of cultivar.

Botelho, D.M.S., E.A. Pozza, E. Alves, C.E. Botelho, A.A.A. Pozza, P.M. Ribeiro Júnior, and P.E. de Souza. 2011. Effect of silicon on the intensity of brown eye spot and on the mineral nutrition of coffee seedlings. Arq. Inst. Biol., São Paulo. 78(1):23–29 (in Portuguese with English Abstract).

Foliar sprays of potassium silicate was compared with water on coffee leaf rust infection, causal agent *Hemileia vastatrix* (**Carré-Misso et al., 2014**). No difference in leaf Si content was observed, however, increased surface deposition of Si was documented and potassium silicate polymerized on the leaf surface. Rust severity was reduced 12% at 36 days after inoculation with the silicate sprays when compared to the water controls. At this time uredia numbers on the leaf surface and leaf fungal colonization was also reduced with the potassium silicate sprays. It was suggested that the effects of foliar sprays of potassium silicate on coffee leaf rust were due to the physical role from potassium silicate surface polymerization and/or its osmotic effect in preventing urediniospore germination.

Carre-Missio, V., Rodrigues, F. A., Schurt, D. A., Resende, R. S., Souza, N. F. A., Rezende, D. C., Moreira, W.R. and Zambolim, L. (2014). Effect of foliar-applied potassium silicate on coffee leaf infection by *Hemileia vastatrix*. Annals Appl. Biol., 164(3):396-403.

Silicon increases coffee plant resistance to root knot nematodes by decreasing their reproductive capacity (**Silva et al., 2009, 2010; Hasty 2010**). Susceptible (cv. Catuaí 44) and resistant (cv. IAPAR 59) coffee (*Coffea arabica*) cultivars to root knot nematode *Meloidogyne exigua*, grown in pots of Si-deficient soil amended with either calcium silicate or calcium carbonate showed increased (152% Catuai 44 & 100% IAPAR 59), in root tissue silicon content silicate vs. carbonate with no difference in calcium. The susceptible cultivar with silicate had reductions in # galls and # eggs, 16.8% and 28.1%, respectively, 150 days after inoculation. Biochemical assays at 5 and 10 days after inoculation showed lignin-thioglycolic acid derivatives to increase 11.5% in susceptible plant roots with silicate. At 10 days, silicate caused increases in root peroxidase activity 39.9% and 31.3% polyphenoloxidase 54.9% and 56.1%, and phenylalanine ammonia lyase activity 26.6% and 62.9% for the susceptible and resistant cultivars, respectively.

Silva, R. V., R.D.L. Oliveira, K.J.T. Nascimento, and F.A. Rodrigues. 2009. XXVIII Congresso Brasileiro de Nematologia | II Congresso Internacional de Nematologia Tropical Nematologia Brasileira Piracicaba (SP) Brasil, 33(4):324.

Silva, R. V., R.D.L. Oliveira, K.J.T. Nascimento, and F.A. Rodrigues. 2010. Biochemical responses of coffee resistance against *Meloidogyne exigua* mediated by silicon.

Plant Pathol., 59(3):586-593.

Hasty, S.E. NewsRx™, Silicon: Researchers at Federal University target silicon. Life Sci. Weekly, 8 June 2010.

Silicon soil supplements to coffee (*Coffea Arabica*) increase root silicon uptake (up to 1% dry root concentrations), increase plant growth and development, mediate resistance in controlling root knot nematodes by enhancing biochemical mechanisms of defense (**Silva, 2009**). Silicon also increased plant nutrient uptake of roots and shoots.

Silva, R.V. 2009. Resistance of the coffee plant to *Meloidogyne exigua*: mechanisms of genetic nature and silicon potencialization. Doctoral dissertation. Universidade Federal de Viçosa, Brazil.

Cotton (*Gossypium hirsutum* L.)

Calcium silicate as a pre-plant soil amendment was evaluated for its effect on cotton bacterial blight control and on plant resistance (**Oliveira, 2010**). No effect was seen on incubation period, disease incidence or bacterial growth inhibition, but at a rate of 1.5 g SiO_2/kg soil, disease severity was reduced 54.9% along with a 35.76% reduction in AUDPC (area under the disease progress curve). An increase in plant height was also documented. Although no increase was seen in leaf silicon content, plants supplied with silicon showed altered levels of soluble proteins, H_2O_2 , and enzyme activity (SOD, APX, Guaiacol peroxidase, PAL, and β Glu at the higher application rate of 1.80 g/kg. It was suggested that the reductions bacterial blight of cotton, mediated by silicon, were likely due to the observed induced resistance.

Oliveira, J. C. 2010 Caracterizaçào de isolados de *Xanthomonas citri* susp. malvacearum e reduçào da mancha-angular do algodoeiro mediada pelo silicĺo. Doctoral Dissertation. Universidade Federak Rural de Pernambuco (in Portuguese with English abstract).

A calcium silicate soil amendment rate of 1.50 g SiO2/kg soil prior to cotton (*Gossypium hirsutum* L.) planting resulted in reduced angular leaf spot disease severity (54.9%) and increased plant height (7%; **Oliveira et al., 2012**). At the 1.80 g/kg rate, antioxidant production was increased and disease was reduced suggesting induced resistance of cotton to angular leaf spot disease with silicon soil amendments.

Oliveira, J.C., G.M.R. Albuquerque, R.L.R. Mariana, D.M.F. Gondim, J.T.A. Oliveira, and E.B. Souza. 2012. Reduction of the severity of angular leaf spot of cotton mediated by silicon. J. Plant Pathol., 94(2):297–304.

Silicon and Bion® (a plant activator seed soak from Syngenta: acibenzolar-S-methyl) treatments, both alone and in combination as part of integrated disease management programs may potentially contribute to increased protection against *Fusarium oxysporum* f. sp. *vasinfectum* by priming defense responses of infected cotton (*Gossypium hirsutum* L.; **Whan 2009**).

Whan, J. 2009. Silicon and acibensolar-S-Methyl induced defense responses in cotton (*Gossypium hirsutum* L.) infected with *Fusarium oxysporum* f. sp. *vasinfetum*. Ph.D. Dissertation, 223 pp. School of Biological Sciences, University of Queensland, Queensland, Australia.

Cucumber, Melon, Squash (*Cucurbitaceae*)

Powdery mildew of cucumber (*Sphaerotheca fuliginea*) was suppressed with silicon nutrient supplements and lower leaf silicon concentrations correlated with higher disease outbreak on leaves (**Adatia and Besford 1986**).

Adatia, M.H. and R.T. Besford. 1986. The effects of silicon on cucumber plants grown in recirculating nutrient solution. Annals Bot., 58:343–351.

For powdery mildew (*Sphaerotheca fuliginea*, *Erysiphe cichoracearum*) control of cucumber cultural recommendations include amending hydroponic nutrient solutions with 100 ppm soluble silicon as potassium silicate to aide in disease control (**Alberta Agriculture, 2007**). 50 ppm is recommended for disease tolerant cultivars.

Alberta Agriculture. 2007. Diseases of greenhouse crops. Chap 4 pp. 30, R. Spencer, chair. In M. Desjardins and N. Deol, (eds.). Guidelines for the Control of Plant Diseases in Western Canada. The Western Committee on Plant Disease.

Applications of sodium silicate at a rate of 100mM was more effective in inhibiting mycelia growth and controlling diseases of Hami melons (*Cucumis melo* L. var. *inodorus Jacq*.) caused by *Alternaria alternata*, *Fusarium semitectum*, and *Trichothecium roseum* than lower rates (25 or 50 mM: **Bi et al., 2006**). Pre-inoculation treatments were more effective than post-inoculation resulting in lower decay incidence and disease severity. Silicon induced resistance was documented as activation of two defense-related enzymes peroxidase and chitinase.

Bi, Y., S.P. Tian, Y.R. Guo, Y.H. Ge, and G.Z. Qin. 2006. Sodium silicate reduces postharvest decay on Hami melons: Induced resistance and fungistatic effects. Plant Dis. 90:279–283.

Leaf sprays of benzothiadiazole, salicylic acid and nanometer silicon (SiO_2) to two different melon cultivars (Yindi and Kalakesai), differing in their susceptibility to powdery mildew (causal agent *Sphaerotheca fuliginea*), were applied five days prior to inoculation and evaluated for their effects on hydroxyproline-rich glycoprotein (HRGP), disease indexes and lignin content of melon seedling leaves (**Chen et al., 2010**). Effects on reduction of disease indexes with the SiO_2 sprays were only seen in the initial days following treatment, while the other sprays (especially benzothiadiazole on the resistant cultivar) continued to be effective throughout the 8 day evaluation period. Lignin and HRGP content of leaves were increased by the other two treatments and from fungal inoculation, but no effect from SiO_2 was seen. Lignin and HRGP content was higher for the resistant cultivar regardless of treatment and appears to be important resistance mechanisms for melon seedlings when challenged with *Sphaerotheca fuliginea*. Note: Although silicon soil applications have been shown to be more effective than foliar sprays, these results confirm that the effects of silicon are different that those seen from fungicidal sprays. And, a delay in disease onset from silicon appears to be a recurring them.

Chen, N.L., Hu, M., Qiao, C.P., Nai, X.Y., and Wang, R. (2010). Effects of BTH, SA, and SiO_2 Treatment on Disease Resistance and Leaf HRGP and Lignin Contents of Melon Seedlings. Scientia Agricultura Sinica, 43(3):535-541.

Potassium silicate additions of 100 or 200 ppm to a recirculating nutrient solution reduced cucumber (*Cucumis sativus* L.) root decay, plant mortality and yield loss associated with *Pythium ultimum* infection (**Chérif and Bélanger, 1992**). Inoculated plants treated with potassium silicate showed increases in root weight and fruit number and quality of fruit, although silicon was not shown to increase yields in the absence of disease.

Chérif, M. and R.R. Bélanger. 1992. Use of potassium silicate amendments in recirculating nutrient solutions to suppress *Pythium ultimum* on Long English Cucumber. Plant Dis., 76(10):1008–1011.

Applications of 100 ppm Si using Kasil no. 6 (23.6% SiO_2) to recirculating hydroponic nutrient solutions reduced plant mortality and disease symptoms and increased overall yields, marketable yields, and plant dry weights of *Pythium aphanidermatum* Edson., infected Long English cucumber (*Cucumis sativus* L. cv. Corona: (**Chérif et al., 1992a**). However, yields were not increased under non-disease conditions.

Chérif, M, N. Benhamou, J.G. Menzies, and R.R. Bélanger. 1992a. Silicon induced resistance in cucumber plants against *Pythium ultimum*. Physiol. Molec. Plant Pathol., 41:411–425.

After nutrient solution amendments of 100 ppm potassium silicate to cucumber (*Cucumis sativus* L.) plants, deposition and polymerization of silicon occurred in cells surrounding trichome hairs, wounded leaves and hypocotyls however, silicon accumulation was not associated with the formation of physical or mechanical barriers to fungal growth and penetration (**Chérif et al., 1992b**).

Chérif, M., J.G. Menzies, N. Benhamou, and R.R. Bélanger. 1992b. Studies of silicon distribution in wounded and *Pythium ultimum* infected cucumber plants. Physiol. Molec. Plant Pathol., 41:371–385.

Suppression of Pythium (*Pythium ultimum*) root disease of cucumber (*Cucumis sativus* L.) has been attributed to a heightened and more rapid response following silicon nutrient solution amendments (**Chérif et al., 1994a**).

Chérif, M., A. Asselin, and R.R. Bélanger. 1994a. Defense responses induced by soluble silicon in cucumber roots infected by Pythium spp. Phytopathol., 84(3):236–242.

Additions of 100 ppm potassium silicate to recirculating solution reduced cucumber (*Cucumis sativus* L.) plant mortality associated with *Pythium aphanidermatum* infection, while increasing yield, marketable fruit yields and plant weight at two sites in Canada (**Chérif et al., 1994b**).

Chérif, M, J.G. Menzies, D L. Ehret, C. Bogdanoff, and R.R. Belanger. 1994b. Yield of cucumber infected with *Pythium aphanidermatum* when grown with soluble silicon. HortSci., 29(8):896–897.

Conclusive evidence of silicon's enhancement of fungal activity in infected cucumber (*Cucumis sativus* L.) leaves (**Fawe et al., 1998**). And that silicon plays an active role in increased resistance of cucumber plants to powdery mildew. This shows that silicon's role in resistance is not strictly passive acting as a mechanical barrier. The low weight fungal metabolite (phytoalexin) was identified as aglycone rhamnetin which is used in chemical defense. This is the first report of such a chemical in the plant kingdom and as a flavonol phytoalexin in cucumbers.

Fawe, A., M. Abou-Zaid, J.G. Menzies, W. Jeblick, and R.R. Bélanger. 1998. Silicon-mediated accumulation of flavonoid phytoalexins in cucumber. Phytopathol., 88:396–401.

Calcium silicate when used as a liming agent for soil pH correction has the potential to suppress powdery mildew *Podosphaera* (sect. *Sphaerotheca*) *xanrhii* (Castagne) U. Braun & N. Shishkoff on pumpkin (*Cucurbita pepo* L. cv. *Howden*) and increase pumpkin yields without increasing production costs (**Heckman et al., 2003**). Pumpkin yields were increased 60% and foliage senescence was delayed in the year of calcium silicate application, with no residual effects on yields seen in year two. However, powdery mildew incidence was reduced by 10% with calcium silicate alone, and a synergistic effect of fungicide and calcium silicate in powdery mildew suppression was seen. Plant leaf tissue silicon uptake was increased fivefold with calcium silicate and similar effects on soil pH were seen when compared with a calcium carbonate control.

Heckman, J.R., S. Johnston, and W. Cowgill. 2003. Pumpkin yield and disease response to amending soil with silicon. HortSci., 38(4):552–554

Silicon soil supplements to field grown pumpkins showed increased yields, delayed onset of powdery mildew disease, later season leaf retention and reductions in powdery mildew disease and near double increases in pumpkin leaf tissue silicon levels (**Heckman, 2005**).

Heckman, J. 2005. An introduction to silicon nutrition of soils and crops with a focus on Cucurbits. The Natural Farmer. Summer Issue pp. 27–29.

Bitter gourd (*Mormodica charantia*) resistance to *Pythium aphanidermatum* root rot is stimulated by a continuous supply (before and after inoculation) of silicon to the whole root system (**Heine, 2005; Heine et al., 2007**). The beneficial effects of silicon on disease suppression are linked to the symplastic pathway (through cellular membranes and living cells) rather than the apoplastic pathway (through cell walls and intercellular spaces.

Heine, G. 2005. Silicon nutrition and resistance against *Pythium aphanidermatum* of *Lycopersicon esculentum* and *Mormodica charantia*. Doctoral Dissertation. Univ. Hannover. Hannover, Germany.

Heine, G. G. Tikum, and W.J. Horst. 2007 The effect of silicon on the infection by and spread of *Pythium aphanidermatum* in single roots of tomato and bitter gourd. J. Exper. Bot., 58(3):569–577.

Root applications of silicon to Cucumber (*Cucumis sativus* L.) suppressed powdery mildew disease (*Podosphaera xanthii* syn. *Sphaerotheca fuliginea*), enhanced the activities of pathogenesis-related proteins (PRs), eg. peroxidase, polyphenoloxidase and chitinase and decreased the activity of phenylalanine ammonia-lyase in inoculated leaves (**Liang et al., 2005**). Foliar-applied Si however, had no effects either on disease suppression, subsequent infection or PRs activity.

Liang, Y.C., W.C. Sun, J. Si, and V. Römheld. 2005. Effects of foliar- and root-applied silicon on the enhancement of induced resistance to powdery mildew in *Cucumis sativus*. Plant Pathol., 54:678–685.

Sodium silicate and silicon dioxide supplements to dipping solutions resulted in reductions in Fusarium root rot (*Fusarium* spp.) infection rate of Chinese cantaloupe (*Cucumis melo* L. cv. Yujinxiang) postharvest (**Liu et al., 2009b**). The mechanisms of rot inhibition however, differed by silicon source. Sodium silicate, but not silicon dioxide, suppressed pathogen mycelia growth, radially, and this suppressive effect increased with increasing silicon concentration rate with complete inhibition of pathogen growth at 100 mM/L. At 24 hours after application of sodium silicate and 72 hours after inoculation, peroxidase activity was increased. However, both applications resulted in smoother surfaces and higher epidermal silicon concentrations of melons. Silicon concentrations were highest at the stomata and at the junction between the exo- and mesocarp. This would suggest that silicon shows promise as a preservative ingredient for melon fruits due to its fungistatic properties.

Liu, L., Y. Guo, Y. Bi, M. Li, J. Zhao, and H. Zhao. 2009b. Inhabited mechanisms of silicon compounds against Fusarium rot (*Fusarium* spp.) of postharvest Chinese cantaloupe. J. Food Process. Preserv., 33:187–202.

Cucumber (*Cucumis sativus* L.) leaves inoculated with powdery mildew (*Sphaerotheca fuliginea*) had reduced disease colony numbers, reduced area of colonization per leaf, reduced conidia germination and reduced individual colony size with increasing silicon levels (**Menzies et al., 1991a**).

Menzies, J. G., D.L. Ehret, A.D.M. Glass, T. Helmer, C. Koch, and F. Seywerd 1991a. Effects of soluble silicon on the parasitic fitness of *Sphaerotheca fuliginea* on *Cucumis sativus*. Phytopathol., 81(1):84–88.

Potassium silicate added to cucumber nutrient solution resulted in reduced time from infection initiation to phenolic production and/or accumulation in cucumber epidermal cells following *Sphaerotheca fuliginea* inoculation (**Menzies et al., 1991b**). The number of cells producing and/or accumulating phenolics increased while the number of haustoria/colony was reduced over time and conidiophore development was delayed at the highest silicon supplement rate (2.3 mm).

Menzies, J.G., D.L. Ehret, A.D.M. Glass, and A.L. Samuels. 1991b. The influence of silicon on cytological interactions between *Sphaerotheca fuliginea* and *Cucumis sativus*. Physiol. Mol. Plant Pathol., 39:403–414.

Potassium silicate supplied as either a supplement to nutrient solution or as a foliar spray to cucumber (*Cucumis sativus* L.), muskmelon (*Cucumis melo* L.), and zucchini squash (*Cucurbita pepo* L.) leaves inoculated with powdery mildew *Sphaerotheca fuliginea* (Schlecht: Fr.) Poll., cucumber and muskmelon, or Erysiphe cichoracearum DC: Merat, zucchini squash resulted in reductions in powdery mildew leaf colonies (**Menzies et al., 1992**). Silicon, rather than potassium was having the effect according to further studies. It was recommended that silicon be applied in advance of inoculation, 7 days prior was recommended for the best disease suppression effects.

Menzies, J., P. Bowen, D. Ehret, and A.D.M. Glass. 1992. Foliar applications of potassium silicate reduce severity of powdery mildew on cucumber, muskmelon, and zucchini squash. J. Amer. Soc. Hort. Sci., 117(6):902–905.

Root rot of cucumber (*Cucumis sativus*); causal agent *Phytophthora melonis*, on greenhouse grown cultivars ('Dominus' & 'Super Dominus') receiving sodium silicate at rates of (0.0, 1.0, and 1.7 mM Si) showed either silicon at either concentration to reduce disease severity and improve growth (**Mohaghegh et al., 2011**). Silicon concentrations positively correlated with root catalase and ascorbate peroxidase activities increasing resistance to disease induced oxidative stress.

Mohaghegh, P., A.H. Khoshgoftarmanesh, M. Shirvani, B. Sharifnabi, and N. Nili. 2011. Effect of silicon nutrition on oxidative stress induced by *Phytophthora melonis* infection in cucumber. Plant Dis., 95(4):455–460.

Silicon application as sodium metasilicate was applied in various concentrations to either or leaves or roots and to both in order to evaluate silicon's its effects in reducing root-knot nematodes (*Meloidogyne incognita*: (**Pedroche, 2012**). Reductions in M. incognita and alleviation of damage to cucumber plants were exhibited for cucumber but not for carrot, celery and tomato, where only a slight reduction in nematode numbers were seen and yields were generally not increased. It was concluded that the benefits from supplemental silicon to cucumbers in reducing nematode numbers and enhancing yield warranted further research. Note: This would seem to suggest that the effects from silicon were not fungicidal, but rather an indirect effect from plant uptake.

Pedroche, N., 2012. Incidence, damage potential and management of the root-knot nematode *Meloidogyne incognita* on semi-temperate vegetables in the Highlands of Benguet Province, Philippines. Doctoral Dissertation. Katholieke Universiteit Leuven, Belgium.

Cucumber (*Cucumis sativis* L.) plants grown hydroponically without silicon but later supplied with silicon showed rapid silicification of leaves with silicon deposited mainly at the base of trichomes (**Samuels et al., 1991a**). Resistance to powdery mildew disease, causal agent, [*Sphaerotheca fuliginea* (Schlecht. Fr.) Poll.], was enhanced with silicon deposits localized to the leaf epidermis in areas surrounding the invading pathogen. When silicon was supplied and then removed during growth, silicon deposits remained in trichome base tissue but did not exhibit disease resistance or silicification of host tissue surrounding the invading pathogen.

Samuels, A.L., A.D.M. Glass, D.L. Ehret, and J.G. Menzies. 1991a. Mobility and deposition of silicon in cucumber plants. Plant Cell Environ., 14:485–492.

Silicon concentration in cucumber (*Cucumis sativus* L.) leaves receiving silicon supplements is mainly concentrated in cells surrounding the base of trichome hairs (**Samuels et al., 1991b**). When infected with powdery mildew [*Sphaerotheca fuliginea* (Schlecht. Fr.) Poll.], cell wall areas adjacent to hyphal germination had high silicon concentrations and morphological surface changes. Hyphal length per colony was reduced with silicon supplements. At early infections stages high silicon concentrations around colonies resulted in reduced fungal growth.

Samuels, A.L., A.D.M. Glass, D.L. Ehret, and J.G. Menzies. 1991b. Distribution of silicon in cucumber leaves during infection by powdery mildew fungus (*Sphaerotheca fuliginea*). Can. J. Bot., 69:140–146.

Soluble silicon concentration, frequency of application and runoff after foliar application was evaluated for its effects on powdery mildew, causal agent *Podosphaera xanthii*, of zucchini (*Cucurbita pepo* L.: **Tesfagiorgis and Laing, 2011**). Reductions in powdery mildew severity were attributed to the foliar sprays with efficacy improved with increasing frequency of application. The best results were with frequent spray application along with runoff to the root zone. The leaf disease inhibition was attributed to direct contact of pathogen and spray while the runoff and subsequent plant uptake from the soil contributed to plant health.

Tesfagiorgis, H.B., and M.D. Laing. 2011. Effects of concentration, frequency of application and runoff of foliar-applied soluble silicon on powdery mildew of zucchini. African J. Agric. Res., 6(10):2243-2248.

Applications of biological control agents with potassium silicate (KSi) sprays were evaluated for their effects in reducing powdery mildew disease, causal agent, *Podosphaera xanthii* (Castagne) of zucchini (*Cucurbita pepo*, F1-Hybrid Partenon), due to environmental concerns with the use of fungicides and continued fungicide resistance development (**Tesfagiorgis, 2008**). Two adjuvants (Break-Thru® (BK), Partner® (PR) were shown to improve the efficacy of silicon sprays. Silicon sprays reduced powdery mildew severity on zucchini regardless of silicon concentration with the best results achieved with more frequent spray applications and when spray runoff was permitted to reach plant roots. Spray applications to leaves resulted in pathogen mycelial death. Adsorption of runoff by roots resulted in increased health of plants. Biological control agents worked well in reducing the severity and development of powdery mildew under greenhouse conditions, regardless of silicon application. Silicon reduced AUDPC, disease severity and final disease level while improving the efficacy of most of the biological control agents. Under high disease pressure, the efficacy of Si was reduced. When these trials were transferred to the field, silicon alone was the most effective in reducing disease. In re-circulating nutrient solutions supplied with KSi, positive correlations between solution Si concentrations and zucchini leaf and root Si concentrations were seen. Zucchini roots accumulated higher levels of Si than the shoots. However, reductions in calcium uptake were associated with increased Si uptake. At nutrient solution additions of 50 mg/L zucchini plant growth increased along with phosphorus, calcium and magnesium uptake. Higher application levels to zucchini did not result in any additional biomass increase. Zucchini fruit nutrient content and fruit characteristics were unaffected by solution Si content. Under disease stress zucchini plants accumulated higher levels of Si and Ca, but less P, in their leaves. Silicon in leaves was concentrated around infection areas and at the bases of trichomes. The recommended rate for the best control of powdery mildew disease for zucchini was determined to be 50-150 mg/L. The recommendations for potassium silicate in controlling powdery mildew disease are to provide a continuous supply and selecting plant species that tend to accumulate high levels of Si in leaves such as zucchini. Silicon was shown to play a protective role prior to infection along with suppression of disease after infection.

Tesfagiorgis, H.B. 2008. Studies on the use of biocontrol agents and soluble silicon against powdery mildew of zucchini and zinnia. Doctoral Dissertation. University of KwaZulul-Natal. Pietermaritzburg, Republic of South Africa.

Greenhouse and field trials were conducted to determine the effects of biological control agents (BCA's) with and without potassium silicate (K_2SiO_2) on powdery mildew disease, causal agent *Podosphaera xanthii*, of zucchini *Cucurbita pepo* L. using foliar applications of BCA's and weekly soil drenches of K_2SiO_2 (**Tesfagiorgis, Laing, & Annegarn, 2014**). Under greenhouse controlled conditions the BCA's reduced disease levels up to 90% while K_2SiO_2 alone achieved a disease reduction up to 35%. However, K_2SiO_2 improved the efficacy of most of the BCA's. As disease pressure increased, the efficacy of K_2SiO_2 was reduced while the BCA's were unaffected. Temperature and humidity affected the efficacy of K_2SiO_2 and the BCA's under field conditions where disease reductions varied greatly from 10–70%. There were variances seen in the preferred temperature and humidity of fungal and bacterial BCA's. However, it was noted that K_2SiO_2, when root supplied to zucchini, increased leaf Si concentrations and was responsible for disease suppression of powdery mildew.

Tesfagiorgis, H.B., M.D. Laing, & H.J Annegarn. 2014. Evaluation of biocontrol agents and potassium silicate for the management of powdery mildew of zucchini. Biolog. Control, 73:8-15.

In pot experiments of marsh soil 20 gram/6 kg additions of calcium silicate or 15 grams/6 kg of sodium silicate increased the incubation period and increased resistance of cucumber (*Cucumis sativus* L.) to powdery mildew (*Sphaerotheca fuliginea*) disease, but not to the degree of 100% disease control (**Wagner, 1940**). It was concluded that fertilizers containing silicon should be applied to silicon deficient soils.

Wagner, F. 1940. The significance of silicic acid for the growth of certain cultivated plants, their nutrient economy, and their susceptibility to true mildews (in German with English Abstract). German Title: Die Bedeutung der Kieselsaure fur das Wachstum einiger Kulturpflanzen, ihren Nahrstoffhaushalt and ihre Anfalligkeit gegen echte Mehltaupilze. Phytopathol. Z. 12:427–479.

Silicon supplements reversed the powdery mildew (*Sphaerotheca fuliginea*) induced metabolic changes in cucumber (*Cucumis sativus* L.) seedlings, decreasing production of free radicals and increasing defense-related enzyme activity (**Wei et al., 2004**).

Wei, G., Z. Zhu, J. Li and Q. Yao. 2004. Effects of silicon supply and *Sphaerotheca fuliginea* inoculation on resistance of cucumber seedlings against powdery mildew. J. Appl. Ecol. 15(11):2147–2151.

Foliar applications of a silicon as a fine mist to cucumber (*Cucumis sativus* L.) leaf blades twice per week at an 8.6% concentration reduced powdery mildew (causal agent, *Podosphaera xhantii*), infection rate by 87% (**Wolff et al., 2008**). Additional benefits of silicon treatment included better growth, along with larger, and darker green leaves.

Wolff, S.A., J. Rohloff, and I. Karoliussen. 2008. Inhibitory effects of foliar applied silicon on powdery mildew in greenhouse cucumber. pp. 106. In Malcolm Keeping (ed.) Silicon in Agriculture Conference South Africa 2008, 4th International Conference Abstracts. University of Kwazulu-Natal, Wild Coast Sun, Port Edward, KwaZulu-Natal, South Africa.

Foliar applications 1 or 2x/week at two different rates using two different silicon-based products were applied to leaves of two powdery mildew disease (causal agent, *Podosphaera xhantii*) susceptible cucumber (*Cucumis sativus*) cultivars ('Euphoria' and 'Jessica') to evaluate commercial use of these materials for disease control under greenhouse conditions (**Wolff et al., 2012**). All treatments reduced disease infection development with more frequent applications increasing the efficacy of the products. The best treatment was with the Carbon Silpower™ at a rate of 56 mM Si applied 2x / week resulting in disease severity reduction up to 87%.

Wolff, S.A., I. Karoliussen, J. Rohloff, and R. Strimbeck. 2012. Foliar applications of silicon fertilisers inhibit powdery mildew development in greenhouse cucumber. J. Food Agricul. Environ., 10(1):355-359.

Crucifers (*Brassicaceae*)

Pythium aphanidermatum extracted from diseased kale (*Brassica oleracea* L. var. *acephala* DC.) root tissue grown in vitro on PDA showed significant reductions in mycelia growth and sporangial production when the growth media was supplemented with any of three different soluble silicon sources (**Rachniyom and Jaenaksorn, 2008**). The fungal growth inhibitory effects increased with increasing concentrations.

Rachniyom, H., and T. Jaenaksorn. 2008. Effect of soluble silicon and *Trichoderma harzianum* on the in vitro growth of *Pythium aphanidermatum*. J. Agric. Tech., 4(2):57–71.

Grapes (*Vitis vinifera* L.)

Application of low nutrient solution levels of silicon (0.08 mM Si) with foliar silicon sprays at 17 mM concentration was more effective in inhibiting powdery mildew [*Unicinula necator* (Schwein) Burrill] of grape (*Vitis vinifera* L.) than root feeding of 1.7 mM Si alone (**Bowen et al., 1992**). Either treatment however, resulted in a similar deposition of silicon surrounding the appressoria. The reduced disease severity with the foliar application was attributed to the formation of a physical barrier to hyphal penetration and to lateral movement of silicon within the leaves to deposition at fungal penetration sites.

Bowen, P., J. Menzies, D. Ehret, L. Samuels, and D.M. Glass. 1992. Soluble silicon sprays inhibit powdery mildew development on grape leaves. J. Amer. Soc. Hort. Sci., 117(6):906–912.

Powdery mildew [*Uncinula necator* (Schw.) Burr.] of grape (*Vitis vinifera* L. spp. cv. 'Yuvarlak Cekirdeksiz') was evaluated in two vineyards under glasshouse conditions with applications of sodium and potassium silicate applied pre-inoculation to potted plants (**Yildirim et al., 2002**). Sodium silicate reduced colony spore formation on young leaves for 4 days while sodium silicate also reduced colony spore formation, but for 7 days and on older leaves. No effects were seen on berry sugar content, and no toxicity or residue was displayed on leaves or bunches. Including sodium or potassium silicates in powdery mildew spraying programs with sulphur, synthetic fungicides or in mixtures is considered an acceptable practice in managing powdery mildew of grapes.

Yildirim, I., E. Onogur, and M. Irshad. 2002. Investigations on the efficacy of some natural chemicals against powdery mildew [*Uncinula necator* (Schw.) Burr.] of grape. J. Phytopathol., 150:697–702.

Greenhouse Crops

A review of silicon research on a variety of horticultural crops. Silicon plays a preventative role in reducing disease caused by a wide array of pathogens affecting different crops (**Bélanger et al., 1995**).

Bélanger, R.R., P.A. Bowen, D.L. Ehret, and J.G. Menzies. 1995. Soluble Silicon: Its role in crop and disease management of greenhouse crops. Plant Dis., 79(4):329–336.

Silicon has been shown to regulate nutrients and alter stress enzyme activities for both Si-accumulating and non-accumulating plant species (**Frantz, 2012**). And, despite clear evidence of silicon's beneficial effects to containerized crops in reducing pathogen symptoms (powdery mildew and Tobacco ringspot virus), aphid populations, susceptibility to Cu toxicity, and increasing salt tolerance and post-harvest longevity; the value of including silicon in fertility programs remains questioned. Cost/benefit ratios still need to be determined in addition to methods of predicting the silicon that is plant available from different sources.

Frantz, J., 2012. Benefits of silicon use in containerized crop production and challenges to its commercial adoption. In Visions for a sustainable planet, Conference Abstracts 406-6. Symposium-Silicon Soil Fertility and Nutrient Management. ASA-CSSA-SSSA International Annual Meetings 21-24 Oct. 2012, Cincinnati, Ohio. Available online at: <http://scisoc.confex.com/crops/2012am/webprogram/Paper71952.html> accessed 16 Oct. 2014.

Poinsettias (*Euphorbia pulcherrima*) grown under a standard greenhouse environment supplemented with 50 ppm silicon in the nutrient solution did not exhibit symptoms of *pythium aphanidermatum* (Edson) Fitzp. infection, were more uniform in height although slightly shorter than controls, but were less susceptible to breakage (**Leatherwood and Mattson, 2010**). When deprived water for 18 days, the plants receiving silicon during production were less wilted and recovered from severe wilt without damage.

Leatherwood, R. and N. Mattson. 2010. Adding silicon to the fertilizer program in poinsettia production: Benefits and facts. Cornell University Cooperative Extension. Ithaca, NY.

Of two chrysanthemum (*Dendranthema grandiflorum* Tzvelev) cultivars ("Polar White" and "Polar Yellow") the former had lower numbers of leaf miner (*Liriomyza spp*) larvae and number of mined leaves (**Polancyk et al., 2008**). Basic slag additions at a rate of 2.8 g/pot promoted reductions in number of larvae over the nine week period. The lack of reduction at higher rates was attributed to higher substrate pH (7.8) affecting availability of nutrients.

Polanczyk, R.A., D. Pratissoli, H.S. Paye, V.A. Pereira, F.L.S. Barros, R.G.S. Oliveira, R.R. Passos, and S. Martins Filho. 2008. Silicate compost used as resistance inductor against the leafminer on Chrysanthemum. Hortic. Bras., 26(2):240–243.

Zinnia (*Zinnia elegans* Jacq.) plants irrigated every two days with a nutrient solution amended with potassium silicate (K_2SiO_2), showed reductions in total green peach aphid [*Myzus persicae* (Sulzer);(*Hemiptera: Aphididae*] fecundity and intrinsic rate of increase, without affecting length of the pre-reproductive period or survivorship (**Ranger et al., 2009**). Higher silicon content was verified using ICP-OES in treated vs. control plant leaf tissue. HPLC-MS of leaf tissue identified increases in defense-related compounds (5-caffeoylquinic acid, p-coumaroylquinic acid, rutin and guaiacol peroxidase activity) in Si treated plants.

Ranger, C.M., A.P. Singh, J.M. Frantz, L. Cañas, J.C. Locke, M.E. Reding, and N. Vorsa. 2009. Influence of silicon on resistance of Zinnia elegans to *Myzus persicae* (*Hemiptera: Aphididae*), Environ Entomol., 38(1):129–136.

A mixture of bagasse (dried sugarcane residue), rice husks, oyster shell powder, and mineral ash from the steel industry (all containing substantial levels of silicon) were combined with urea, potassium nitrate and calcium superphosphate to produce an inexpensive soil amendment mixture named S-H after the two researchers who developed it in Taiwan (**Sun and Huang, 1985**). This soil amendment was effective in reducing various diseases (Clubroot, Phytophthora blight, Southern blight, Rhizoctonia blight, Sheath blight, Bacteria wilt and Fusarium wilt) of Chinese cabbage, cucumber, pepper, bean, rice, tomato, and watermelon consecutively while increasing yields. The researchers were granted a patent in 1984 for their mixture and contracted with a fertilizer manufacturer for production of the material.

Sun, S.K, and J.W. Huang. 1985. Formulated soil amendment for controlling Fusarium wilt and other soilborne diseases. Plant Dis., 69(11):917–920.

Applications of biological control agents with potassium silicate (KSi) sprays were evaluated for their effects in reducing powdery mildew disease, causal agent, *Glovinomyces cichoracearum* (DC) Gelyuta, V.P., of zinnia (*Zinnia elegans* cv. Jakobrekop Sunbow), due to environmental concerns with the use of fungicides and continued fungicide resistance development (**Tesfagiorgis, 2008**). Two adjuvants (Break-Thru® (BK), Partner® (PR) were shown to improve the efficacy of silicon sprays. In re-circulating nutrient solutions supplied with KSi, positive correlations between solution Si concentrations and leaf and root Si concentrations were seen for zinnia plants. Zinnia had the highest silicon content in leaves. Reductions in calcium uptake with increased Si concentration were seen. At nutrient solution additions of 50 mg/L zinnia had increased phosphorus, calcium and magnesium uptake. Under disease stress zinnia accumulated higher levels of Si and Ca, but less P, in leaves. Silicon in leaves was concentrated around infection areas and at the bases of trichomes. The recommended rate for the best control of powdery mildew disease for zinnia was determined to be 50-150 mg/L. Potassium silicate additions at 50-200 mg/L rates to hydroponic solutions along with biological control agents during zinnia growth resulted in reduced AUDPC and disease severity of powdery mildew by 87-95%, much higher than the reductions seen using selected biological control agents alone. The recommendations for potassium silicate in controlling powdery mildew disease are to provide a continuous supply and selecting plant species that tend to accumulate high levels of Si in leaves such as zinnia. Silicon was shown to play a protective role prior to infection along with suppression of disease after infection. There is a potential for combining biological control agents with Si to provide effective control powdery mildew of zinnia grown hydroponically.

Tesfagiorgis, H.B. 2008. Studies on the use of biocontrol agents and soluble silicon against powdery mildew of zucchini and zinnia. Doctoral Dissertation, University of KwaZulul-Natal, Pietermaritzburg, Republic of South Africa.

Diatomite, a chalklike, very fine grained; porous, siliceous material can be used as an ingredient in orchid (*Orchidaceae*) media (**Wang, 2005**). It is inert, does not decompose, and absorbs high levels of moisture. As a powder it has been used as an insecticide but was not effective in controlling fungus gnats when mixed with growth media. However, diatomaceous earth can kill insects by abrading their bodies leading to water loss and death.

Wang, Y.T. 2005. Diatomite: A new material for growing orchids. Orchids 74(9):652–653.

Leafy Vegetables

The combination of high electrical conductivity 4.0–4.5 mS cm−1 (0.95 g/L NaCl) and potassium silicate amendments resulted in increased butterhead (Bibb/Boston type) lettuce (*Lactuca sativa* cv. Cobham Green), biomass and very satisfactory control of downy mildew (*Bremia lactucae*) under a hydroponic production (**Garibaldi et al., 2012**).

Garibaldi, A., G. Gilardi, E.E. Cogliati, and M.L. Gullino. 2012. Silicon and increased electrical conductivity reduce downy mildew of soilless grown lettuce. Eur. J. Plant. Pathol., 132:123–132.

Trees

Treatment of wood with a silicic acid/boric acid mixture reduced *Fomitopsis palustris* wood decay (**Yamaguchi, 2005**). At high boric acid concentrations, complete mycelial growth inhibition was obtained. However, silicic or boric acid alone conferred no decay protection. Wood stakes treated with colloidal silicic acid-boric acid and placed in a termite-infested field for three years remained mostly undamaged, while the controls were eaten by termites. High boric acid completely inhibited termite damage. The procedure requires only 1 injection of the silicic acid/boric acid mixture. Conversion of the mixture to a non-leachable solid substance occurs at room temperatures. It is likely that silicic acid/boric acid mixtures can serve as ecologically friendly wood preservatives, protecting woods from weather, fire, and termite damage.

Yamaguchi, H. 2005. Silicic acid/boric acid complexes as ecologically friendly wood preservatives. Forest Prod. J., 55(1):88–92.

Pepper, Potato, Tomato, Tobacco (*Solanaceae*)

Field trials in Ethiopia demonstrated that silicon fertilizer increased yields and silicon content, and reduced bacteria populations of bacterial wilt (*Ralstonia solanacearum*), mean wilt incidence, severity index %, area of disease incidence, and disease severity progress curve of a moderately susceptible tomato (*Lycopersicon esculentum* Mill.) cultivar "King Kong 2" (**Ayana et al., 2011**). These effects were not seen using a moderately resistant cultivar "Marglobe".

Ayana, G., C. Fininsa, S. Ahmed, and K. Wydra. 2011. Effects of soil amendment on bacterial wilt caused by *Ralstonia Solanacerum* and tomato yields in Ethiopia. J. Plant. Prot. Res., 51(1):72-76.

Silicon along with imidacloprid at ½ the recommended rate was effective in reducing green peach aphid [*Myzus persicae* (Sulzer)] colonization on potato (*Solanum tuberosum* L.); **Gomes, Moraes and Assis, 2008**).

Gomes, F.B., J.C. Moraes, and G.A. Assis. 2008. Silicon and imidacloprid on plants colonized by *Myzus persicae* and on vegetative development of potato. Ciência Rural, Santa Maria., 38(5):1209–1213. (In Portuguese with English abstract).

Slag-based silicon fertilizer did not affect aphid *Myzus persicae* (Sulzer) preference for potato (*Solanum tuberosum* L.) leaves, but decreased aphid fertility and population growth (**Gomes et al., 2008**). Lignin content of leaves increased with silicon supplied as foliar (silicic acid) and/or soil (slag-based fertilizer) and tannin leaf concentrations increased only with the slag + foliar application, suggesting, that silicon is an inducer of potato resistance to aphid.

Gomes, F.B., J.C. Moraes, C.D. dos Santos and C.S. Antunes. 2008. Use of silicon the inductor of the resistance in potato to *Myzus persicae* (Sulzer) (*Hemiptera: Aphididae*). Neotrop. Entomol., 37(2):185–190.

In comparison to the controls, silicon additions either foliar or soil applied reduced potato (*Solanum tuberosum* L.) foliar lesions from San Antonio beetle [*Diabrotica speciosa* (Germar)] and leaf minor (*Liriomyza* spp.) damage (**Gomes, Moraes and Neri, 2009**).

Gomes, F.B., J.C. Moraes, and D.K.P. Neri. 2009. Fertilization with silicon as resistance factor to pest insects and promoter of productivity in the potato crop in an organic system. Ciênc. agrotec., Lavras., 33(1):18–23. (In Portuguese with English abstract).

Reductions in severity of Fusarium disease (*Fusarium oxysporum* f. sp. *radicis-lycopersici*) on tomato (*Lycopersicon esculentum* Mill.) stems resulted from silicon amendments four weeks post-inoculation (**Huang, Roberts and Datnoff, 2010**). Disease progress showed silicon to delay onset of root infection and translocation of disease from roots to stems. Silicon content of roots and shoots was increased with silicon supplements. A negative correlation was seen between root silicon content and severity of root, crown and stem. It was not determined whether silicon's effect was in inducing plant resistance or in reducing fungal colonization.

Huang, C.H., P.D. Roberts, and L. Datnoff. 2010. Indo–US Workshop on Silicon in Agriculture. Abstract #3, 25–27 Feb. 2010. Bangalore, India.

Supplemental silicon at rates of 100 or 200 ppm to recirculation nutrient solution reduced motility, root decay, and yield losses attributed to *Phytophthora capsici* infection on two varieties (PBC 137 and PBC 602) of peppers (*Capsicum annuum* L.); (**Lee et al., 2004)**. Silicate additions resulted in increased root dry weights, number of fruit, and number of high quality fruit with no difference attributed to rate of silicate application.

Lee, J.S., S.T. Seo, T.C. Wang, H.I. Jang, D.H. Pae, and L.M. Engle. 2004. Effect of potassium silicate amendments in hydroponic nutrient solution on the suppressing of Phytophthora Blight (*Phytophthora capsici*) in pepper. Plant Pathol. J. (Korea), 20(4):277–282.

Sodium silicate at 100 and 200mM rates had direct fungitoxic effects on Fusarium sulphureum that causes dry rot of potato (*Solanum tuberosum* L.) tubers (**Li et al., 2009**). Effects from sodium silicate included inhibited spore germination and mycelial growth along with sparse and asymmetrical mycelium, and swelling, curling and cupped shaped hyphae with thickened cell walls. Hyphal cells were distorted with cavities or dense material. Hyphal daughter cells and new daughter hyphae within collapsed hyphal cells often were found in the cytoplasm, however, septa of treated hyphae did not vary. In vivo, sodium silicate was effective in controlling tuber dry rot.

Li, Y.C., Y. Bi, Y.H. Ge, X.J. Sun, and Y. Wang. 2009. Antifungal activity of sodium silicate on *Fusarium sulphureum* and its effect on dry rot of potato tubers. J. Food Sci., 74(5):M213–M218.

Silicon supplements to water stressed pepper (*Capsicum annuum* L.) plants resulted in maintenance of higher levels of relative leaf water content, transpiration, stomatal conductance, chlorophyll a and b, and carotenoids, thus increasing tolerance to water stress (**Lobato et al., 2009**).

Lobato, A.K.S., G.K. Coimbra, M.A.M. Neto, R.C.L. Costa, B.G. Santos Filho, C.F. Oliveira Neto, L.M. Luz, A.G.T. Barreto, B.W.F. Pereira, G.A.R. Alves, B.S. Monteiro, and C.A. Marochio. 2009. Protective action of silicon on water relations and photosynthetic pigments in pepper plants induced to water deficit. Res. J. Biol. Sci., 4(5):617–623.

Silicic acid as a soil drench (2 ton/ha SiO_2 rate) was as effective as acibenzolar-s-methyl in reducing green peach aphid [*Myzus persicae* (Sulzer)] colonization of potato (*Solanum tuberosum* L.; **Nascimento et al., 2010**).

Nascimento, A.M., F.A. Assis, J.C. Moraes, V.F. Silva, and M.L. Peixoto. 2010. Resistance inductors on *Myzus persicae* (Sulzer) in potato. Revista de Agricultura (Piracicaba), 85(1):21–27. (In Portuguese with English abstract).

Exogenous silicon supplements to potted tomato (*Lycopersicon esculentum* Mill.) plants reduced Bacterial Wilt (*Ralstonia solanacearum*) disease index from 19.18-52.7% when compared with controls (**Wang et al., 2013**). With silicon supplements plant tissue silicon was increased and the silicon concentration in roots was higher than in shoots. When incolulated with *R. solanacearum* soil urease activity increased and soil sucrase activity decreased, but no effect was seen on soil acid phosphatase activity. Silicon amendment affected increases in soil urease and soil acid phosphatase activity under pathogen-inoculation. *R. solanacearum* infection reduced soil bacteria and actinomycetes by 52.5 % and 16.5 %, respectively, while increasing the soil fungi/soil ratio by 93.6 %. With silicon, soil bacteria and actinomycetes were increased and the soil fungi/soil bacteria ratio was reduced 53.6 %. It is suggested that Si-mediated resistance of tomato against *R. solanacearum* is associated with soil microbial numbers and soil enzyme activity.

Wang, L., K. Cai, Y. Chen, and G. Wang. 2013. Silicon-mediated tomato resistance against *Ralstonia solanacearum* is associated with modification of soil microbial community structure and activity. Biol. Trace Elem. Res., 152(2):275–283.

Hydroponic solution supplemented with silicon during tobacco (*Nicotiana tabacum*) infection by Tobacco ringspot virus resulted in delayed symptom onset and reduced leaf area affected, but did not prevent viral infection later on (**Zellner, Frantz and Leisner, 2010**). Uptake of silicon by tobacco was associated with both viral infection and with the supply of silicon. Inoculated plants supplied with silicon took up more silicon than non-inoculated plants.

Zellner, W., J. Frantz, and S. Leisner. 2010. Silicon delays tobacco ringspot virus systemic symptoms in *Nicotiana tabacum*. Indo–US Workshop on Silicon in Agriculture. Abstract #20, 25–27 Feb. 2010. Bangalore, India.

Hydroponically grown tobacco (*Nicotiana tabacum*), considered a low silicon accumulating plant, inoculated with Tobacco ringspot virus (TRSV) had delayed systemic disease symptoms and reductions in affected leaf area when the solution was supplemented with high levels of silicon (**Zellner, Frantz and Leisner, 2011**). Infection resulted in higher foliar silicon accumulation. However, silicon did not reduce Tobacco mosaic virus (TMV) symptoms nor did plants accumulate higher levels of silicon when inoculated with TMV suggesting that silicon's effects are virus-specific.

Zellner, W., J. Frantz, and S. Leisner. 2011. Silicon delays Tobacco ringspot virus systemic symptoms in *Nicotiana tabacum*. J. Plant Physiol., 168:1866–1869.