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Silicon in Day Today Life

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Abstract: Silicon, the most abundant element is not considered essential but all life forms contain it to varying degree. Plants, particularly monocotyledons absorb silicon in the form of silicic acid from soil and accumulate it as silica which gets deposited as layer on epidermal cells or as phytoliths in lumen of cells. Man and animals ingest silicon as silica in the food and feed. Most of the ingested silica is excreted in faeces and urine and only a small quantity is absorbed which plays a vital role in bone development. Silicon, although considered as cytotoxic never gets accumulated to the toxic level as it is excreted out. It always plays a positive role in plant or animal but the silicosis of lungs occur in miners is a health hazard. The essentiality of silicon is still in debate even though its beneficial role is well established. Like salt in food, which itself is not a nutrient or food item but adds to the taste and palatability. Similarly silicon though not essential confers rigidity and strength to plants, protects them from pests, diseases and abiotic stresses and plays an essential role in diatoms and in bone development of higher animals. The occurrence of silicon and its role in all spheres of anthropogenetic activity forms the present review.

Key words: Silicon uses · Nutrition · Cosmetics · Pharmaceuticals · Agriculture

INTRODUCTION

The planet earth is endowed with both animate and inanimate entities. The former comprises of all life forms on earth including microorganisms, plants and animals varying in size and form and diverse in habitats. Yet all of them are made up of carbonaceous materials, perish after a life span, fall on earth as debris and degraded rapidly or slowly ultimately turning into carbon and ash containing the minerals. The inanimate solid mass, the soil, including rocks and minerals buried underneath, are non degradable, water insoluble and therefore ever lasting as a substratum is made up of silicon compounds that serve for the foot hold for animals and anchorage for plants simultaneously serving as a repository of nutrients to plants. Not only soil but also the inanimate air and pure water are important in supporting the life forms. As per mythological belief man was created from inanimate materials and ultimately reaches soil whether buried or consigned to flames. It is important to note that life forms are made up of carbon compounds that are biodegradable and soil is made up of silicon compounds that are not biodegradable and this trait keeps life forms to come, live and leave the earth but soil remains forever sustaining all of them. Silicon is an element of earth and carbon is a non mineral element of life.

Silicon (Si), available abundantly on earth's crust is second only to oxygen [1]. It occurs to the tune of 27.7% (w/w) in the earth's crust . Although it is 146 times more abundant than carbon, it rarely appears as an integral component of biological materials. It is similar to carbon and shares many properties of carbon which forms the backbone of most organic molecules. Silicon seldom forms an integral component of any biomolecules as the Si-Si bonds are considerably weaker than C-C bonds and the Si-H bonds are relatively unstable and react readily with oxygen unlike C-H bonds. The larger size of the silicon atom (atomic radius 111ppm) compared to carbon (atomic radius 67ppm) also renders it unsuitable as a building block despite the fact that it can also form bonds with four other atoms creating a three dimensional network similar to carbon. Even though a few organisms absorb and accumulate silicon it is not considered as an essential nutrient by the physiologists. However it is found in

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Table 1: Mineral elements in crop plants

Element	Range of concentrations (Dry weight basis)	Remarks
Nitrogen, %	0.5-6	
Phosphorus, %	0.15-0.5	
Sulfur, %	0.1-1.5	Essential
Potassium, %	0.8-8	Macronutrients
Calcium, %	0.1-6	
Magnesium , %	0.05-1	
Iron, ppm	20-600	
Manganese, ppm	10-600	
Zinc, ppm	10-250	
Copper, ppm	2-50	
Nickel, ppm	0.05-5	Essential
Boron, ppm	0.2-800	Micronutrients
Chlorine, ppm	10-80,000	
Molybdenum, ppm	0.1-10	
Cobalt, ppm	0.05-10	Essential in all nitrogen Fixing systems
Sodium, %	0.001-8	Essential for some
Silicon, %	0.1-10	often beneficial
Aluminium, ppm	0.1-500	Not known to be essential
		Often toxic to plants on acid soils

[3]

diatoms, Chrysophytes, Silicoflagelletes, some Xanthophytes, insects and vertebrates [2]. Plants absorb and accumulate silicon and its content in plants ranges from 0.1–10% (10^3–10^5mg kg^{-1}) on dry weight basis, an amount equivalent to or even exceeding several macronutrients [3]. The mineral concentration of plants is given in Table 1. The animals devouring the plants certainly digest silicon compounds absorb and excrete them and therefore contain around 4 to 650 mg/kg of body weight. This varies with the animals and their tissues and depends on their food or feed ingested [4]. Apart from the nutritional point of view silicon and its compounds are used in diverse fields from cosmetics to construction materials. The presence of silicon in soils, plants and animals and its role in crop production has been reviewed [5-7]. However a comprehensive review on the role of silicon in all spheres of human life is still lacking. The utility of silicon in relation to anthropogenic activity is reviewed hereunder.

Silicon in Household: Silica based earthenwares are quite common in households. Mudpots (Utensils made of mud to store water or cook food), *Pathayams* (storage bins), *Thazhees, Chulas* are prepared by skilled artisans (pot makers) using clay which are dried and burnt in kilns so that they become strong and water proof. These utensils are used for cooking, storing water, grains, pickles, curd etc. It may be of interest to note that there are restaurants which exclusively cook food in earthenwares whose sign board depicts "*mannpaanai samayal*"(cooking made in earthernware vessels) indicating that metal based utensils are avoided. Rice and curries cooked in mud pots remain free from metal contamination and are unique in taste as earthenwares get heated up slowly and cool quickly after removing from the fire. But the contents remain hot for longer time. It may be of interest to note that even in houses utilizing metal utensils, leavening of milk, fish curry preparation and *koozh* (porridge) are usually made in earthernwares only, due to the unique flavor and taste they contribute.

Plates and cups made up of ceramic clays are also used widely as they are non sticky and easy to wash. In any case kitchen of rich or poor have silica based wares. Until the advent of washing powder, detergent cakes for cleaning utensils, either ash containing silica or soil itself was used for cleaning the utensils. The abrasive action of these siliceous materials cleaned the utensils free of dirt and oil.

Silicon in Building Materials: There are several building materials made of partly or entirely of silicate materials. Bricks, cement, fire bricks, tiles, asbestos are the products readily available in market, however sand, clay, limestone etc naturally available are also used. Mud walls (earthern) of huts are made up of clay, red soil etc which are only silica. After compaction and drying they act as durable solid walls resisting heat and chillness and lasting for years [8]. Bricks, roofing tiles are prepared out of clay. Construction of brick walls with clay mortar and plastering with clay also have been done in olden days. Stabilized pressed block of clay is also used in building construction with or without cement [9]. Lime mortar is prepared by grinding slacked lime and sand (quartz-SiO2) mixed ground and used for brick walls. With the advent of readily available manufactured cement, the use of lime mortar has vanished. The strength of lime mortar shall not be underestimated as the dams and temples built by ancient kings survived for centuries. Cement is a mixture of *tri*calcium silicate (Alite), *di*calcium silicate (Belite), *tri*calcium aluminate, *tetra*calcium aluminoferric. Sand which is totally silica is used in building along with cement for concrete. Lateritic stone, granite etc cut into required sizes are also used to build walls, steps in houses and in wells. These are also silicate materials only.

Huts always have a roof made up of coconut thatches or palmyrah or date palm fronds [10]. Such roof is always covered with materials like rice straw, sugarcane trash or water reed *Phragmites communis*. Rice straw has been traditionally used for roofing and packing [11]. Structural roofing system of domes and vaults supported by cementitious straw bricks is also made to have economical and environmental friendly houses [12]. Several types of grasses like Marram grass (*Ammophila arenaria*), Thatch grass (*Saccharum spontaneum*) and Cat tails (*Typha angustifolia*) are being used for covering thatches. Their silica content made them durable and resistant to decay and insulate the thatches from heat and cold. Man has chosen these materials that are rich in silica because it can withstand heat or cold and do not decay easily during rain.

Drain pipes in buildings, irrigation and drainage pipe lines, sewage lines were laid using earthen pipes or stonewares specially prepared for the purpose. Such stone wares are also made up of special type of clay. This was replaced by asbestos pipes and off late by poly vinyl chloride (PVC) pipes. Fire bricks are used in lining walls of furnace to withstand high temperature. They are also made up of silica. They contain 50% silica (SiO2) and 30–40% alumina (Al2O3).

Asbestos sheets, ropes are used for roof tops, brake lining and gaskets for insulating steam pipes. It is prepared from a set of six naturally occurring silicate minerals out of which 95% of the world trade in asbestos is from chrysotile, the white asbestos. In recent times the use of asbestos is discouraged as it is considered as "Killer dust" causing asbestosis (fibrosis of lungs), lung cancer, mesothelioma, asbestos warts, pleural plaque, diffuse pleural thickening and cancer of larynx and ovary.

Silicon in Industrial Applications: Silicates have multivarious industrial applications. They are used in muffle repair, fitting paste and as a sealant for leaking head gasket in automobiles. It is used as paper cement for producing paper cartridges used in cylinder revolvers. Its use in drilling fluids, as a binder of solids for insulating of materials used in refractory, waste water treatment, egg preservation, in passive fire protection materials, detergent auxiliaries, magic rock toys and in dying textiles are well known [13].

Microchips used in computers and electronic devices are silicon cut down to microproportions with governing instructions imprinted on them through photographic process. They are used to run computer, cell phone and gorming devices [14]. Quartz crystals used in watches, radios and pressure gauges are also of silicate origin [15]. These crystals produce rhythmic high frequency vibration and hence used as oscillators as the crystal emit a rhythmic beat when hooked up to an electronic source and movement piece can be logged.

Silicon based semiconductors are also used in nuclear weapons. Ceramic tiles are used in space shuttle to protect it from high temperature. Silicon carbide (SiC) is a hard crystalline material manufactured by fusion of silica (sand) and carbon (coke) in an electric furnace at a temperature of 2200°C. This is commercially known as carborandom and used as abrasives, semiconductors, capacitors and other electronic components [16].

Silicone oils find wide use as lubricants, hydraulic fluids, cooking fluid in diffusion pumps and electrical insulation because of this non-flammable nature. Silicone oils are polymerized siloxanes with organic side chains and can form long and complex molecules [17]. Silicone oil like simethecone is used as an antifoaming agent (defoamer) in fermentation industries to avoid foams during aeration. These oils are also used in the manufacture of polyurethane foam.

Silicon in Cosmetics: A variety of cosmetic products from soap, face powder, tooth paste, dental powder, sunscreen products, sun ban lotions etc. are in use in modern days. Soaps were originally prepared with goat tallow and wood ash containing silica. The soap manufacturing was improved and sodium silicate or potassium silicate is used instead of wood ash in recent times. The talcum powder every one use is made up of talc (52% SiO2) to which perfumes are added. Talcum powder removes oil in the skin and keeps the skin moist. Nowadays specially formulated moisturizers containing silicates have come into use to protect the skin from sun ban. Synthetic silica like fumed silica, silica gels and precipitated silica find wide applications in cosmetics, toiletry and indentrifice goods [18].

In recent times beauty parlors have been established even in villages to arrange for facials, make up etc for brides. Young girls also have become conscious of their appearance and take up special treatment in such parlors. Most of the materials used in such parlours are based on silica. *Multhanimeti,* a type of talc powder applied to face is of silica only. Silica silyate is incorporated in lip glass, eye liner, eye shadow, mascara, nail polish etc.

Amorphous silica or microspheres, a round form of silica or fumed silica is allowed in cosmetics. Silica and silica aero gel are widely used. This keeps the product in good condition and is added to stabilize suspension for viscosity stabilization, thixotrophy and as an anti caking agent. It serves as an abrasive agent, as absorbent, bulking, opacifying agent, suspending agent. Face powder, rouge, eye shadow, mascara, cosmetic pencils are optimized with silica products [19]. Silica improves the flow of powder, prevents, reagglomeration of the pigments. It is an effective mattifying agent that prevents face from appearing shiny. In nail polish addition of silica improves the nail polish pigments and prevents from setting. Silica improves the homogenous distribution of pigments in lipstick. Pigment migration or bleeding into the fine line of lips is contained by silica on lipstick application.

Silicon in Pharmaceuticals: Soil was applied to injury as a protectant from infection wherever no immediate medicine was available. This has been practiced particularly during war time. Silicates are used as a raw material for antacid products. Magnesium silicates, magnesium aluminum silicate, magnesium trisilicates are used in several formulations. Silicates serve as carrier for modulating drugs. Mesoporous silicates of pores of 2–50 nm are used for drug delivery devices or for sustained release of poorly water soluble drugs [20, 21]. Silica aerogel drug formulations are widely used as drug delivery systems for drugs whose immediate release is desirable [22].

Smectite clays are used as excipients in pharmaceutical formulations. They serve as suspension and emulsion stabilizers in liquids, control the drug release in ointments and suppositions, as a binder in solid dosage forms and as disintegraters in wet formulation. Micronized forms of smectite are used for direct compression of tablets.

Silicon in Water: Water contains silicon and its content is unusually low. The dissolved silicon in water is in the form of o-silicic acid. Silicates are abundant in soil but these differ in water solubility. The most common form of silicon in soil is silicon dioxide (sand, quartz) and this has a very poor water solubility of 0.12% / l. As natural water has direct contact with soil, sand, silt etc. the quantity of silicon in water varies greatly.

Rain water may not contain any appreciable quantity of silicon but it can collect dust in the air and add its own silica content. The cloud water content of Si ranged from 0-1.5 ppm Si / l while through fall and stem flow showed an average of 0.21 ppm Si / l and ranged from 0.5 – 5.5 and 0-1.25 ppm Si / l respectively [23]. The through fall and stem flow had relatively higher content of silicon because they fall on canopy with deposited particles. Rain water when falls can particulate and aerosol materials containing soluble silicon. The runoff water, water in streams, rivers and dams may contain more silicon as the run off water leach this from soil of catchment area. The silicon concentrations of most river water were found to vary from 4.7–16 ppm Si [24]. Si in river water depends on the chemical nature of rocks in the catchment area. Rivers flowing over volcanic ash may contain more silicon in water. Silicon concentration in well water of Kerala (India) ranges from 2.4–3.2 ppm Si and that of irrigation water from the dam showed 5.6 ppm Si [25].

In Japan Si found in river water flowing through region of sedimentary rocks was 4–7 mg Si/l and 21 mg Si/l for those near volcanic rocks [26]. Similar observation was also made in Chile [27]. As high as 23–28 mg Si/l was found in deep ground water. Surface layer of ocean water exhibit a silicon content of 30 ppb whereas deeper layers contain 2 ppm silicon. The silica (SiO2) content in well water ranges from 1–100 mg/l and that of mineral water is less than 20 mg/l. Highly purified water too contains about 20 mg Si [28].

Si occurs in natural waters as ionic and molecular. Si aggregate, Si as colloid, solid and or gel, Si adsorbed on sesquioxide, organic Si complexes like humites, metal Si complexes, and in long organisms and those released from decaying plants and animals [29]. The total silica in water includes ‘reactive silica’ (silicates) dissolved, slightly ionized but not polymerized and unreactive silica which is colloidal and polymerized. Particulate silica compounds like silt, clay and sand may be present (1 µm or higher) but these can settle down upon standing. Soil and sediments form the primary source of silicon in water. A variety of silicate containing materials used in aquaculture, automobiles, drilling fluids in food preservation, fly ash, slags and ashes from industries, detergents and concrete may find its way into the water when they are added to soil during or after use.

Silicon in Food: The food consumed by man or animals is not free from silicon and contain varying levels of silicon [30, 31]. Water, vegetables, fruits, milk and milk products contain varying levels of silicon (Table 2). Plant products are relatively higher in silicon content than meat and meat products. There are many silicon supplements in market. Bamboo silica, organic silicon like monomethylsilanetriol is marketed for their therapeutic value. Extracts of horse tail (*Equisetum arvense*) rich in silicon is consumed in certain parts of the world as a health toner. It is also a common practice to eat the pulp of *Typha domingensis* stems in sudan [32]. It is claimed that silicon enhances the function of iron, calcium, magnesium and boron besides it's essentially for collagen and bone development. In certain African countries boiled clay suspension is consumed as porridge to quench the apatite. A practice practiced done occasionally has become a routine one during severe famine periods.

Cattle reared in low silicon soil were reported to feed on saprolytic basalt rock on the edge of roadways. Despite feeding with mineral supplements animals continue to feed on the rocks. This clearly indicates that cattle prefer silica for its mineral nutrition. Ground rock and Tennasse valley slag added to mineral boxes were readily eaten by cattle [33]. These indicate both man and animals prefer silica as food and feed supplement.

Silicon in Plants: Among the 118 elements so far discovered about one-sixth is found in life forms. Silicon concentrations are found to be higher in monocotyledons than in dicotyledons. The difference between graminaceous plants and legumes has been known since the first observation of silica in plants [34]. Some plants absorb more silica than they require and this gets deposited on tissues as it cannot be excreted [35]. Silicon content of plants varies greatly from 0.1–10% on dry weight basis. The highest concentration is found in horse tails. Its content increased from legumes < fruit crops < vegetables < grasses < grain crops [36]. The aerial parts accumulate more silicon than roots. In general the silicon content of shoots tend to decline in the order of liver worts > horse tails > club mosses > mosses > angiosperms > gymnosperms > ferns [37]. Based on the silicon levels in tissues three groups of plants were recognized viz (i) dicotyledons with less than 0.1% on dry weight basis, (ii) dry land grasses like oats and rye with 1.5 % and (iii) wet land grasses and paddy grown rice with silicon content 5% or higher [5]. Plants of the family Poaceae, Equisetaceae and Cyperaceae exhibit high silicon accumulation (>4% Si), the Cucurbitales, Uritcales and Commellinaceae show intermediate levels (2–4% Si) while most other species contain less silicon (<2% Si). The mean relative silicon content of certain plant species are given in Table 3.

Table 2: Silicon content in food

Food	mg Si / 100g
Cereal and cereal products	
Biscuits	2.44
Bread brown	6.17
Bread (whole meal)	2.25
Bread (whole grain)	4.45
Bread (white)	1.79
Corn flakes	1.88
Oat bran	23.36
Oat cakes	18.26
Rice white boiled	1.86
Brown rice boiled	3.76
Wheat biscuits	5.25
Wheat bran	10.98
Fruits	
Apple raw	0.21
Banana raw	4.77
Dates dried	16.61
Grapes	0.49
Mango (fresh raw)	2.00
Legumes	
Chick pea	0.76
Lentils (red boiled)	4.42
Soybeans	1.19
Peas (Fresh / boiled)	0.19
Potatoes, fresh,peeled, boiled	0.34
Spinach (fresh/ boiled)	5.12
Beer	2.19
Caja beer	2.84
Wine	1.24
Black tea	0.86

[30, 31]

Table 3: Si (SiO2) content of different plant species

Crop	Soil type/pH	SiO2 (%)
Barely		1.95
Rye	Humic acid, pH 5.2	1.58
Red clover		0.12
Blue lupin		0.24
Oats	Sandy loam, pH6.2*	2.04
Rye		2.41
Rye grass		2.34
Crimson clover		0.12
Peas		0.25
Mustard		0.15
Rice`		1.5-8.0

[5]

Silicon is absorbed by plants in the form of *ortho*-silicic acid (H4SiO4) along with water but its availability in soil solution is low and ranges from 0.1–0.6 mM [38]. Soil itself is polymerized silica but it is not available to plants unless depolymerized to monosilicic acid by weathering or biological activity of roots and microbes. The absorption is a non selective and a passive process and the transport from root to shoot is in the transpiration stream in xylem. The water is lost in transpiration concentrating the level of silicic acid in the plant which polymerizes and form a hydrated amorphous silica gel or opal.

Silica deposition is observed in almost all parts of plants but the concentration varies. The silicon content of different parts of rice is given in Table 4. It is deposited mostly in cell walls but sometimes as silica bodies in the lumen of cells. Individual silica bodies may be oval, dumb-bell shaped, rectangular or rod like particles in plants [40]. Silicification occurs in epidermal cells, scelernchyma, vascular bundles and in florescence bracts of cereals. Silicified structures as discrete knobs and rosettes covered in spicules present in the epidermal surface of entire cell walls in *Equisetum*. The thickness of silica surface layer was 3–7 µm in the stem and 1–2 µm in leaf. In the Poaceae silica is deposited as 2.5 µm layer beneath the cuticle forming a double layer of silica-cuticle in leaf. Globular, fibrous and sheet like micro structures was observed in plants of Poaceae and Equisetaceae.

Silicon in Animals: Animals like cattle, sheep and goat feeding on vegetable matter, particularly grasses consume more silica. Herbivores, birds, feeding on whole grains including hulls, straw and hay ingest large amount of silicon in the form of silica. Dogs and other animals that feed on dead animals and food thrown in soil take up sand/ soil particles along with their prey or feed [4]. The entire silica ingested is not absorbed but mostly excreted out in urine as silicic acid and also expelled in feces. Carnivorous and omnivorous animals have a lower urinary excretion of silicic acid than herbivores. It may be noted that the urinary excretion of herbivorous, sheep, rabbit and guinea pigs are relatively higher than the higher animals tested (Table 5). The extent of urinary excretion is influenced by the diet or feed. It is found that about 85% of ingested silica is expelled in feces and the remaining is excreted in urine of animals and only a small portion is retained in the body. In spite of excretion, a part of silica is also observed after being converted to silicic acid and seen in bones, cartilage, hair and feathers of animals.

Table 4: Distribution of Silicon (Si) in Rice plant

Plant Parts	Si content (g kg^{-1})
Polished rice	0.5
Rice bran	50.0
Rice straw	130.0
Rice hulls	230.0
Rice joints (base of the grain)	350.0

[39]

Table 5: Silica content in urine of animals

Animals	mgSiO2/100 ml of urine*
Human (normal)	0.8-2.1
Humans (Silicotic)	1.4-6.6
Dog	0.7-2.7
Cat	0.4-0.8
Sheep	12.8-17.2
Rabbit	7.2-27.2
Guinea pig	8.2-28.6

[4] *Ranges recorded from more number of sample

Table 6: Silica content in tissues of animals

Animals	mg Si02
Foetus: Mouse (whole foetus)	10.7
Calf foetus muscle	24.2
Calf foetus lung	3.8
Calf foetus kidney	9.6
Calf foetus liver	10.6
Calf foetus spleen	11.2
Human lung	9.8
Human liver	3.8
Human kidney	13.3
Human spleen	20.3
Human heart	20.4
Human brain	22.0
Tissues Human lung (normal)	143.0
Human lung (silicotic)Human liver	196.0
Human spleen	15.1
Human bone marrow	26.0
Ox lung	103.0
Ox liver	21.0
Dog lung	115.0
Dog kidney	28.7
Chicken feathers	15.1
Rabbit lung	148
Rabbit liver	360-687
Rabbit kidney	380-647
Rabbit hair	16.5
Guinea pig lung	78.0
Guinea pigs hair	19.4

[4]

Eggs of birds, both white and yolk contain small amount of silicon [41]. Appreciable quantities of silicon were also observed in individual organs and whole foetus of mammals and tissues of adult animals (Table 6). Entry of silica into the body also occurs through inhalation by lungs causing silicosis and cancer of lungs.

This is more common with miners. In other cases a fewer particles inhaled is expectorated while a few get lodged in cells and drawn into lung parenchyma.

In animals too silicon accumulation may pose certain health hazards. In rats and dogs fed with relatively large doses of magnesium trisilicate and sodium silicate in the feed, polydipsia, polyurea and soft stools were observed in rats. Feeding dogs with a diet containing high silica resulted in not only polydipsia, polyurea but also renal damage with gross cortical lesions in kidney [42]. Urinary calculi composed chiefly of silica are common in some animals and this caused serious economic problem in rearing of cattle. Such as urinary calculi were also observed in human patients ingesting magnesium trisilicate tablet over several years. However it is the fact that animals and human tissues carry silica right from the foetus.

Silicon in Man: Silicon constitutes approximately 1g in human body which is present in various tissues and body fluids. It is present in connective tissues including aorta, bone, skin, hair, nails, tendon and trachea. It is believed to be present as silicinolate, ether or ester like derivative of silicic acid, cross linking the structural carbohydrates of connective tissues. Silica is glue for ligaments that anchor the brain to skull and holds the kidney in place. It appears that any type of supporting tissue that requires both strength and flexibility contains silica. Silica separates one bone from another.

The silicon content in aorta, arterial vessels and skin declines with aging while it increases in kidney, brain, liver, spleen and lungs. The source of silicon is water and food. Plant food contains a higher quantity of silica while animal food contains a low quantity. The excess of silicon is excreted through urine or expelled in feces.

Silicon in Bone: Silicon is important for bone formation, growth and development [43]. It is required for the proper function of polyhydroxylase which is responsible for the formation of collagen in bone and elastine, cartilage and other connective tissues. Silicon is known to prevent osteoporosis that normally sets in older people. Silicon deficiency causes weak and malformed bones of the arms, legs and hand, osteoporosis, alzheimer's disease, bone decalcification, cardiovascular diseases, atherosclerosis, abnormal skeleton, split, ridged and brittle nails and hair [44]. Silicon play an important role in the synthesis of glucosaminoglycans and collagen and hence in bone formation. Silicon containing implants and ceramics such as Si- substituted hydroxyapatites and bioglass have been shown to bond much better to bone than non-silicon containing materials. This also indicate involvement of silicon in bone [45, 46]. It is believed that high levels of soluble silicon may reduce neurotoxicity of aluminum and prevents binding of aluminum to the gut [47, 48].

Silicon is involved in hardness of enamels and in prevention of bleeding gums. Perhaps that is why our ancestors used high silica containing materials like ash as tooth powder for cleaning teeth. Villagers have traditionally used river sand or brick powder for cleaning teeth. It may be recalled here that the common tooth powder umikari (husk char) and uppu (salt) adopted to clean the teeth in the morning in some parts of Tamilnadu, India may not be only for abrasive action but also as a sort of silica application to enamels.

Silicon in Blood and Blood Vessels: Silicon maintains the structural integrity, elasticity and permeability of blood vessels. Silicon exists as undisassociated monomeric silicic acid and its concentration remains relatively constant in blood as it is readily distributed to tissues or excreted in urine [49]. Human blood was found to contain 110–250 µg Si/l [50]. However pregnant women record low silicon in serum (33–44 µg Si/l) and infants a higher concentrations (340–69 0µg Si/l).

Alzheimer's disease occurs in old people primarily because of aluminium accumulation in brain tissues. Silicon facilitates removal of aluminium in tissues and it is believed that a deficiency of silicon leads to the disease. Although no dietary intake is stipulated for human it is felt that silicon is essential to maintain proper health. The habit of eating bamboo sprouts, tender bamboo shoot and drinking *arugambul* (hariali grass *Cyanodon dactylon*) juice in certain tracts may be to supply silicon besides antioxidants.

Silicon and Hair: Every one of us man or woman is interested to have a good crop of hair. Beautiful hair is largely due to the intake of silica. Human hair contains 1-10 ppm of Si [51]. Silicon strengthens the hair, renders it less brittle and split. At optimum silicon uptake the skin and hair is well hydrated and maintain a lusture that is attractive and young looking. Most of the hair conditioners keep the moisture in hair and silica does this job only. Silica can help to prevent baldness but it cannot be used as a cure. It stimulates growth of hair and keeps it healthy and strong making it more beautiful and attractive.

The practice of applying *shikkakai* powder (prepared from legume pods and with fine clay powder) on long hairs of women twice a week (adopted in Indian households) keeps the hair free from dust and washes off creaminess due to oil used. Invariably finely sieved clay is said to be always mixed with *shikakkai* powder even though it is not declared as a constituent.

Silicon and Diseases: Silicon absorbed from food is excreted and eliminated in urine continuously probably as *ortho*-silicic acid and magnesium *ortho*-silicate [49]. Men excrete between 12–16 mg Si/day. Urinary excretions of 3 mg Si/day and around 20 mg Si/day have also been reported. Excess of silicon in diet normally causes no harmful effect or diseases as this is excreted out. *ortho*-silicic acid is the major form of silicon present in drinking water, beer and other liquids. Pytoliths present in plants when eaten gets digested and converted to *ortho*-silicic acid and this is bioavailable. A safe upper level for daily consumption of silicon at 700 mg Si/day for adults over a life time (equivalent to 12 mg Si/kg of body weight /day) for a 60 kg adult was fixed by the Expert of Vitamins and Minerals [50]. Such a large level may not be present in the food an adult consume. However certain drugs taken in the form of tablets and syrup contain silicates and this may add to the silica intake. The EFSA panel on dietetic products, nutrition's and allergies estimated that a dietary intake of 20–50 mg Si/day (equivalent to 0.3–0.8 mg/kg body weight/ day in a 60 kg of person) is unlikely to cause any adverse effect.

However a siliceous type of urinary calculus in sheep and in dogs is associated with silicon compounds in food. Absorbed silica in human is excreted by the kidneys without any evidence of toxic accumulation in the body [52]. Cases of urinary calculi related to the use of magnesium trisilicate as an antacid has been observed. The incidence of silicon containing urinary calculi was found to be 0.07% of just all kidney stones in man. Silicosis, a lung disease is a common one in miners and those handling asbestos. Asbestos and crystalline silica inhaled affects human health. These are considered as carcinogen causing malignant lung cancer or mesothelioma. Silica and silicates may disturb immune functions such as autoimmunity and tumour immunity [53].

Silicon in Agriculture: Soil itself is a polymerized silica and without this base that provide substratum for anchorage and absorption of nutrients agriculture cannot exist. Hydroponics play a role in the production of fruits and vegetables. But the production from soil based agriculture feeds the millions of population. Soil also serves as a storage reservoir for tubers atleast for a short period. Application of sand to fishes and prawns to prevent quick spoilage is also common in markets.

The beneficial effect of silicon in crop production is well recognized. About 20 elements are considered essential for plant growth some of which are required in large quantities (macronutrients NPK) while a few others are considered in smaller quantities (secondary nutrients Ca, Mg, S) and still others are required in micro quantities (micronutrients Fe, Cu, Zn, Mn, B, Mo, Cl). Silicon, not considered as an essential element as it does not constitute a part of any metabolite nor its absence poses any difficulty in completion of life cycle of plants. Although it does not satisfy the criteria considered by the physiologists for an essential element agronomists consider this as a beneficial element that accelerate plant growth, confers rigidity and strength, resistance against pests and diseases and mitigate the ill effects of abiotic stresses like drought, salt or metal toxicities. However silicon benefits the plants in several ways and increases grain yield. Crops like rice, millets, sugarcane etc. are known silica accumulators and they require large quantities of silicon. Even though silicon is not considered as essential in the physiologist's point of view agronomists consider this element as an agronomically beneficial element [54, 55].

Silicon is required for the healthy and productive development of the rice plant [56]. It is estimated that a rice crop producing a grain yield of 5 t/ha normally removes 234–470 kg Si/ha (500–1000 kg SiO2/ha) on an average from soil [57]. Silicon removal of 12 rice varieties differing in duration from 90–140 days grown in inceptisol during dry season showed a removal of 205–611 kg Si/ha [58]. Because of its high requirement rice responds well for silicon application. With the advent of nitrogen responsive high yielding rice varieties the demand for silicon increased. Nitrogenous fertilizers favor succulence in plants predisposing the crop for lodging. Silicon on the other hand nullifies the ill effect of nitrogen and confers rigidity and strength. Nitrogenous fertilizers decrease the silicon uptake in rice [59]. Silicon was found to be beneficial to barley, wheat, corn, sugarcane, cucumber, tomato, citrus and other crops [3]. Its beneficial effect on sugarcane production suppressing pests and diseases of sugarcane has been well established [60, 61]. It is estimated that a 12 month old sugarcane crop in a hectare accumulates about 380 kg Si/ha.

Silicon nutrition benefits rice crop in several ways. Silicon confers rigidity and strength making the rice plants erects facilitating effective interception of sunlight thus enhancing photosynthesis, photoassimilation and ultimately plant growth and yield [62]. An increase in water use efficiency by reducing excessive transpiration was also observed. Silicon alleviates certain nutritional disorders like akiochi or bronzing. It confers lodging resistance to plants, resistance against pests (Table 7) and diseases (Table 8) and mitigate the ill effects of abiotic stresses (Table 9) like drought, salt injury, heavy metal toxicities [5-7, 117-119].

Silicon Fertilization: Realizing the beneficial effects of silicon in sustainable crop production and the response of several crops to silicon nutrition in solution and soil cultures silicon fertilization to crops to sustain crop yields has become a component of integrated nutrient management in certain countries. Experiments have been conducted in Japan, Korea, China and India on rice and sugarcane in Brazil on the effect of application of naturally occurring or synthetic silicates. The traditional practice of collecting the ashes from the back yard of houses accumulated over a period of time from household chulas burning fire wood, twigs, trashes, cow dung cake etc. and applying them to fields before the commencement of cropping supplies not only supply potash but also silicon. Off late ashes (husk char) from rice mills, sugar factories, lignite fly ash from thermal power stations are used as fertilizer. It is to be noted that rice farmers in Cauvery delta in India regularly apply 3–5 t river sand (SiO2) /ha once in 2–4 years. It is presumed that sand loosens the heavy clay but in reality it restores the silicon removed from soil by continuous monoculturing of rice.

The concept of silicon fertilization to crops has gained momentum world over and several countries have experimented different sources of silicon and used them as fertilizers [6, 120, 121]. Wallostonite ore, slags from Iron and Magnesium ore smelters slowly cooled slag, air-cooled slag, quenched slag and fused phosphate slag [121] electric furnace calcium silicate slag [86, 122] lignite fly ash [123] have all been tested. In certain countries like China potassium silicate solution is supplied as a fertilizer to supply both K and Si. It is evident that these sources of silica increased the grain yield. The increase in yield of planted and ratoon cane due to silicon nutrition was also observed (Table 10).

Table 8: Diseases suppressed by Si nutrition

Disease	Pathogen
Rice	
Leaf and neck blast	*Pyricularia oryzae* [83]
Brown spot	*Bipolaris oryzae* [84]
Sheath blight	*Rhizoctonia solani* [85]
Leaf scald	*Monographella albescens* [84]
Grain discoloration	*Bipolaris fusarium* [83]
Stem rot	*Magnaporthe salvinii* [86]
Sugarcane	
Sugar rust	*Puccinia melanocephala* [87]
Ring spot	*Leptosphaeria Sacchari*
	Phyllosticta sp. [anamorph] [88]
Banana	
Panama wilt	*Fusarium,oxysporium,f.sp.cubense* [89]
Cucumber	
Powdery mild dew	*Sphaerotheca fuliginea,Pythium* [90, 91]
Wheat	
Powdery mildew	*Erysiphe graminis, Oidium monilioides,*
	Blumeria graminis sp.tritici [92]
Cowpea	
Rust	*Uromyces phaeseoli typia* [93]
Cucumber	
crown and root rot	*Pythium ultimum* [94]
Melon	
fruit decay	*Alternaria alternate* [95]
	Fusarium semitectum [95]
	Trichothecium roseum [95]
Soybean	
Downy mildew	*Peronospora manshunica,*[96]
Frogs eye leaf spot	*Cercospora sojina,* [96]
Asian rust	*Phakospora pachyrihizi,* [96]
Seedling damping off	*Fusarium semitectum* [97]
Stem canker	*Diaporthe phaseolorum*
	f.sp.meridionalis [98]
Soybean sudden death syndrome	*Fusarium silani* [99]
Carrot	
Cercospora blight	*Cercospora carotae* [98]
Alternaria blight	*Alternaria dauci*
Coffee	
Frog's eye spot	*Cercospora coffeicola* [100]
Avocado	
Anthraconase	*Colletotrichum gloesporioides* [89]
Augustine grass	
gray leaf spot	*Magnaporthe grisea* [101]

Table 9: Role of silicon in mitigation of / alleviating the abiotic stress in plants

Physical stress	
Lodging	
Drought	
High temperature	All crops [101, 102, 103, 104]
Freezing	
Radiation, UV etc.,	
Chemical stress	
Salinity	Rice [105]
	Wheat [106]
	Mesquite [107]
	Maize [108]
Mn toxicity	Cucumis [109]
	Bean [110]
Al	Rice [111]
Cu	Arabidosis [112]
Fe	Sugarcane [113]
Cd	Rice[114,115]
	Maize [116]
Zn	Maize [116]

Table 10: Effects of calcium Silicate on average cane yields of two cultivars

	Plant Cane			Ratoon			
Treatments	1968	1969	1970	1971	1972	1973	Mean
Control	40.0	78.4	53.8	71.1	61.1	55.2	59.9
Calcium Silicate 7.1 t	63.5	92.2	62.1	83.9	72.8	68.5	73.8
Calcium Silicate 14.2 t	68.5	96.2	64.5	90.5	76.8	72.0	78.1

[61]

Table 11: Influence of SSB inoculation on the yield parameters in Rice

Treatments	No. of grains Per panicle	1000 grain Weight (g)	Fully filled grains (%)	Biomass (t/ha)	Grain yield (kg/ha)
Control	54	22.14	76.7	10.24	3400
SSB	62	22.84	78.1	11.27	3800

[131]

***In Situ* Solubilisation of Silicates:** The use of biofertilizers that hairness atmosphere nitrogen solubilise phosphates and plant growth promoting rhizobacteria has come into vogue in modern day farming. Improvement of plant growth and crop yield by liberating the soil nutrients through seed bacterization and soil application of biofertilizers are practiced by farmers all over the world [124, 125]. The solubilization of silica by bacteria is considered as a source of supply for crops. The entire soil is polymerized silica wherein silicates predominate and is not bioavailable silicon. Plants absorb monosilicic acid only. Even if exogenous silicate minerals are used as fertilizer these have to be solubilised. The ability of bacteria to depolymerise crystalline silicate was demonstrated [126]. Several microbes like *Bacillus caldolytyicus*, *Bacillus mucilaginosus* var *siliceous*, *Proteus mirabilis*, *Pseudomonas*, *Penicillium* were found to release silica from natural silicates [127, 128]. Field inoculation of silicate bacteria was found to augment yield of maize, wheat, potato and tomatoes [129]. 'Silicabacterin' and 'Azotobacterin' inoculation increased the raw cotton yield [130].

A *Bacillus* sp was isolated from granite crusher yard soil and upon inoculation this silicate solubilising bacteria (SSB) to rice increased the biomass and grain yield [131, 132] (Table 11). In soil incubation studies with four different soils he found that SSB inoculation released silicon and concurrently released phosphorus and potassium. It was suggested that besides silicon, silicate minerals contain potassium, calcium, magnesium, iron and zinc and therefore inoculation of SSB to soil may benefit the crop by releasing several of these nutrients.

Silicates as a Carrier for Bioproducts: The organic agriculture is gaining momentum as the problem of pesticides residues in food commodities and due to the concern of environmental pollution through their indiscriminate use. Biofertilizers are widely used in modern day agriculture to minimize the use of chemicals. These are mostly carrier based materials. Talc [133], vermiculite [134] and phytosil [135] serve as a good absorbent for the bacterial and fungal cultures. Talc based formulation of biopesticides like *Beauveria, Metarrhizium, Paecilomyces*, and biocontrol agents like *Trichoderma and Pseudomonas* are available in market. Vesicular arbuscular mycorrhiza inoculum is supplied in vermiculite. Phytosil also has the potential as a carrier but not widely used because of its lesser whiteness compared to talc.

CONCLUSION

The presence of silicon in plants, animals and man is well established. It plays a positive role in plants conferring rigidity and strength and protects the plants from biotic and abiotic stress. Silicon nutrition and application of silica materials to crops either naturally occurring or thrown as waste from industries boosts crop yields. Therefore its use in agriculture has become world wide. Its requirement to animals and man becomes important for the development of bone, fairness of hair and also prevention of certain cardiovascular diseases even though it is a serious health hazard causing silicosis of lungs upon inhalation. This is a problem with those working in mines and asbestos industry. Yet silicon products have emerged for use in food, cosmetics and computers which men and women use in day today life.

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