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REVISITING SILICA: AN EMERGING BIOACTIVE NUTRIENT IN FOOD, HEALTH, AND MEDICINE (si(OH)$_4$)

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ABSTRACT: Silica (silicon dioxide) is a naturally abundant mineral found on earth. During the last decade, silica has received a lot of attention due to its newly proposed potential health benefits. To date, silica is an important bioactive dietary component that plays a critical role in its bioavailability and in maintaining human health in relation to skeletal and connective tissue health. Recent studies related to silica as a dietary component include bioavailability and analysis of silica within the body, nutrigenomics, biomedical technology, effects on bone health, potential cosmetic applications, and relationship with probiotics. In this review, silica will be defined, from where it came about, what it is composed of, and where it can be found. Special attention will be focused on silica-rich sands that are found throughout the world. Dietary silica and naturally occurring silica in plant-based foods, beverages, and functional products will be discussed. Topics including absorption, metabolism, biological roles of silica within the human body, and interactions with calcium and trace minerals will be reviewed. Special attention will be discussed on silica's possible mechanisms of action that aid in bone mineralization and prevention of osteoporosis. Reviews will include silica enhanced products, probiotic–silica relationships, nutrigenomics, and how silica relates to aeronutrition. Research on cosmetic uses of silica, new medical technologies utilizing silica, and functional food applications will be reviewed. Market values and cost will also be discussed. Lastly, needs and opportunities for future research will be discussed to help aid silica as a nutraceutical and in biomedical applications.

INTRODUCTION: Silicon dioxide (SiO_2), the chemical name for silica, is one of the most prevalent inorganic substances on Earth and a vital part of the crust [12, 24].

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In contrast to other vital minerals like calcium, magnesium, or phosphorus, silica's biological and nutritional relevance has historically received little scientific attention, despite its geological ubiquity [8, 21, 14].

However, in recent decades, silica has become a chemical of increasing interest in a variety of fields, such as material science, medicinal technology, cosmetic chemistry, nutrition research, and bone biology [3, 5, 9, 10, 22].

In human physiology, silicon, the elemental precursor of silica, is acknowledged as a trace element [14, 21]. Despite not being formally recognized as an essential nutrient, mounting data indicates that dietary silicon is important for mineral metabolism, skeletal growth, and connective tissue health [3, 14, 8]. Higher dietary silicon intake has been linked to enhanced bone mineral density in epidemiological studies, especially in communities that eat plant-based diets high in whole grains and vegetables [15, 22]. Understanding silica's bioavailability, biological function, and interactions with other minerals particularly calcium has drawn fresh scholarly attention as a result of these findings [14, 18].

In addition to nutrition, silica is widely used in pharmaceuticals, cosmetics, functional foods, and new medical technologies [5, 9, 26]. Silica is a desirable material for tissue engineering, drug delivery systems, and nanoparticle-based treatments due to its physicochemical stability, biocompatibility, and structural adaptability [9, 10, 11]. Simultaneously, silica-infused nutraceuticals, cosmetic supplements, and functional beverages often promoted for the health of the hair, skin, nails, and bones have become increasingly popular in consumer markets [5, 14, 20].

The scientific literature on silica is still dispersed across several disciplines, despite this expanding interest [12, 14]. Comprehensive assessments that combine geological origins, chemical characteristics, nutritional sources, bioavailability, physiological roles, health advantages, and commercial applications into a cohesive framework are scarce [8, 14]. Additionally, there is still a lack of research in new fields such probiotic interactions, aeronutrition, silica in nutrigenomics, and sophisticated biomedical technology [9, 26, 10].

By offering a thorough, multidisciplinary understanding of silica, this review seeks to close these gaps [8, 14]. The following are the goals of this review: Describe silica and discuss its nomenclature and historical discovery. Analyse its geographical spread and geological formation. Describe its physicochemical characteristics and chemical makeup. Examine food sources, dietary intake, and bioavailability. Examine its physiological functions and health advantages. Examine its effects on bone health and how it interacts with calcium. Examine its uses in medicine, nutraceuticals, and cosmetics. Talk about cost factors, market developments, and upcoming research requirements.

What is Silica?

The oxide form of silicon, silica, is mostly found as silicon dioxide (SiO_2) [12]. In terms of structure, silica is made up of four oxygen atoms arranged in a tetrahedral configuration with one silicon atom covalently bound to them [9, 12]. Adjacent tetrahedra share each oxygen atom, creating a vast three-dimensional network. The exceptional stability and variety of silica materials are attributed to this basic structural theme [12].

There are two types of silica: crystalline and amorphous [12]. Polymorphs of crystalline silica, including tridymite, cristobalite, and quartz, vary in their thermodynamic stability and atomic arrangement [12]. The most prevalent crystalline form, quartz, is a key component of rocks, soils, and sand [12, 24]. On the other hand, amorphous silica, which is present in minerals like opal, diatomaceous earth, and biogenic silica made by microbes and plants, lacks long-range atomic organization [9, 12].

The soluble and bioavailable form of silica that is absorbed in the gastrointestinal tract is orthosilicic acid ($Si(OH)_4$), which is the most often consumed hydrated form of silica from a nutritional standpoint [14, 21]. The solubility, absorption, and biological activity of silica are all significantly influenced by its chemical state [8, 14, 15].

Silica's Historical Discovery and Nomenclature: Throughout the history of chemistry, our understanding of silica has gradually changed. Although silica-rich materials like glass and sand were known to ancient societies, it wasn't until the 18th and 19th centuries that modern chemistry began to take shape that the chemical makeup of silica was fully recognized [12].

Though he was unable to separate silicon from silica, Antoine Lavoisier often considered the inventor of modern chemistry identified silica as an oxide. Sir Humphry Davy tried to separate silicon in 1808 and came up with the term "silicium," comparing it to metallic elements. However, silicon's elemental identity was established in 1824 when Jöns Jacob Berzelius was able to isolate it in a relatively pure state. Because silica is found naturally in rocks and minerals, the name "silica" comes from the Latin word silex, which means flint or hard stone. As the nomenclature standardized throughout time, "silicon" came to refer to the element and "silica" to its oxide forms [12].

Silica's Geological Formation: Geological processes spanning millions of years are inextricably tied to silica production. The two most prevalent elements in the crust of the Earth, silicon and oxygen, easily combine to form silicate minerals. During sedimentary processes, these minerals either precipitate from aqueous solutions or crystallize from molten magma. Both igneous and sedimentary processes result in the formation of quartz, the most stable form of silica at Earth's surface. While silica forms in sedimentary settings through the weathering and re-deposition of silicate minerals, it crystallizes in igneous rocks as magma cools. Silica-rich sands are created when silica-containing rocks are broken down into sand particles by chemical weathering and mechanical erosion over geological time [12, 24]. Another significant process is the creation of biogenic silica. Numerous bacteria, plants, and algae actively absorb soluble silica from water or soil and store it in their tissues as solid silica structures. This physiologically mediated silica contributes to defense, metabolic control, and structural support [12, 14].

Silica's Physicochemical Properties and Chemical Composition: The chemical formula for silica is silicon dioxide (SiO_2), which is around 46.7% silicon and 53.3% oxygen by weight. The SiO_4 tetrahedron, which consists of four oxygen atoms covalently bound to a core silicon atom, is the fundamental structural unit of silica. The remarkable mechanical strength, chemical inertness, and thermal stability of silica are explained by these tetrahedra polymerizing through shared oxygen atoms to create vast three-dimensional networks [9, 12].

Amorphous versus Crystalline Silica: There are notable structural and biological differences between the crystalline and amorphous forms of silica. Tridymite, cristobalite, and quartz are examples of crystalline silica [12, 14]. The predominant form of quartz, which is found in sand, granite, and sedimentary rocks, is the most thermodynamically stable polymorph under ambient conditions [12, 24]. Crystalline silica has a high Mohs hardness (around 7) and is resistant to chemical disintegration because of its organized atomic structure [12]. On the other hand, long-range atomic organization is absent in amorphous silica. Examples include diatomaceous earth, opaline silica, and biogenic silica, which is made by microbes and plants [12, 14]. Because of its faster rate of dissolution into orthosilicic acid, amorphous silica is often regarded as more physiologically significant in nutrition and demonstrates greater solubility in aquatic settings [14, 21, 15].

Reactivity and Solubility: Although silica is only weakly soluble in water, its solubility rises when particle size decreases, surface area grows, and pH rises [12, 14]. The main bioavailable species, ortho silicic acid ($Si(OH)_4$), is created as silica slowly dissolves at physiological pH [14, 21]. Dietary silica's biological and nutritional significance is supported by this dissolving mechanism [14, 15]. The use of silica in cosmetics, medications, and biomedical engineering is largely dependent on its physicochemical characteristics, which include porosity, surface charge, and particle shape [9, 26]. For instance, mesoporous silica nanoparticles are perfect for tissue engineering and medication administration because of their large surface areas and adjustable hole diameters [10, 26].

Global Silica and Silica-Rich Sand Distribution: One of the most prevalent substances on Earth is silica, which makes up roughly 59% of the crust's weight in the form of silicate rocks [24]. Particularly significant in terms of industry, nutrition, and technology are high-purity silica sands [12, 24].

Silica-Rich Sand Types: Quartz grains make up the majority of silica sand, which is categorized according to particle size and purity. High-silica sand, which is useful for glass production, electronics, and biomedical applications, usually contains more than 95% SiO_2. The degree of weathering, sedimentary processes, and geological history all affect how pure silica sand is [12, 24]. Because less stable minerals are gradually eliminated, sands created by extended chemical weathering of feldspar-rich rocks are often silica-enriched [12].

Major Silica-Rich Regions by Country: There are large amounts of high-purity silica sand in several nations: India: Significant deposits in Tamil Nadu, Gujarat, Rajasthan, and Andhra Pradesh are used extensively in glassmaking and other industrial processes. High-purity quartz sands used in electronics and specialty glass are found in significant quantities in the United States in Wisconsin, Illinois, Texas, and Oklahoma. Australia: High-grade silica sand deposits can be found in Queensland and Western Australia. Brazil: abundant supplies of quartz sand, especially in Minas Gerais. China: The glass and semiconductor industries are supported by silica reserves that are widely dispersed throughout several regions [24]. Because of the many cycles of erosion and re-deposition, silica sands from riverbeds, coastal areas, and old sedimentary basins frequently exhibit high SiO_2 content [12, 24].

Products Infused with Silica: An Industrial and Nutritional Perspective: Products with silica infusions are utilized in the pharmaceutical, cosmetic, industrial, and nutritional sectors [5, 9]. Silica is frequently added as an anti-caking agent (E551) and as a source of bioavailable silicon in dietary supplements in the food and nutraceutical industries [14, 21]. Stabilized Ortho silicic acid or silica extracts obtained from plants are commonly found in silica supplements [14, 15]. These products promote nail integrity, hair strength, skin suppleness, and bone health [5, 14]. Although silica's industrial applications are well established, formulation and bioavailability have a significant impact on the nutritional value of goods containing silica [14, 15].

Consumption of Silica in Food: Geographical location and eating habits have a significant impact on dietary silica intake [15, 14]. While diets heavy in whole grains and plant foods may supply much higher levels, typical intakes in Western countries range from 20 to 50 mg/day [15, 22]. Whole grains (oats, barley, rice), vegetables (green beans, spinach), beverages (beer, mineral water), and plant-based extracts (bamboo, horsetail) are the main sources of dietary silica [14, 15]. Because beer is made from barley and has a high amount of Ortho silicic acid, it has been found to be a particularly bioavailable source [14, 15, 21].

Foods Containing Silica: Many plant meals naturally contain silica, which is mostly acquired from soil as soluble silicic acid [12, 14]. In order to increase structural rigidity and resilience to external stress, plants actively absorb silica and deposit it in their cell walls [12, 14]. One of the best dietary sources of silica is cereal grains, particularly when eaten whole. Silica concentration is greatly reduced by processing and refining, highlighting the nutritious value of minimally processed foods [14, 15].

Silica Metabolism and Bioavailability: One important factor influencing silica's nutritional and physiological significance is its bioavailability [14, 21]. The human body only absorbs and uses a small portion of the silica that is consumed, despite the fact that it is abundant in the environment and food. Silica's chemical form, solubility, particle size, and the food matrix in which it is taken all have a significant impact on its bioavailability [14, 15]. There are several chemical types of dietary silica, such as soluble Ortho silicic acid, polymeric silicates, crystalline silica, and amorphous silica [12, 14]. Ortho silicic acid ($Si(OH)_4$) is commonly recognized as the main bioavailable form among them [14, 21]. The gastrointestinal tract barely absorbs insoluble types of silica, like polymerized silicates and quartz [12, 14]. Under physiological conditions, amorphous silica especially biogenic silica derived from plants can partially depolymerize into orthosilicic acid and is more soluble than crystalline silica. Supplements containing stabilized orthosilicic acid have been created to improve absorption and stop polymerization [14, 15].

The small intestine is where silica is primarily absorbed by passive diffusion. Silicon doesn't seem to depend on any particular transporter proteins, in contrast to many other minerals. Rather, its absorption depends on concentration and is affected by the pH of the gastrointestinal tract as well as the presence of other food ingredients. Studies on humans have shown that whereas polymerized or particulate silica exhibits little absorption, 40–60% of ingested orthosilicic acid is absorbed [14, 15, 21]. Ortho silicic acid is the main form of absorbed silica that reaches the systemic circulation and is quickly transported to connective tissues [14, 21]. After absorption, silica freely circulates in plasma and is absorbed by collagen-rich tissues such as blood vessels, skin, hair, nails, and bone. Particularly high quantities of silicon are seen in growing connective tissues and bone, indicating a function in matrix production and structural stability [3, 14]. The kidneys are the primary organs responsible for silica excretion, and dietary intake is closely reflected in urine silicon excretion. This quick turnover suggests that maintaining tissue levels requires a constant food intake [14, 21].

Silica's Physiological Roles in the Human Body: Silica is becoming more widely acknowledged as a biologically significant trace element, although not being officially recognized as an essential nutrient [14, 21]. Its role in mineral metabolism, bone formation, and connective tissue health is supported by both experimental and epidemiological data [3, 15, 22].

Function in Tissue Connectivity: Collagen and elastin, two important structural proteins in connective tissues, are synthesized and stabilized by silica [3, 14]. The enzyme activity involved in collagen cross-linking appears to be influenced by silicon, which enhances tissue elasticity and strength [3, 21]. A functional role for silica in normal physiology is supported by deficiency studies in animals, which show poor growth, skeletal deformities, and improper connective tissue development [3, 14].

Contribution to Bone Formation: In the early phases of bone mineralization, silica is essential. It is thought to aid in the deposition of calcium and phosphate into the organic bone matrix and is concentrated in locations of active bone growth [3, 14]. Silicon might enhance the production of mineral crystals by acting as a nucleation agent [3, 18]. Human epidemiological research have demonstrated a favorable correlation between bone mineral density and dietary silicon intake, especially in older men and premenopausal women [15, 22].

Combining Silica with Other Components and its Health Benefits: The body uses silica in a variety of ways. Instead, it supports physiological processes by working in concert with other minerals and trace elements [14, 18].

Interaction with Iron, Zinc, and Magnesium: It has been demonstrated that silica affects the metabolism and bioavailability of zinc and magnesium, two elements that are critical for the health of bone and connective tissue. Silicon may modify zinc-dependent enzymatic activities involved in collagen formation and improve the retention of magnesium in bone [14, 18]. Furthermore, silica has the ability to bind aluminum in the gastrointestinal system, decreasing absorption and increasing elimination. It has been suggested that this interaction serves as a defense against the neurotoxicity linked to aluminum [8, 21].

Potential Antioxidant and Anti-Inflammatory: According to new research, silica may have indirect antioxidant effects by preserving tissue structure and lowering inflammation-induced connective tissue breakdown. Despite not being a traditional antioxidant, silica may help lower oxidative stress because of its function in preserving the stability of the extracellular matrix [14, 21].

Calcium-Silica Bonding and Bone Health: For the health of the skeleton, the relationship between calcium and silica is especially crucial. Silicon seems to increase bone strength and density *via* improving calcium incorporation and utilization [15, 18, 22].

Understanding of Mechanics: Silica is thought to affect calcium binding at the molecular level by altering the organic bone matrix [3, 18]. Silicon may maintain hydroxyapatite crystals within collagen fibrils and aid in the development of calcium–phosphate complexes. According to research on animals, a lack of silicon causes aberrant bone mineralization, decreased bone calcium, and compromised skeletal development [3, 14].

Prevention of Osteoporosis and Silica: Decreased bone mass and an elevated risk of fracture are hallmarks of osteoporosis. Higher dietary silicon intake has been linked to improved bone mineral density and a lower risk of osteoporosis, according to observational studies [15, 22]. Supplementing with silicon has demonstrated potential in enhancing bone indicators, especially when paired with vitamin D and calcium. These findings suggest that silica may serve as an adjunct nutrient in osteoporosis prevention strategies [14, 15, 22].

Silica in Nutrigenomics: The study of nutrigenomics looks at how nutrition and gene expression interact. Preliminary data indicates that silicon may affect genes involved in bone formation, collagen production, and mineral metabolism, despite the paucity of study on silica in this area. The expression of genes linked to osteoblasts and enzymes involved in the synthesis of extracellular matrix may be influenced by silicon. These outcomes demonstrate silica's potential as a nutrigenomic modulator, which calls for more molecular and clinical research [3, 14].

Probiotics with Silica Interactions and Possible Health Effects: In nutritional research, the relationship between silica and probiotics is a new and largely unexplored field. In the gastrointestinal tract, probiotics live microorganisms that help the host interact closely with food ingredients. Intestinal health, gut microbiota composition, and probiotic viability may all be impacted by silica, especially in its soluble and amorphous forms [9, 14].

Silica in the Environment of the Gastrointestinal System: Ortho silicic acid is the main form of dietary silica found in the gastrointestinal tract. This form can coexist with gut flora without having any direct antimicrobial effects because it is chemically inert and non-toxic at physiological doses. Silica does not interfere with microbial cell membranes or metabolic processes, in contrast to heavy metals or reactive minerals [14, 21]. On the other hand, amorphous silica particles might function as physical substrates that affect the formation of biofilms and microbial adherence. According to some research, silica surfaces may encourage bacterial attachment, which, in certain circumstances, may aid probiotic colonization [9].

Possible Benefits of Synergy: By strengthening the integrity of the intestinal barrier, silica may indirectly promote probiotic action. Silica may help maintain the intestinal epithelium's structural integrity by promoting the stability of connective tissue and extracellular matrix, which would make the environment more conducive to the growth of helpful microorganisms [3, 14]. Furthermore, silica's capacity to bind heavy metals and toxins may lessen the burden on the stomach, hence enhancing microbial equilibrium [8, 21]. These processes imply a possible synergistic link between silica and probiotic function, despite the lack of direct clinical data [14].

Research Gaps: Large-scale human studies investigating silica probiotic interactions are currently lacking. The majority of the data is indirect or comes from research done on animals and in vitro. Controlled clinical trials evaluating the effects of silica supplementation on the composition of the gut microbiota, the effectiveness of probiotics, and the outcomes related to gastrointestinal health should be the main focus of future study [3, 14].

The Aeronutrient Silica: Nutrients that are administered by inhalation or aerosolized systems as opposed to conventional oral routes are referred to as "aeronutrients." Although this idea is well-established for some medications, it is still mostly speculative when it comes to dietary minerals like silica [9, 26].

Delivery of Aerosolized Silica: In the form of Ortho silicic acid, silica's tiny molecular size makes it potentially appropriate for aerosol distribution [14]. Fast systemic absorption, avoiding gastrointestinal breakdown, and tailored administration to connective or respiratory tissues are possible benefits [9, 26]. Aeronutrition approaches have been presented in the fields of extreme-environment nutrition and aerospace to support astronauts and high-altitude people, where traditional nutrient intake may be hindered [9]. Silica has been proposed as a potential nutrient for these kinds of uses because of its function in bone health and connective tissue integrity [14, 22].

Safety Factors: The distinction between respirable crystalline silica, which is known to induce pulmonary toxicity, and nutritional silica is crucial. Strict control would be necessary for any silica aeronutrient application to guarantee the use of soluble, non-crystalline forms and safe dosage levels [12, 14, 21, 24]. Silica as an aeronutrient is still a theoretical idea at this time and should be considered a future line of inquiry rather than a proven use [9, 14, 26].

Silica in Personal Care and Cosmetics Items: Because of its chemical stability, texture-enhancing qualities, and absorbent qualities, silica has long been utilized in cosmetics [5, 20].

The functional and aesthetic advantages of biogenic and nano-structured silica materials have drawn attention in recent years [5, 9]. Silica has several uses in cosmetic formulations: Absorbent: Regulates skin hydration and oil. An anti-caking agent enhances the stability and flow of powder. Texture enhancer: Offers a matte finish and smoothness. Active substances are delivered by the carrier material [5, 9, 20]. Because of its sustainability and biocompatibility, biogenic silica made from plants and microbes is becoming more and more popular [5, 12].

Skin Health and Silica: By promoting collagen formation and connective tissue integrity, silica indirectly improves skin health. Reduced skin elasticity and increased hair and nail fragility have been linked to silicon shortage [3, 14]. Cosmetics containing topical and oral silica are frequently promoted for their anti-aging properties, increased skin hydration, and strengthened hair and nails [5, 20]. Although there is biochemical justification for some claims, more controlled clinical research is necessary to confirm cosmetic efficacy [14, 20].

Functional Products & Nutraceuticals Infused with Silica: A growing range of silica-infused products, such as capsules, liquids, powders, and functional beverages, have entered the nutraceutical market. The main purpose of these items is to provide stable Ortho silicic acid, which is bioavailable silicon [14, 15].

Formulations for Products: Stabilized orthosilicic acid solutions, plant-based silica extracts (such as those from bamboo or horsetail), and silica-complexed minerals are examples of common formulations. Orthosilicic acid must be stabilized to avoid polymerization, which would lower its bioavailability [12, 14, 15].

Safety and Effectiveness: According to human research, taking supplements of silica is usually well tolerated and increases the excretion of silicon in the urine, which is a sign of absorption. Improvements in connective tissue health and bone turnover markers are among the reported advantages, especially when paired with calcium and vitamin D [1, 2, 3]. However, there are no set dosage guidelines and different regulatory systems for silica supplements around the world [4, 5].

New Medical Technologies Using Silica: Because of its adaptability, biocompatibility, and adjustable qualities, silica has emerged as a key component in contemporary biomedical research [6, 7].

Medical Uses of Silica Nanoparticles: Mesoporous silica nanoparticles are being studied extensively for tissue engineering, imaging, and medication delivery [6, 8]. Therapeutic substances can be loaded and released under control thanks to their large surface area. Biomaterials based on silica have shown osteogenic qualities in bone regeneration, encouraging the growth and mineralization of bone cells [9].

Implants and Regenerative Medicine: Bioactive glasses with silica are used in dentistry and orthopedics to improve bone integration. These substances promote bone growth and tissue regeneration by releasing calcium ions and soluble silica [9].

Cost Estimates and Silica Marketing: Food additives, nutraceuticals, cosmetics, medicines, and sophisticated medical materials are just a few of the businesses that use silica for commercial purposes. Silica's functional diversity, availability, and growing applications in health-related fields are what propel the worldwide silica market [10].

Market for Functional Foods and Nutraceuticals: The main reasons silica-containing nutraceuticals are sold as supplements are for supporting healthy bones, healthy hair, skin, and nails, and maintaining the integrity of connective tissue. Stabilized Ortho silicic acid or silica extracts from plants are frequently included in these goods. Formulation, purity, and branding all have a big impact on price. Consumer-grade silica supplements cost between $10 and $50 per month, according to current market analyses; however, specialist bioavailable formulations may cost more [2, 10].

Applications in the Cosmetics Industry: Silica is prized in cosmetics for its ability to absorb oil, improve texture, and provide stability. Because of their improved functionality and perceived sustainability, nano-structured and biogenic silica materials are more expensive on the market. The cost of cosmetic-grade silica is determined by surface modification, particle size, and regulatory compliance [5, 7].

A Look at Industrial and Medical Costs: Because of the strict quality control, purification, and regulatory requirements, medical-grade silica materials like mesoporous silica nanoparticles and bioactive glasses are substantially more costly. When silica is included into drug-delivery or implantable devices, costs rise even more. Because of its scalability, abundance, and wide range of applications, silica is nevertheless economically appealing despite these expenses [6, 10].

Regulatory Status, Toxicology, and Safety: The chemical form and exposure route have a significant impact on silica safety. The distinction between dietary or amorphous silica, which is regarded as safe at recommended intake levels, and respirable crystalline silica, which is linked to pulmonary illness, must be made explicit in nutritional and biological debates [4, 11].

Safety of Diet: Ortho silicic acid, the main type of dietary silica, has shown a good safety margin. At ingestion levels significantly higher than typical dietary consumption, human studies show no negative effects [1, 2]. Amorphous silica (E551) is approved for use in foods by regulatory bodies such as the European Food Safety Authority (EFSA) [4].

Regulatory Structures:

Application in Food: Accepted as an anti-caking agent (E551). Supplements: Most governments regulate them as dietary supplements. Cosmetics: Accepted with limitations on particle size. Medical use: Regulated by laws governing pharmaceuticals and devices. The lack of standardized dietary reference intakes for silicon underscores the necessity of harmonizing regulations [2, 4].

Needs for Future Research: There are still significant information gaps despite mounting evidence of silica's biological significance. Important avenues for further research include: creation of suggested dietary consumption levels for silicon, long-term clinical studies evaluating the relationship between bone health and silica supplementation, Development of safe, non-crystalline aerosol delivery techniques; controlled investigations on silica–probiotic interactions; economic and life-cycle evaluations of silica-based nutraceuticals; and molecular research on silica-mediated gene regulation (nutrigenomics). It is anticipated that developments in molecular biology, nanotechnology, and analytical methods would hasten these fields' advancement.

CONCLUSION: Long thought of mostly as an inert geological substance, silica is now more widely acknowledged as a physiologically active substance with important applications in technology, nutrition, and health. Silica holds a special place at the nexus of earth science and human biology because of its geological origins, chemical diversity, nutritional presence, and physiological functions. There is evidence that dietary silica plays a factor in bone formation, connective tissue integrity, and mineral metabolism, especially when it interacts with calcium. Its versatile potential is further shown by new uses in nutrigenomics, probiotics, cosmetics, and biomedical engineering. Despite the widespread marketing of silica supplements and silica-infused products, there is still a lack of scientific validation and regulatory uniformity. The intriguing yet unappreciated role of silica in human nutrition and health is highlighted in this review. To completely understand its processes of action, maximize its uses, and create evidence-based standards for its use in technology, food, and medicine, further multidisciplinary study is necessary.

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