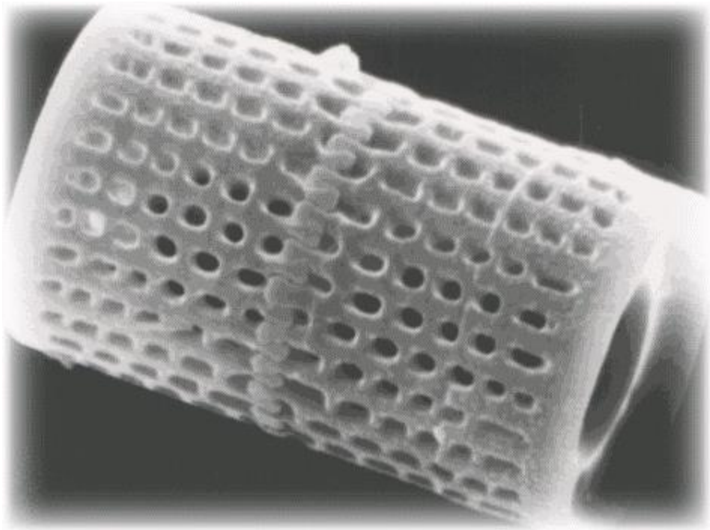
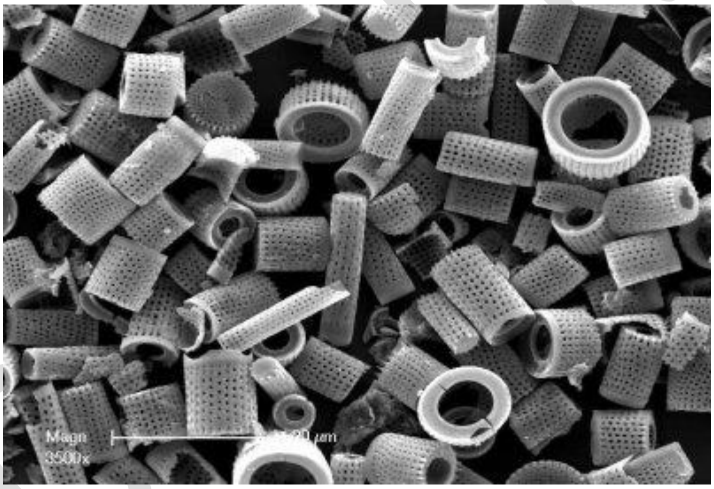
A Review of Silicon and its Benefits for Plants





In 1939, the Nobel Prize winner for chemistry, Professor Adolf Butenant, proved that life cannot exist without Silica.

In the 2003 book "Water & Salt" Dr. Barbara Hendel states: "Silica it the most important trace mineral for human health!"

Silica plays an important role in many body functions and has a direct relationship to mineral absorption. The average human body holds approximately seven grams of silica, a quantity far exceeding the figures for other important minerals such as iron.

Geoffrey Kirton June 2015

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Silicon (Si)

Silicon (Si) is not yet classed as an essential nutrient but it exists in all plants grown in soil and is recognised as a functional nutrient.

The benefits of silicon include increasing pest and pathogen resistance, drought and heavy metal tolerance, and improved quality and yield of agricultural crops.

Adequate silicon fertilization greatly boosts rice yield and mitigates biotic and abiotic stress, and improves grain quality through lowering the content of cadmium and inorganic arsenic. (C Meharg, A. Meharg et al, 2015)

Si is taken up at levels equal or greater than essential nutrients such as Nitrogen and Potassium in certain plants such as rice and sugarcane, for which it is considered agronomically essential for sustainable crop production (Savant et al, 1999). [3]

What is silicon?

What is Plant Available Silicon (PAS)?

Silicon (Si) is one of the most abundant elements in the earth's crust. Soils generally contain from 5 to 40% Si (Kovda, 1973) consisting of mainly poorly soluble quartz and crystalline silicates, which are inert. Whilst silicon is plentiful, most sources of silicon are insoluble and not in a plant available form.

Plants can only absorb Si in the form of soluble monosilicic acid, a non-charged molecule. Monosilicic acid, or plant available silicon (PAS), is a product of Si-rich mineral dissolution (Lindsay, 1979). Different Si sources have different dissolution rates; the solubility of quartz is low compared to the easily soluble amorphous silica, diatomaceous earth (Savant et al, 1999).

PAS is absorbed by plants, benefiting the plant in terms of growth and resistance to disease and environmental stresses. PAS also has a significant effect on soil texture, water holding capacity, adsorption capacity, and soil erosion stability.

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Silicon and Plant Physiology

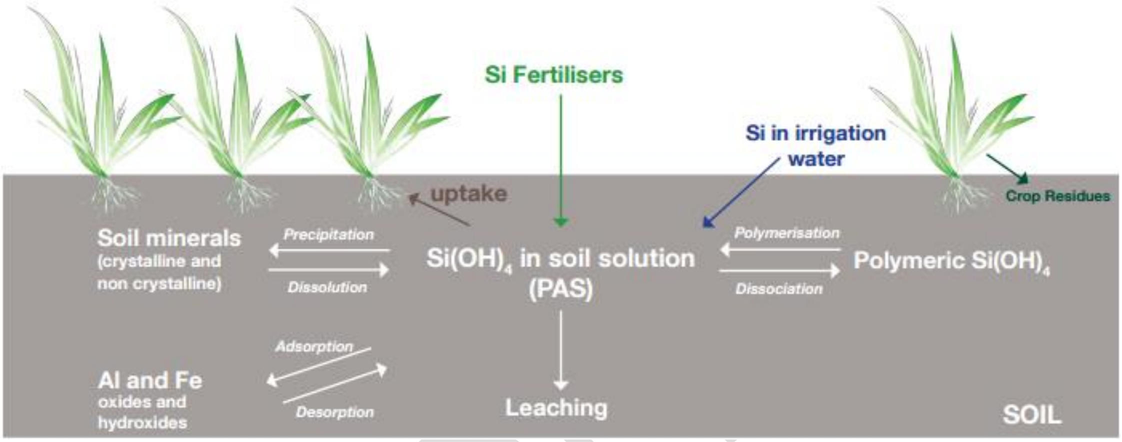
Soils that have low silicon concentrations are commonly amended with silicon compounds to increase the quality and quantity of agricultural crops.

PAS may be absorbed by roots from the growing medium but PAS can also be absorbed as a foliar application (Muir et al, 2001). Approximately 90% of the absorbed PAS is probably carried via the xylem in the transpiration stream so that its concentration is greater in the foliar tissues than the root tissues (Jones and Handreck, 1967). Root absorption by some plants such as oats may be directly related to water uptake, while other plants such as beans may expend energy for Si to cross the root cell membranes (Jones and Handreck, 1967). Mycorrhizal fungi may enhance the root uptake of PAS in acid soils (Clark and Zeto, 1996). The difference in Si accumulation between species has been attributed to differences in Si uptake ability of the roots (Ma and Yamaji, 2006).

Si accumulates in greater concentrations with increasing age of the tissues, dependent on the species, cultivar and the external availability of PAS.

PAS forms deposits of amorphous silica, known as phytoliths (sometimes in association with cellulose and proteins), in the plant tissues (Neumann et al, 1997). Phytoliths from plant litter may contribute 1-2% to the weight of the soil and they normally degrade slowly to return soluble Si to the soil. However, the degradation is too slow to release sufficient PAS to enable benefits in the following crop of wheat, for example (Rodgers-Gray and Shaw, 2000).

Si is accumulated in plants to total concentrations in dry matter similar to those of essential macro-nutrients such as Potassium (K), Calcium (Ca), Magnesium (Mg), Sulphur (S) and Phosphorous (P) (Epstein, 1994).



Why Should PAS Be Measured?

Soil testing is required to measure the amount of Si present in the soil in order to optimise the nutrient requirements for the crops' needs. Given that many soils are Si-deficient, it is important to understand the extent of this deficiency before recommending a treatment program.

Testing of the plant tissues for Si is informative in determining how effectively the plant is taking up Si from the soil or foliar amendments.

How Is PAS Measured?

It is often recommended that the soil, plants and Si fertilizers are tested for Si content in order to make Si management in crops efficient and affordable for farmers (Savant et al, 1999).

Plant testing:

The amount of Si accumulated by the plant is measurable and generally recognised as a reflection of the amount of PAS (Andersen et al, 1991). Plant testing for Si status mainly consists of leaf tissue sampling and its chemical analysis. X-ray fluorescence is a direct method used on oven dried plant matter. Alternatively the Si in the plant tissue can be solubilised and indirectly measured in the extracted solution.

Soil testing:

The forms of Si in the soil can be defined as Total, Extractable and Soluble but it is the Soluble Si (PAS) that is agronomically important and this may have no relation to the Total Si in the soil[2] (Berthelsen et al, 2003). In addition, the concentration of Soluble Si in soils is dynamic and affected by the soil type, moisture and exchangeable/dissolution reactions. The measurement of PAS relies on extracting monosilicic acid from the soil using a water-based extractant. Several wet chemical methods are available to measure monosilicic acid to provide an indication of its availability to plants in the growing substrate. It is important to carefully choose the extraction method as the extraction process itself may solubilise more Si compounds in the soil than usually available to plants in the natural environment (Muir et al, 2001). Most of the methods that have been developed apply an anion to replace adsorbed Si and are then test by determining the correlation between the Si analysed in the extract and crop yield (Sauer et al, 2006). The most common methods use CaCl2, acetate/acetic acid or citrate.

The acetate extraction was found to be too strong for soils previously fertilised with calcium silicates, because it dissolved some non-available Si from the fertiliser (Nonaka and Takahashi, 1990).

Other researchers (Berthelsen et al, 2001) concluded that citric acid and sulphuric acid methods attack silicates, such as clay minerals, both chemically (silicates are solubilised by acid extractants) and mechanically (via the agitation required to carry out the method) and therefore overestimate the plant available Si.

[1]The measurement of Total Si by methods such a atomic absorption spectrophotometry does not provide an accurate reflection of the plant available Si (PAS) as it also measures the Si bound up in other compounds such as silicates (Muir et al,2001).

Alkaline wet chemical dissolution techniques, such as extraction with NaOH or Na2 CO3 are often used to analyse amorphous Si in soils (Follet et al, 1965). This method uses the fact that the solubility of amorphous silica increases at higher pH values. It has been found, however, that NaOH can dissolve part of the silicate minerals in the soils, that is, those that aren't plant available. Recently an extraction method has been proposed (Pereira et al, 2002) to quantify the Si potentially available to plants by using an alkaline extractor of NH4 NO3 and Na2CO3.

The weakest extractant after water is CaCl2, which only extracts the easily soluble Si fraction (Berthelsen et al, 2001). It is reported (Haysom and Chapman, 1975) that Si extracted by CaCl2 showed the highest correlation to sugar cane yield (r2 = 0.82) compared to other extractants.

Si Source testing:

With the recognition that Si is an important element for the growth of plants, many methodologies have been used to determine the plant available Si of the Si source, or fertiliser, although there has been no systematic survey of these methodologies (Sauer et al, 2006).

The chemical extractant methods used to estimate the PAS of the Si source often do not correlate well with the plant uptake of Si once applied to the soil (Berthelsen et al, 2003), therefore it is important to carefully select the extraction method.

The chemical reactivity of Si fertilizers can be determined using the following testing procedures (Savant et al, 1999):

1) Direct Chemical Extraction In this procedure, Si is directly extracted from the Si source with a chemical solution such as CaCl2, acetate/acetic acid or citrate, sulphuric acid, NaOH and/or Na2CO3

2) Indirect Chemical Extraction after Soil Incubation

The silicon source to be evaluated is incubated with soil for varying periods and the chemical extractant is used to determine Si released in the soil from the Si source.

(Note: The particle size of the Si source must be defined when evaluating its chemical reactivity as particle size affects Si solubility)

While many chemical extractants may provide the first estimate of the potential value of a Si source, the more reliable method of determining the PAS of a Si material is through indirect chemical extraction after soil incubation (Savant et al, 1999), and the author of this review proposes CaCl2 as the extractant from personal communications with a notable researcher in this field.

Why Do Plants Need Silicon?

Si exists in all plants grown in soil (Takahashi, 1990) and its content in plant tissue ranges from 0.1 to 10% (Epstein, 1999). Si is considered as a nutrient of agronomic essentiality in that its absence causes imbalances of other nutrients resulting in poor growth, if not death of the plant (Epstein, 1995; Savant et al, 1997).

Numerous laboratory, greenhouse and field experiments have shown the benefits of silicon fertilisers for agricultural crops and the importance of silicon fertilisers as a component in sustainable agriculture (Matichenkov and Calvert, 1999).

There are two different effects on plants due to silicon fertilisers:

1. An indirect influence through soil fertility, and

2. A direct influence on the plants

The benefits of Si on plants include (Ma, 2006 and Savant et al, 1999):

- Increased growth and fruit yields in some species
- Tolerance to abiotic stress:
    - Frost, drought and salinity,
    - Toxicity by Al, Mn, heavy metals,
- Tolerance to biotic stress:
    - Insects and infection
- Resistance to lodging[2]

The beneficial effect of Si is more evident under stress conditions because Si is able to protect the plant from multiple biotic and abiotic stresses (Ma and Yamaji, 2006).

Abiotic stress is the negative impact of environmental factors upon living organisms and biotic stress concerns pest pressure.

Si is accumulated primarily in the epidermal tissues of both roots and leaves in the form of a silica-gel (phytoliths). This thickened epidermal silicon-cellulose layer supports the mechanical stability of plants, thereby resisting lodging and also a greater retention of seed, especially in grasses (Savant et al, 1999). The increased mechanical strength also increases the light receiving posture of the plant. Leaves were reported to be darker green, stiffer and slower to senesce, increasing their potential for photosynthesis and hence growth (Epstein, 1994). The deposition of Si in the culms, leaves and hulls also decreases transpiration from the cuticle and this increases resistance to lodging, low and high temperature, radiation, UV and drought stress (Ma and Yamaji, 2006). Figure 1.

More recent studies suggest that Si also plays an active role in the biochemical processes[3] of a plant and may play a role in the intracellular synthesis of organic compounds (Matichenkov et al., 2008). Given that PAS in the sap may constitute between 0.5-8.0% of the total Si in the plant, it is likely to play an active role in the biochemical processes of the plant (Fawe et al, 1998).

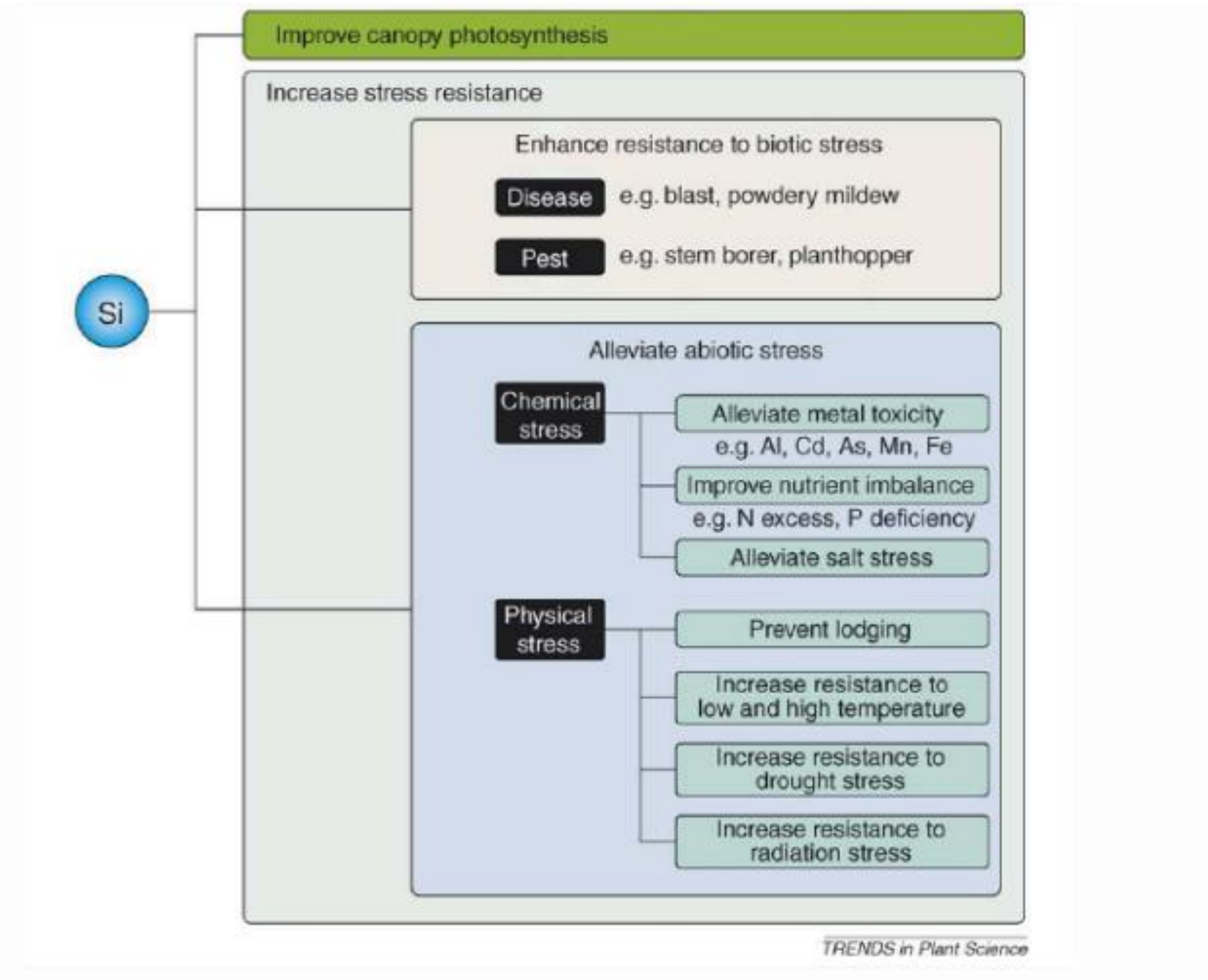


Figure 1***: Extracted from Ma and Yamaji (2006) Beneficial effects of silicon on plant growth in relation to biotic and abiotic stresses***

Structural silicon provides physical protection to plants against microbial infection and insect attack as well as reducing the quality of the tissue to the predating organisms. The abiotic benefits are due to silicon's effect on overall organ strength. This helps protect against lodging, drought stress, high temperature (through efficient maintenance of transpiration), and photosynthesis by protecting against high UV. Furthermore, silicon also protects the plant from saline stress and against a range of toxic metal stresses (arsenic, cadmium, chromium, copper, nickel and zinc). Added to this, silicon application decreases grain concentrations of various human carcinogens, in particular arsenic, antimony and cadmium. (Meharg C., Meharg A., 2015)

Si also controls the chemical and biological properties of soil with the following benefits:

Reduced leaching of phosphorous (P) and potassium (K) (Sadgrove, 2006)

Reduced Aluminium (Al), Iron (Fe), Manganese (Mn) and heavy metal mobility (Maichenkov, 2002),

Improved microbial activity (Matichenkov, 2002),

Increased stability of soil organic matter

Improved soil texture (Sadgrove, 2006),

Improved water holding capacity[4] (Sadgrove, 2006),

Increased stability against soil erosion (Sadgrove, 2006), and

Increased cationic exchange capacity (CEC) (Camberato, 2001)

Therefore even if a plant is a low Si-accumulator, it will benefit from the improved soil properties resulting from the application of Si.

2 Tendency of crops (particularly cereal crops) to bend over

3 Biochemical processes mean chemical processes happening in a living organism, in this case the plant. For example, chemical processes such as the synthesis of organic compounds by plants etc

4 Silicon fertilisers usually possess a very large surface area therefore their application increases the water holding capacity of sandy soils and raises the soil's adsorption capacity (Savant et al, 1997)

cheap and could easily be integrated with other pest management practises (Laing et al, 2006).

It has been reported that silicon suppresses insect pests such as stem borers, brown plant hopper, green leafhopper, white backed plant hopper, and non-insect pests such as spider mites (Savant et al, 1997, Ma and Takahashi, 2002).

Sugarcane – improved silicon nutrition has been shown to:

Reduce leaf freckling (Elawad et al, 1982),

Increase tolerance to shootborer (Chilo infuscatelus) (Rao, 1967),

Increase resistance to stem borer (Diatracea saccharalis F.) (Anderson and Sosa, 2001), and

Increase resistance to stalkborer (E.saccharina) (Elawad et al, 1982, Keeping and Meyer, 2003)

Wheat – improved silicon nutrition has been shown to:

Increase tolerance of Hessian fly larvae (Phytophaga destructor Say) (Miller et al., 1960)

Increased crop resistance and reduced pest infestation, both in the field (Kordan et al, 2005) and in storage (Korunic, 1997)

Rice – improved silicon nutrition has been shown to:

Increase resistance to the African striped borer Chilo zacconius Bleszynski (Ukwungwu and Odebiyi, 985)

Prevent attack by the larvae of the yellow rice borer, Scirpophaga incertulas (Panda et al, 1975)

Reduce susceptibility to the stem borer Chilo suppressalis Walker (Sasmoto, 1961)

Inhibit sucking against the brown planthopper Nilaparvata lugens (Yoshihara et al, 1979)

Reduce the number of nymphs becoming adults; reduce adult longevity and female fecundity of plant hoppers (Salim and Saxena, 1992)

Maize - improved silicon nutrition has been shown to:

Improve resistance to stalkborer, Chilo zonellus Swinhoe, damage (Sharma and Chatterji, 1972)

Reduce larval survival of the borer Sesamia calamistis Hampson (Lepidoptera: Noctuidae)

Increase resistance to Ostrinia nubilalis Hubner (Lepidoptera:Pyralidae)

Other crops – the contribution of silicon content to pest resistance has also been recorded in

Other crops, such as:

Vegetables (Chelliah, 1972)

Citrus (Matichenkov et al, 2000)

Turf (Korndorfer et al, 2004)

Laing et al (2006) report silicon controls red spider mite on dicotylendonous crops such as green beans, brinjal, tomato and cucumber.

Furthermore, silicon deposits in plant organs were reported in most crops, including the mono and dicotyledonous families (Jones and Handreck, 1967; Nishimura et al., 1989). This implies that Si plays a role in pest resistance in most, if not all, cultivated crops.

Several mechanisms have been proposed to explain the tolerance and resistance of plants to insect pests. According to Bernays and Barbehenn (1987) most of the plant silicon occurs in the epidermis, which might dislodge young larvae before they can establish in the stem. Various studies have demonstrated that silicon increases the hardness of plant tissue, which negatively impacts insect larval boring and feeding ability. Djamin and Pathak (1967) showed that increased silicon content in rice plants resulted in mandibular teeth loss of stem borer larvae.

Recently, a parallel mechanism as that seen in the resistance of plants to diseases via an activation of the plant's own defence mechanisms by soluble silicon has been observed for insect pests. Sieburth et al (1990b) reported such a mode of action against insects such as the noctuid Trichoplusia ni, the coccinellid Epilachna varivestis, the aphid Acyrthosiphon pisum, and the cockroach Periplaneta americana. Similarly, Keeping and Meyer (2005) reported the resistance of sugarcane to E.saccharina.

Diatomaceous Earth as a Grain Protectant

Silica in the form of diatomaceous earth sprayed or dusted onto plants has also been reported to kill insect pests such as; Cryptolestes ferrugineus, Rhyzopertha dominica, Sitophilus oryzae and Sitophilus granarius (Saez and Mora, 2007), amongst others. This mechanism differs from the soil amended Si application and works by dessicating the insects when they physically contact the silica dust (Korunic, 1997).

Diatomaceous earths are the most common inert dusts registered for the protection of grain in storage (CSIRO, 2001).

How Silicon Alleviates Soil Metal Toxicity

Aluminium, Iron and Manganese

Many metals found naturally in the soil can be potentially toxic to plants. These metals often become a problem when there is a change in the soil environment, such as the acidification of soil. This low pH environment solubilises iron (Fe), Manganese (Mn) and Aluminium (Al).

Excess Al is toxic to plants causing:

Stunted roots

Reduced availability of phosphorus (P),

Reduced availability of sulphur (S),

Reduced availability of other nutrient cations through competitive interaction.

Multiple laboratory and field experiments have shown that silicon fertilisation is more effective than liming for reducing aluminium toxicity (Matichenkov and Calvert, 1999). Five different mechanisms of Al toxicity reduction involve Si-rich compounds:

1. PAS can increase the pH of acid soils

2. PAS can be adsorbed onto aluminium hydroxides impairing their mobility

3. PAS can form ions with Al, thereby precipitating it out of solution

4. The mobile Al ion can absorb onto a surface of strong adsorption capacity, such as a silica surface

5. Mobile Si compounds can increase a plant's tolerance to Al.

These mechanisms can work simultaneously although there is usually a prevalent one.

Aluminium toxicity is reported to decrease on increasing Si in the nutrient supply to cotton, maize, soybean and barley (Epstein, 1994; Hodson and Evans, 1995). Aluminium oxides, either added or already present in the soil, also reduce the availability of Si for plant uptake; a situation occurring naturally in heavily weathered and/or acidified soils in Australia (Jones and Handreck, 1965; Exley, 1998; Perry and Keeling-Tucker, 1998).

Plants take up manganese from the soil solution. Manganese deficiency occurs in plants grown in alkaline soils and toxicity occurs on very acid and poorly drained soils. A deficiency of Si causes an increased uptake of Manganese in rice, barley, rye and ryegrass causing toxicities (Lewin and Reimann, 1969). Si fertilisaton relieves this toxicity (El-Jaoual and Cox, 1998). The proposed mechanism may be increased oxidation of Mn at the root surface if there is sufficient oxygen present, and redistribution of Mn to prevent necrosis (Lewin and Reimann, 1969; El-Jaoual and Cox, 1998).

Iron is classified as a trace element, or micro-nutrient, because it is only needed in small amounts. Too much iron can be toxic to plants, producing stunted growth of roots and tops, dark green foliage, or dark brown to purple leaves on some plants. Iron toxicity is a particular problem in rice paddies that show the symptom of brown leaves, called "bronzing". Silicon deficiency also causes an increased uptake of Iron (Fe) in rice while adding Fe oxides to soil will reduce the plant availability of Si (Jones and Handreck, 1995; Lewin and Reimann, 1969). The presence of sufficient PAS at the root surface may increase the oxidative power to precipitate toxic levels of Fe as for Mn (Jones and Handreck, 1967; Perry and Keeling-Tucker, 1998).

Recently, Ma and Yamaji (2006) suggested that the deposition of Si in the roots reduces apoplastic bypass flow and provides binding sites for metals, resulting in a decreased uptake of toxic metals and salts from the roots to the shoots.

Heavy Metals

Mining, manufacturing, and the use of synthetic products can result in heavy metal contamination of urban and agricultural soils. Heavy metals also occur naturally, but rarely at toxic levels.

Heavy metals enter the food chain through the soil and become hazardous contaminants of food, entering the human body as a cumulative poison (Benavides et al., 2005). The rehabilitation of soil contaminated by heavy metals relies on methods such as managing the mobility of heavy metals in the soil so that they don't leach into waterways or get taken up by plants. This can be achieved by changing the pH (heavy metals are less mobile at high pH) or by adding soil amendments to increase the soil's adsorption capacity thereby reducing the plant's ability to access the heavy metal. However, these measures may not be sufficient or are costly and inefficient.

A recent report (Matichenkov and Bocharnikova, 2010) demonstrated that the leaching of heavy metals (Cu, Pb, Cr, Ni, and Co) was reduced significantly, by over 50%, with the addition of a Si fertiliser (diatomaceous earth). This reduction in leaching of heavy metals may be explained by the interaction between the heavy metals and Si-rich substances, such as diatomaceous earth.

Several mechanisms are proposed in this recent report as responsible for inactivating the heavy metals: a weak physical or strong chemical adsorption between the heavy metals and the diatomaceous earth and a reaction between PAS (monosilicic acid) and the heavy metals.

How Silicon Enhances Plant Disease Resistance

There is substantial evidence that when several high Si accumulator plants are fertilised with Si, they benefit from reduced severity of disease, with associated yield increases over infected plants that weren't fertilized with Si (Belanger et al, 1995). Several fungal diseases of rice, sugarcane, cereals, roses and lettuces, amongst others, are reduced in severity, as listed in Table 1.

Mostly the findings are for foliar pathogens and there are some instances where root diseases caused by Fusarium and Pythium are reduced. The protective effect has been reported for hydroponics systems, soil applications (e.g. rice) and foliar applications (e.g. grape). The effect may occur within 24 hours of spray treatment for foliar pathogens, and can take up to three weeks against root pathogens by root uptake (Bowen et al, 1992).

There is increasing evidence that PAS is required continually in sufficient concentration in sap to provide protection (Samuels et al, 1991b). Two mechanisms for Si-enhanced resistance to diseases have been proposed (Ma and Yamaji, 2006). One is that Si acts as a physical barrier, where Si is deposited beneath the cuticle such that the Si layer mechanically impedes penetration by fungi, thereby disrupting the infection process.

Another mechanism proposed recently is that soluble Si acts as a modulator of host resistance to pathogens (Ma and Yamaji, 2006). Foliar fungal pathogens live parasitically in living plant tissues, removing cell nutrients until the sporulation process on the surface of the plant excludes light and the tissues senesce (Muir et al, 2001). Plants respond to foliar pathogens by releasing chitinases and other proteins and phenolic compounds to kill its own cells, isolate the pathogen and prevent the infection of adjacent cells.

Several studies in monocots (rice and wheat) have shown that plants supplied with Si can produce phenolics and phytoalexins in response to fungal infection such as those causing rice blast and powdery mildew (Fawe et al, 1998; Belanger et al, 2003; Remus-Borel et al, 2005; Rodrigues et al, 2004). Similarly, it has been shown (Samuels et al, 1991; Cherif et al, 1994) that nutrient solutions amended with Si activate defence mechanisms in dicots (cucumber) by enhancing the activity of chitinases, peroxidises and polyphenoloxydases.

These biochemical responses are only induced by soluble Si and the biochemical pathways of the plant that lead to disease resistance remain unknown, although several potential mechanisms have been proposed (Ma and Yamaji, 2006).

Effect of Silicon on the Uptake of Other Nutrients

The presence of Si in nutrient solutions affects the absorption and translocation of several macro and micro-nutrients (Epstein, 1994). Increased Si fertilisation increases Zinc (Zn) uptake if deficient, especially if P is excessive (Marschner et al, 1990).

Si fertilisation retards the toxic uptake of Phosphorous (P) by roots, such as in cucumbers (Marschner, 1990), while promoting its translocation to grain in rice and wheat (Lewin and Reimann, 1969). Cultivated plants can use only about 30% of applied Phosphate fertiliser, if leaching is low. The mixture of active Si with P fertiliser can increase the efficiency of P fertilisation by 40-60% (Matichenkov et al, 1997b).

Si interaction with Potassium (K) varies, depending on the anion in the fertiliser (Jones and Handreck, 1967). Transpiration decreases if the chloride salt is used, yet increases if the sulphate salt is used so there is greater uptake and deposition of Si for the latter K fertiliser.

Importantly, Si-rich amendments are recommended for the reduction in leaching of nitrogen, phosphorous and potassium based fertilizers (see Section: “The role of silicon in improving the efficiency of NPK fertilizers”).

The damage to plants caused by salt (NaCl) depends considerably upon the salt tolerance of plants. One of the mechanisms considered as being responsible fore salt toxicity to plants is ionic phyto-toxicity which is caused by excess amounts of salt ions (Na and Cl) in the plants (Liang and Ding, 2002). Si-fertilisation has been shown to alleviate Sodium (Na) uptake in rice, wheat and barley (Savant et al, 1997a). Liang et al (1996) proposes a mechanism for salt tolerance as a reduction in membrane permeability of the leaf cells of the salt-stressed plant, reducing the uptake of Na. Liang and Ding (2002) also proposed that Si causes sodium and chloride ions to be more evenly distributed over the whole root section, which improves the salt tolerance of the plants. Therefore ensuring that a plant has sufficient PAS will reduce the effects of salinity.

What Is the CEC and Why is it Important

Cations are positively charged ions such as calcium (Ca2+), magnesium (Mg2+), and potassium (K+), sodium (Na+) hydrogen (H+), aluminium (Al3+), iron (Fe2+), manganese (Mn2+), zinc (Zn2+) and copper (Cu2+). The capacity of the soil to hold on to these cations is called the cation exchange capacity (CEC), and is a measure of fertility and nutrient retention capacity of the soil. The higher the CEC, the more suitable the soil is as a growth media, with the exception of those plants that are suited to harsher soils.

Many essential plant nutrients exist as cations (eg K+, Ca2+, Mg2+, NH4+) and often only a small percentage are available for plant uptake as affected by soil texture and pH, amongst other factors. These cations are held by negatively charged clay and organic matter particles in the soil through electrostatic forces (negative soil particles attract the positive cations). These cations are easily exchangeable with other cations and as a result, they are plant available. Thus, the CEC of a soil represents the total amount of exchangeable cations that the soil may adsorb[6] (Cornell University Agronomy Fact Sheet #22).

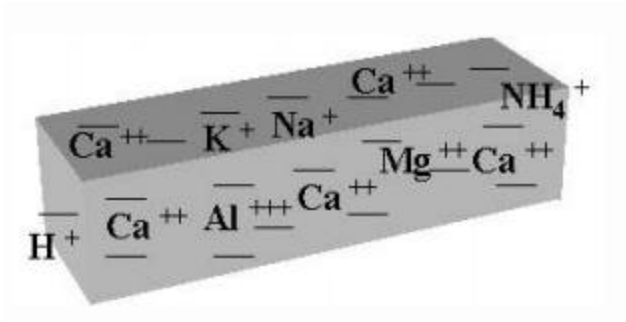


Figure 2: ***Schematic of a clay particle with negative charges on the surface attracting various cations (from Camberato, 2001).***

The CEC of a soil is expressed in cmolc/kg (centimol positive charge per kg of soil) or meq/100g (milli-equivalents per 100 grams of soil), where 10 cmolc/kg = 10 meq/100 g.

Sandy soils low in organic matter have a very low CEC (less than 3 cmolc/kg) while heavier clay soils or soils high in organic matter generally have a much higher CEC (greater than 20 cmolc/kg). This means sandy soils require more frequent fertilizer application than clayey soils.

The pH of the soil is another important consideration in optimising the soil environment. When plants transpire they form carboxylic acid, resulting in increased acidity (H+ cations) around the roots. These H+ ions occupy the negative sites on CEC materials, decreasing the retention of the plant nutrient cations. Increasing the pH will remove the H+ ions, freeing the CEC sites for the plant nutrient cations. In dry climates, sodium may occupy an important portion of the CEC.

Therefore, the actual CEC of the soil will depend on the pH of the soil. Given the same amount and type of organic matter, a neutral soil (pH ~7) will have a higher CEC than a soil with e.g. pH 5, or in other words, the CEC of a soil will increase with an increase in pH.

Liming of soils can increase the pH, depending on how well buffered the soil is, however, a more effective method is to increase the CEC. Diatomaceous earth can be added to increase the CEC. 50meq/100g for diatomaceous earth (Camberato, 2001) is a typical value.

What Are The Implications Of The CEC?

1. The higher the CEC the more clay, silica/te or organic matter present in the soil. This usually means that high CEC soils have a greater water holding capacity than low CEC soils.
2. Low CEC soils are more likely to develop potassium and magnesium (and other cation) deficiencies, while high CEC soils are less susceptible to leaching losses of these cations. So, for sandy soils, even a large one-time addition of cations can lead to large leaching losses.
3. The lower the CEC, the faster the soil pH will decrease with time. So, sandy soils are typically limed more often than clay soils.
4. The CEC is important in providing a reservoir of plant nutrients to replenish those removed by plant uptake or leached by excessive rainfall or irrigation.

Behaviour of Silicon in Soil

In the soil solution, or liquid phase, Si is present as monosilicic acid ($Si(OH)4$, referred to as PAS) and polysilicic acid (the polymer of PAS) as well as complexes with organic and inorganic compounds such as Al oxides and hydroxides (Berthlesen et al, 2003). While it is the PAS that is taken up by the plants and has a direct influence on crop growth, the polysilicic acid and inorganic and organic complexes are important sources/sinks that replenish the PAS following crop use. They also have an important and significant effect on the soil properties such as improving soil aggregation and increasing soil water holding capacity as well as increasing the exchange and buffering capacity of the soils (see CEC section) (Berthelsen et al, 2003).

The solubility of Si in the soil is affected by a number of dynamic processes occurring in the soil (see Figure 3 below) including the particle size of the Si fertiliser, the soil pH7 , organic complexes, presence of Al, Fe and phosphate ions, temperature, exchangeable/dissolution reactions and soil moisture[7] (Berthelsen et al, 2003).

[5] Adsorption means the adhesion of the cations to the soil particles

[6] PAS is only present in solution at less than pH 9 and has a solubility of 65mg/L, which is constant between pH2-8.5 (Jones and Handreck, 1967).

[7] There is a polymerisation of PAS to form a silica-gel if it exceeds a concentration of 65mg/L or if there is a dehydration of the soil, which is reversible on dilution (Savant et al, 1999).

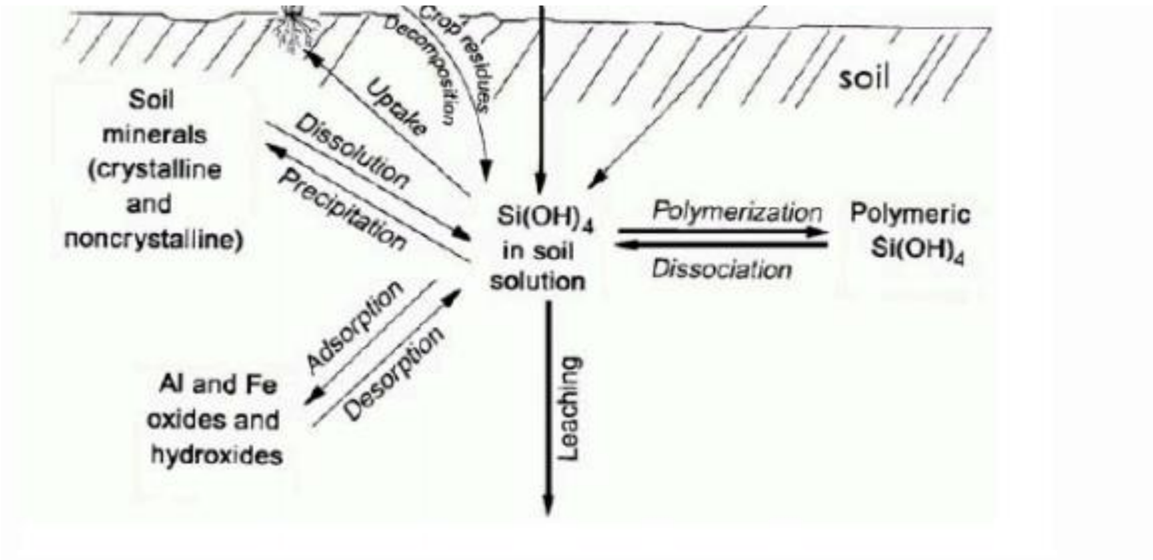


Figure 3: ***The main processes influencing Si concentration in the soil (extracted from Savant et al, 1997), where Si(OH)4 is PAS.***

Si can be added via irrigation water and fertilisation but it is lost through plant absorption and leaching.

Why is there a Need for Silicon Fertilisation?

Silicon deficiency in crops has been recognised since the 1970s. The optimisation of silicon nutrition has been shown to have positive effects on plants. In particular, substantial research on rice and sugarcane has shown that silicon application can significantly enhance insect pest and disease resistance with consequent yield increases.

Plants differ in their ability to accumulate Si (Ma and Yamaji, 2006) but in order for any plant to benefit from Si it must be able to acquire this element in high concentrations.

The concentration of PAS in the soil is dynamic and influenced by soil pH, temperature, composition of the soil and moisture, amongst others. Si fertiliser is necessary to improve soils deficient in Si and replace Si removed by cropping and leaching.

The composition of soils in terms of the level of Si is an important parameter to measure in order to determine its Si-deficiency. For example, Queensland sugarcane soils are considered deficient in Si if the concentration is less than 10-15mg Si/kg dry soil following extraction with 0.01M $CaCl_2$ (Muir et al, 2001).

Berthelsen et al. (2003) analysed three different Australian soils: Bundaberg (Hydrosol soil), Mossman (Tennosol) and Innisfail (Ferrosol). These soils varied in their levels of PAS in the order: Hydrosol>Tennesol>Ferrosol.

Areas of high rainfall and temperature undergo significant weathering where important nutrients (Ca^{2+}, Mg^{2+}, K^+ and Na^+) are stripped from the soil resulting in acidification of the soil, which in turn dissolves aluminosilicate clay minerals with the concomitant leaching of Si.

Matichenkov & Calvert (2002) report that 210-224 million tons of plant-available Si is removed from arable soils globally on an annual basis, assuming 70-800kg ha-^{1} of plant available silica is removed with the harvesting of crops. Harvesting cultivated plants usually results in Si being removed from the soil. In most cases much more Si is removed than other macronutrients (Savant et al., 1997; Datnoff, 2005):

- Potatoes remove 50 to 70 kg Si ha-^{1},

- Cereals remove 100 to 300 kg Si ha-^{1},

- Rice removes 230 – 470kg Si ha

- Sugarcane removes 500 to 700 kg Si ha-^{1} (Anderson, 1991).

In continuous cropping with high Si-accumulator species such as sugarcane and rice, the removal of PAS can be greater than the supply via natural processes releasing it into the soil unless fertilised with Si (Savant et al, 1997b)

While other plant-available elements are restored by standard fertilization, Si is not.

Comparison of Silicon Fertilisers

Silicon exists in a variety of forms but most are poorly soluble, and therefore do not contribute significantly to the PAS. Quartz (SiO_2) is commonly found in sandy soils; however, this inert form of Si has a poor adsorption capacity, low water holding capacity and very low solubility.

While Si is an abundant element it is not found free in nature but combined as silicates or oxides.

Many sources have been assessed for use as an agricultural amendment. Before any source can be considered for agricultural applications, it must meet a number of criteria, such as solubility, availability, have suitable physical properties and be free of contaminants (Gascho, 2001). One of the most important, and most difficult to achieve, is solubility.

Liquid silicates such as sodium silicate and potassium silicates are effective for foliar applications and used in greenhouses but are generally uneconomical to use for the rates needed for soil application (Berthelsen et al, 2003).

Calcium metasilicate (CaSiO3, often referred to as simply calcium silicate) from slag has been used by the Hawaii sugar industry for years (Medina-Gonzales, 1988). Calcium silicate occurs naturally as wollastonite, however, the availability and solubility of wollastonite depends on the degree of metamorphosis involved during its geological formation (Muir et al, 2001), and can be low compared to some synthetic or slag silicates.

Silicate slag has been used extensively in the USA; however, the furnace temperatures influence the formation of insoluble silicate glasses (Prakash 1999). Slags can be variable in composition and although they have high concentrations of total Si, often only a small proportion is easily solubilised (Gascho, 2001). An important consideration with silicate sources derived from industrial by-products is the possible high level of heavy metals associated with their origin or processing (Berthelsen et al, 2003). These are not only toxic to plants but leach into waterways causing environmental damage. Likewise, cement and cement building board waste can contain heavy metals (Muir et al, 2001).

Other sources of Si include magnesium silicate, basalt dust, dolomite and rock phosphate, but these only contain traces of PAS (Savant et al, 1999).

The advantage of silicate materials is that they also supply other nutrients such as Ca2+, in the case of CaSiO3 and increase the pH of the soil. In sugarcane trials in Australia, USA-imported calcium silicate showed the best results compared with other silicate sources and it was a slow release amendment, which is ideal for broadcast application every few years (Berthelsen et al, 2003). However, the authors of the report noted that there was a lack of locally available and economical source of Si.

Since 1970, Hawaiian Sugar Planter Assoc. researchers have tested several silicate materials and their findings include (Savant et al, 1999):

The degree of Si solubility from siliceous materials is dependent on particle size and chemical composition (HSPA, 1979), Extractable Si levels were higher in the finer silicate particles (HSPA, 1980).

Calcium metasilicate was generally much more soluble and readily available to sugarcane than calcium ortho-silicate.

There have been a number of studies on silicates (such as calcium silicate) given the abundance of furnace slag and its use on sugarcane crops in the USA. There is less availability of furnace slag, in many countries aside from the inherent disadvantages of cost and heavy metal contamination. Other silica sources such as diatomaceous earth have recently been studied (Berthelsen et al, 2003[8]; Matichenkov and Bocharnikova, 2010) and field trials completed.

Diatomaceous earth is a natural source of Si and has a large surface area due to its structure and is readily soluble due to its amorphous nature. Solubility is an important parameter to consider when selecting the appropriate Si fertiliser as solubility determines the concentration of PAS. PAS is the only form of Si that the plant can use in realising the benefits described above.

Type of Si fertiliser	Potential Benefits/ Negatives					
	PAS	Available in S.E.	Economical	Retains moisture	Increases soil pH	Contains other contaminants
Calcium silicate slag	Depends on slag	No	Depends	No	Yes	Yes
Wollastonite	Low	No	No	No	Could	Depends
DE	Yes	Yes	Yes	Yes	slightly	No
Potassium silicate	Yes	Perhaps	No	No	Unknown	No

What is Diatomaceous Earth?

The term 'Diatomaceous earth' (DE) refers to a sedimentary rock which results from the deposition of silica-rich unicellular life forms known as 'diatoms'. Other names for diatomaceous earth include Diatomite, Tripoli, Kieselguhr and Infusorial earth. Diatoms are aquatic algae, and hence DE forms in water, both salt and fresh (Smol & Stoermer, 2001). Freshwater lake beds are the source of Trisap's DE.

The cell walls of these dead diatoms consist of **amorphous silica** ($SiO_2.H_2O$). The fossilised skeletal remains (a pair of symmetrical shells - frustules) vary in size but are typically 10 to 200 microns across and have a broad variety of shapes, from needles to discs or balls.

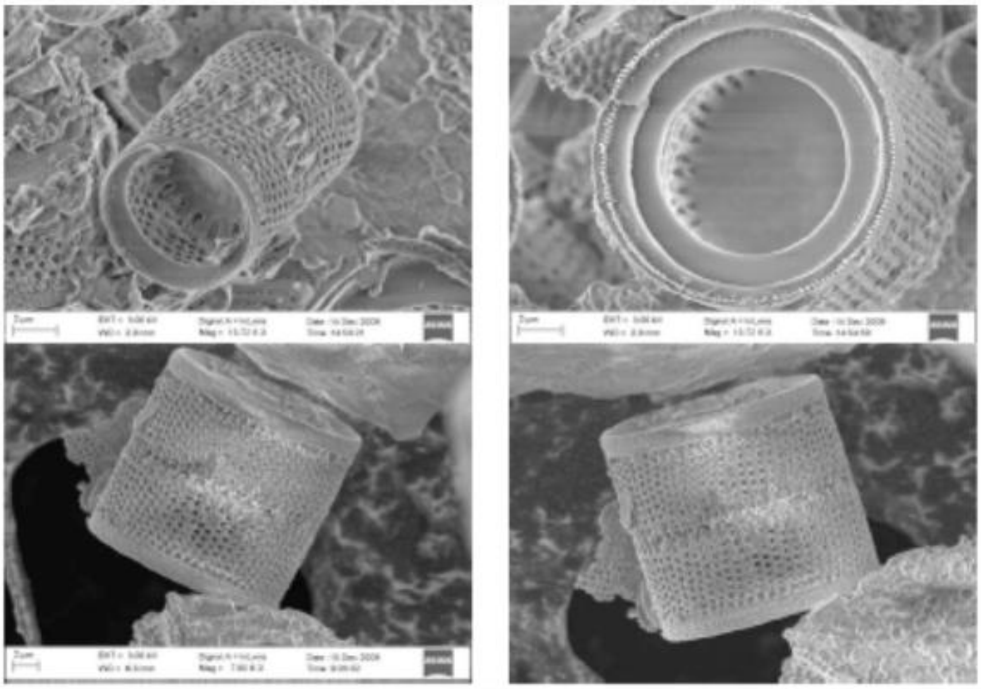


Figure 4: ***Scanning electron microscopy images of samples of Agripower showing the morphology of individual diatoms***

[8] **The DE used in the CSIRO trial was not optimal given its large particulate size**

Fertilisers

A CaCl2 extraction was carried out (James Cook University, Agripower results, 2010) on a number of Si materials commonly referred to in the literature as Si amendments. A CaCl2 extraction has a similar ionic strength to the soil solution so it is assumed to approximate what is present in the soil solution in determining readily soluble Si.

The extraction was carried out at different extraction ratios as the availability of monosilicic acid (PAS) varies with dilution given that at high concentrations it polymerises[9] to polysilicic acid.

The diatomaceous earth product shows a higher amount of PAS at all extraction ratios compared to the commercially available slag.

Impact of NPK and Silicon Fertilisers on soil health and the Environment

In Australia soils often lack essential nutrients such as nitrogen, phosphorous and potassium, especially after years of intensive agriculture (Sadgrove, 2006). Mineral fertilisers are a major input into Australian agricultural production and account for over 12% of the input costs (www.fifa.asn.au).

NPK (Nitrogen, Phosphorous, and Potassium) fertilisers are synthetic, inorganic fertilisers which are used to improve crop yields. Their widespread use is blamed for the degradation of natural resources, especially soil (Bunemann et al, 2006).

[9] Polymerisation is the formation of a large molecule from a number of small ones. Therefore monosilicic acid (a small molecule) binds with many other monosilicic acid molecules to form a large molecule which is no longer plant available

1. How they are made,

2. How they affect long term soil nutrition, and

3. How they affect waterways through runoff

Ammonia is the major feedstock used to produce the nitrogen based fertiliser but the production of ammonia is a very energy intensive process, relying predominantly on natural gas. Potassium and Phosphorous come from limited natural sources. Manure is also a source of N, P and K.

Si fertilisers such as diatomaceous earth are a natural resource found in the earth's crust and an organic fertiliser, not requiring a synthetic route of manufacture. This means no emissions are generated and minimal energy is required in its production.

Various practises in agriculture are productive in the short term but increase soil acidity (Mason et al, 1994). A significant concern regarding nitrogen based fertilisers is that they cause soil acidification.

Acidic soils cause many problems such as (Mason et al, 1994):

Limited growth and production of crops

Toxic levels of aluminium and manganese which are more soluble at low pH

Phosphorous deficiency caused by aluminium toxicity

Deficiencies of cationic nutrients (calcium, magnesium and potassium), and

Reduced activity of micro-organisms (such as the critical nitrification of ammonium-N to nitrate)

It has been shown, for example in a long term trial in Western Australia on wheat, (Mason et al 1994) that the continued use of a nitrogen and phosphorous based fertiliser progressively lowered the soil pH giving rise to the problems listed above. Limestone was shown to only have short term effectiveness and required repeated applications.

Also, many synthetic fertilisers may not replace trace elements which are depleted by crop uptake.

Studies on sandy loam soils in Australia (Hati et al, 2006) showed that a balanced application of mineral (essential plant nutrients) fertiliser with organic manure yielded higher crop productivity compared to no fertiliser, although the impacts on soil acidification and leaching were not considered.

Silicon based fertilisers such as diatomaceous earth do not have long term negative impacts on soils since they are a natural product. Not only does diatomaceous earth improve soil nutrition through its higher cationic exchange capacity and ability to retain moisture, it provides plant available silica, an important nutrient in crop productivity.

Calcium silicate slag, a potential source of Si, often contains contaminants such as heavy metals which affect soil health and productivity.

The final consideration in terms of fertilisers is their effect on the greater environment, such as waterways. During high periods of rainfall, varying amounts of nitrate are washed from the farmland into nearby waterways, such as oceans, lakes and groundwater. The addition of excess nitrates or phosphates into the water system through fertilisers is known as eutrophication. It results in the death of fish and other organisms (Presley et al, 2006). High levels of nitrates stimulate the growth of plankton, which may initially result in increased fish numbers with the excess food availability; however, eventually oxygen may be depleted to a fatal level, a situation in which masses of fish die (Presley et al, 2006). This is seen as a major challenge in the developing countries of Asia where over use or poor management practises particularly with the use of nitrogenous fertilisers (urea, ammonium sulphate etc) is causing heavy pollution to river systems.

Silicon based fertilisers, such as diatomaceous earth, pose no such risk to waterways.

The Role of Silicon in Improving the Efficiency of NPK Fertilisers

NPK (Nitrogen, Phosphorous, Potassium) based fertilisers are often considered a necessary part of intensive crop cultivation. These macronutrients are consumed in large quantities by plants and NPK fertilisation is a way of improving crop production. Organic manures are also used as a source of these macronutrients, alone or in combination with synthetic NPK fertilisers. Blood and bone meal is another source of these macronutrients, though predominantly of organic nitrogen (nitrogen combined with carbon).

The application of fertilisers for plant nutrition and animal farming, are major sources of natural water pollution. Many soils are susceptible to leaching due to the high rainfall and widespread use of irrigation and drainage can lead to leaching from well-drained soils to water of 20% to 80% of added nutrients and agrochemicals (Matichenkov and Botcharnikova, 2010).

However minimising fertiliser application may have a negative impact on yield.

Two independent studies into the application of NPK fertiliser with diatomaceous earth found:

1. Reduced nutrient and pollutant leaching
    a. Reductions in leaching of P by 60%, of K by 60%, and of N by 54% at 100kg/ha NPK + DE in Grey Forest Soil (Matichenkov and Bocharnikova, 2010
    b. Reductions in leaching of (Sadgrove, 2006):

        i. N by 60% for sandy soil and 10% for potting mix
        ii. P by 30% for sandy soil and by 95% for clay
        iii. K by 60% for sandy soil and 15% for potting mix
2. Improved crop productivity
    a. Increased barley biomass (Matichenkov and Bocharnikova, 2010)
    b. Increased quality and quantity of rice, grass, citrus, tomato and corn (Matichenkov, 2001, 2002)
    c. Rhodes grass grown in the DE amended soils was significantly taller and darker green than the grass in unamended soils (Kerr, 2007)

Si-rich amendments are therefore recommended for the reduction in leaching of N, P and K.

Southern Cross University, Queensland, Australia study

Synthetic fertilisers and manure supply nitrogen in the form of ammonium (NH_4^+) (blood and bone meal supply organic nitrogen which is converted by soil bacteria into ammonium). Ammonium can realise one of several fates once in the soil:

1. 'volatilised' into ammonia
2. 'nitrified' into nitrite (NO_2) then nitrate (NO_3) by bacteria
3. fixated by high cationic exchange materials
4. taken up by plants, or
5. 'immobilised' by bacteria that turn it back into organic nitrogen

Nitrate and ammonium are the plant available forms of nitrogen; however, once ammonium is converted into nitrate, it is very soluble and easily leached from the soil.

Diatomaceous earth when added with a NPK fertiliser was found to interrupt the first three nitrogen fates listed above and improve the efficiency of nitrogen uptake by plants through the following mechanisms:

1. A reduction of volatilisation, therefore reducing loss of nitrogen in the form of ammonia from the soil (Sadgrove, 2006)

2. Diatomaceous earth amended soils show a reduced loss of nitrate, particularly the sandy soils and potting mix (Sadgrove, 2006). This is significant given that nitrification (conversion of ammonium to nitrites then to nitrates by bacteria) is generally promoted in well aerated soils, so these normally nitrification susceptible soils were improved through the addition of diatomaceous earth

3. Retention of the ammonium ions by an order of magnitude (Kerr, 2007).

The results show that DE improves the efficiency of nitrogen fertiliser by reducing losses via leaching and volatilisation and increasing its availability by immobilising ammonium for plant uptake.

Rhodes grass grown in the DE amended soils was significantly taller and darker green than the grass in unamended soils. Furthermore, potassium and phosphate levels improved for all soil types amended with DE (Sadgrove, 2006). This is attributed to DE's ability to retain moisture as well as its high cationic exchange capacity which enables DE to retain plant available nutrients such as ammonium, potassium and phosphate. [34]

Why is Silicon Especially important in Acidic Soils?

Soil acidification is one of Australia's leading soil problems. Soil acidification arises in areas of high rainfall and temperature undergoing significant weathering where important nutrients (Ca2+,Mg2+, K+, and Na+) are stripped from the soil. The acidic conditions in the soil in turn dissolves aluminosilicate clay minerals causing leaching of Si.

The acidification of soil and leaching of Si have several impacts:

A greater availability of potentially plant toxic ions such as Al, Fe and Mn, which are more soluble at low pH

Limited growth and production of crops

Phosphorous deficiency caused by aluminium toxicity

Deficiencies of cationic nutrients (calcium, magnesium and potassium)

Reduced activity of micro-organisms (such as the critical nitrification of ammonium-N to nitrate)

Reduced cationic exchange capacity

Low levels of PAS

In order to combat the loss of nutrients, fertilisers are added, such as ammonium (Synthetic fertilisers and manure supply nitrogen in the form of ammonium). However, ammonium releases hydrogen cations which further increase the acidity of the soil.

It is common practise to lime soils to increase the pH and thus the soil's CEC. The amount of lime that is required to change the soil's pH depends on the soil type, the more clayey the soil the more lime it requires. However, often soils have a high pH buffering capacity (meaning that the soil resists a change in pH when chemicals are added to it) it is often uneconomical to increase the pH above 6. It is often more efficient to raise the CEC by adding amendments such as diatomaceous earth or calcium silicate which also supply PAS to these Si-deficient soils. In fact, too much liming can have a marked (negative) effect on the availability of Si.

Multiple laboratory and field experiments have shown that Si fertilisation is more effective than liming for reducing aluminium toxicity.

How Should Silicon Be Applied?

Silicon application rates are mainly influenced by the chemical makeup of the Si source, Si levels in the soil, and in the plant (Savant et al, 1999). The TRG diatomite is rich in plant available silica (upto75%).

It is important to determine a soil's responsiveness to Si; soils that are not deficient in Si are likely to have a low response to Si amendments (Datnoff and Snyder, 1991). Many Australian soils are deficient in Si due to high leaching conditions which results in a loss of plant available silica.

Si deficiency occurs more in highly weathered, low base saturation and low pH soils such as Oxisols and Ultisols (Datnoff, 2005). Organic soils (Histosols) are also deficient in PAS because of the greater content of organic matter and low content of minerals. Entisol soils have a high content of quartz sand (SiO2) but are low in PAS. Soils from the Tully-Innisfail cane growing area in Northern Queensland have inherently low levels of PAS and this level could be insufficient to maintain optimum crop growth (Berthelsen et al, 1999).

Si can be applied as a soil amendment or foliar spray, depending on the form of the Si fertiliser. Potassium silicate is often applied as a foliar spray as it is a liquid silicate; however, it is costly and often non-economical for large crop applications. In addition, spray applications of potassium silicate have been reported as less efficient than soil amendments of calcium silicate (Rezende et al., 2009).

Si fertilisers that are applied as a soil amendment:

- Broadcast spread and incorporated into the top 10-20cm using an off-set disc plough or rotary hoe for sugarcane (Berthelsen et al, 2003)
- Generally, all Si is applied to soil before planting (Savant et al, 1999)

Dramatic results have been found with silicate slag applied at 2 or more tons per hectare on sugarcane and citrus fields (Berthelsen et al, 2003; Matichenkov et al, 2001). Diatomaceous earth has shown significant results at rates as low as 100kg/ha. The difference in application rate between the slag and DE is at least partially attributed to differences in PAS (see Figure 5)

Treating Hydroponics with Silicon Fertilisers

Hydroponics growers have generally used 19-50mg Si/L in hydroponic solutions for increased plant growth and reduced disease (Menzies and Belanger, 1996). Potassium silicate is the most soluble silicate, but it may be a slow release form if it polymerises at high concentrations.

Sodium and Potassium metasilicates are very alkaline but can supply adequate Si for uptake.

Metal silicates are highly alkaline with a pH of 9-10; therefore they require acidification to pH 5-7.5 before they can be used as a fertiliser in the hydroponics system (Muir et al, 2001).

Diatomaceous earth has also been shown to provide plant available silica in a hydroponic system of sugarcane (Parr, 2007). The mean leaf Si content for plants treated with diatomaceous earth was 1.44% versus 0.87% for the plants grown without diatomaceous earth. This was a statistically significant difference and indicates that the sugarcane was able to assimilate silica and would be expected to benefit from the increased silica content.

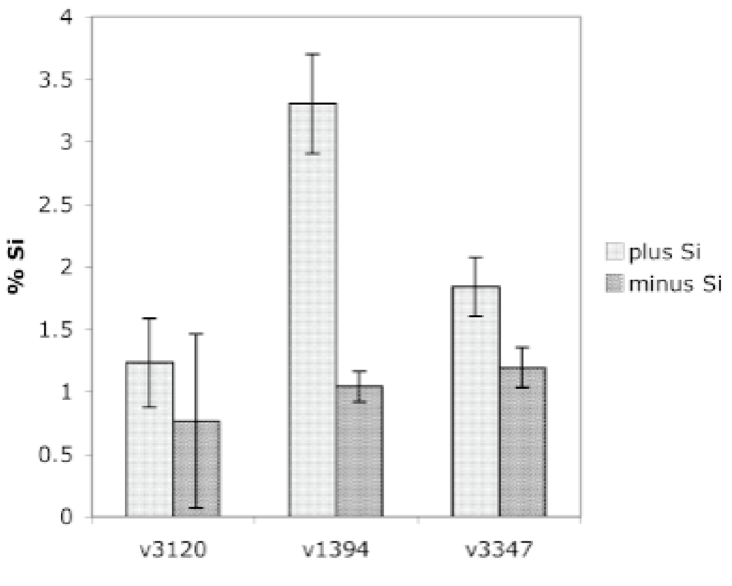


Figure 6: ***Silica content of hydroponic sugarcane leaf with and without diatomaceous earth addition to nutrient solution (Parr, 2007)***

Which Plants does Silicon Help

Si has been proven to be influential in maintaining the health of many plant species for decades (Muir et al, 2001). Rice and horsetail will not grow without Si and cucumbers, soybeans, strawberries and tomatoes have been shown to suffer adverse effects on growth if grown without Si (Epstein, 1994).

Plants differ in their ability to accumulate Si (Ma and Yamaji, 2006). There are some general trends in

[11] The angiosperms, species from the monocot orders Paoles and Arecales accumulate substantially more Si than from the other monocot clades and dicots such as cucumber are unable to accumulate high levels of Si in their shoots (Ma and Takahashi 2002). Flowering plants can be classified as monocotyledons (single seed leaf) and dicotyledons (2 seed leaves) and have other differences such as leaf structures.

Plants can be categorised in terms of Si-accumulation (Jones and Handreck, 1967):

- Wetland grasses (rice and horsetail): 10-15% dry matter (High Si accumulator)
- Dryland grasses (sugarcane, cereal and turf): 1-3% dry matter (medium Si accumulator)
- Dicots (especially legumes): less than 1% dry matter (low SI accumulator)

Members of the grass family in particular accumulate Si and several reports demonstrate the importance of Si nutrition for rice and sugarcane. Large growth and yield responses appear to occur more rapidly with Si fertilisation in high Si-accumulator plants than others, but low Si accumulator species also show increased growth and health in the presence of added Si (Epstein, 1999).

Benefits of Diatomaceous Earth as a Soil Conditioner

Tests carried out at Southern Cross University Queensland, Australia on soils amended with NPK fertiliser as the control with various rates of diatomaceous earth (Sadgrove, 2006). The soil nutrient level improved markedly as a result of the addition of DE:

Reduced leaching of nitrate, particularly in sandy soils and potting mix

Improved retention (reduced leaching) of ammonium, phosphate and potassium cations

These tests also revealed that DE improved the retention of moisture in potting mix, turf soil and sandy soil but not clayey soil. DE improved water retention in two ways:

1. During watering events soils with DE held a greater bulk quantity of water, and

2. Soils with DE dried at a slower rate

It has been shown that DE increased drought resistance when added to the sand of golf putting greens (Waltz and McCarty, 2001). DE acts in a similar way to silica gel (which is not really a gel but an amorphous silica) where both readily absorb moisture.

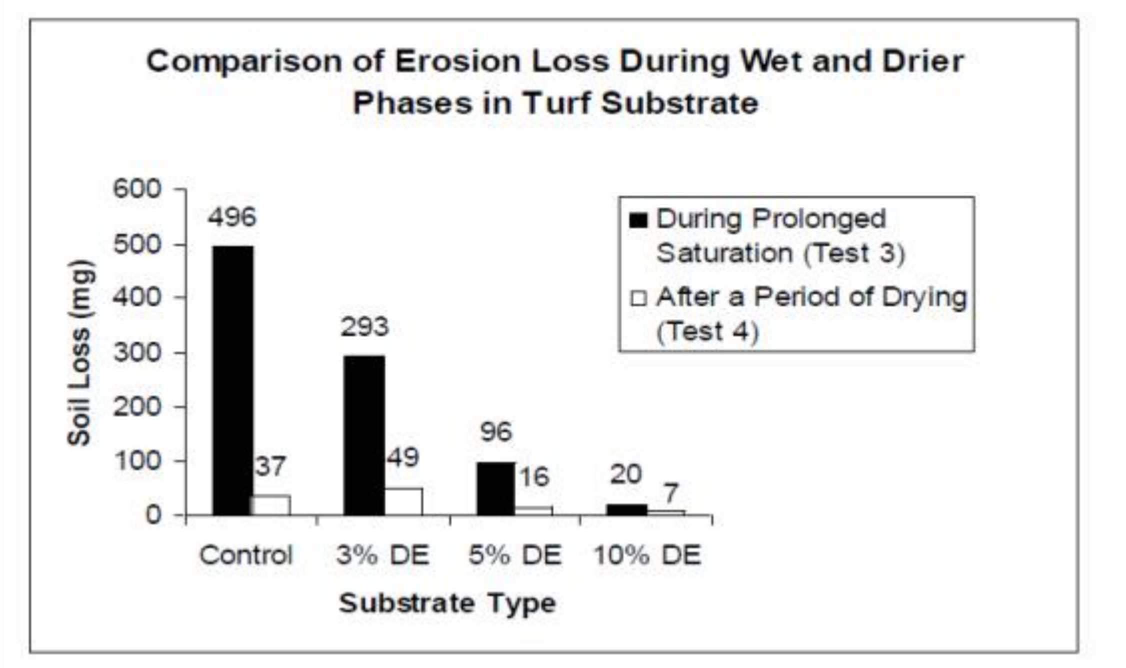


Figure 9: ***Effect of drying and DE rate on subsoil erosion in the turf substrate (Sadgrove, 2006)***

Benefits of Diatomaceous Earth in Mine Rehabilitation

A study carried out by Southern Cross University. Queensland, Australia (Kerr, 2007) to determine the benefits of Diatomaceous Earth in the rehabilitation of mine sites.

A large area of the upper Hunter Valley, New South Wales, Australia has been disturbed during open cut coal mining operations. Prior to mining it is a requirement that topsoil be removed and stockpiled, however, some topsoil is unsuitable due to poor quality. For example the water holding capacity for sandy soil is low. Diatomaceous earth was tested to determine whether it could improve the water holding capacity and nutrient retention ability of the sandy soil. Water holding capacity is particularly important in revegetation as it allows the growth of a substantial root structure which in turn limits the soil's susceptibility to erosion.

Obvious differences in the colour, size and vigour of the Rhodes grass grown in soil amended with fertilizer only compared to that where DE plus fertilizer was used. Moisture probes indicated that the DE treated land retained more water within the root zone. There was also a decrease in the leaching of the fertilizer in the DE treated sites. In particular the ammonium was retained rather than being leached or volatilised to the atmosphere.

Conclusion

Silicon has become widely accepted as an important element in considering soil condition and plant nutrient programs. Over the past few decades a significant body of knowledge has developed regarding the role of silicon in soil health and increased crop yield and productivity.

Studies from the rice industry in Japan to the sugar cane industry in North America have shown the importance of silicon as an important element in the nutrition programs of key economic crops and beyond that the ability of silicon to enhance the efficacy of delivering other elements in broader fertilisation programs. This is of particular importance for the highly weathered soils of Australia. Silicon is a beneficial element in its own right with particular impact on certain types of grasses such as rice and cane.

Silicon is also a soil conditioner with the ability to lock up toxic elements such as aluminium and heavy metals while at the same time increasing the availability of essential nutrients such as nitrogen, potassium and phosphate.

As the understanding of the role of silicon in soils and plant nutrition has developed, the accuracy in monitoring and measuring silicon's impact for various crops in various soil conditions has improved. One of the key developments in this area is the concept of Plant Available Silicon or PAS and the emergence of methodologies in measuring PAS. This has enabled researchers and growers to more effectively predict the impact of various sources of silicon in nutrient programs and consider their cost effectiveness.

It has also emerged over recent years that some traditional sources of silicon such as calcium silicate slags carry contaminants that ultimately prove detrimental to soil productivity and this factor needs to be considered when incorporating silicon as an element in a nutrient program.

In weighing the key factors above, Diatomaceous Earth or DE has been shown to be a preferential source of silicon for plant nutrition with a particularly high PAS. In addition to the high PAS scores for DE , it has certain physical properties that are of additional benefit to soils and plant nutrient programs. The absorbent qualities of DE lead to a reduction in irrigation requirements when it is used in fertilisation programs and the low specific gravity of DE leads to a low transport, handling and spreading cost for the grower in applying it to the soil. DE has been overlooked as a source of silicon due to concern over the incidence of cristobalite contamination within most supplies, but with the emergence of a cristobalite free source of DE it is becoming the product of choice for an international silicon fertiliser market.

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