

Review

Integrating Silicon into Fertigation Strategies for Cannabis Production: A Comprehensive Review

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Abstract

Silicon (Si) is a beneficial, non-essential element used in cannabis (*Cannabis sativa* L.), yet cannabis-specific evidence is scattered across hemp and drug-type cannabis. Because the marketable organ in drug-type and medicinal cannabis is the inflorescence, whose cannabinoid and terpene quality and strict residue limits make every fertigation input unusually consequential, a cannabis-focused synthesis of silicon use is needed. This comprehensive review aims to synthesize that evidence and clarify when, how, and in what form Si supplementation is justified across the crop cycle, based on a four-database search (covering the literature up to May 2026, with the cannabis-specific evidence base spanning 2019–2026). Cannabis is an intermediate Si accumulator depositing silica in bast fibers and trichomes, with benefits clearest in propagation and vegetative growth. Root Si lowers cadmium and zinc uptake and supports antioxidant defense; foliar nano-Si aids drought tolerance, and Si suppresses powdery mildew while raising tissue Si ~2.1-fold and inflorescence biomass ~1.2-fold without reducing cannabinoid or terpene quality. On current evidence, Si appears best deployed as a resilience-enhancing, stage-specific input within an integrated program rather than a universal additive. Future research should prioritize genotype- or chemotype-resolved dose–response studies on cannabinoid and terpene yields and late-flower-application safety.

Keywords: *Cannabis sativa* L.; medicinal plants; THC; silica; soilless cultivation; phytocannabinoids; hydroponics; CBD; stress tolerance; mineral nutrition



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1. Introduction

Silicon (Si) occupies an unusual position in plant nutrition because, although it is not formally classified as essential for higher plants, it repeatedly improves plant performance under stress by reinforcing tissues, modifying water relations, supporting antioxidant capacity, and restricting pathogen penetration [1–5]. The mechanism of these effects remains debated, with one influential view framing Si as a largely extracellular, apoplastic agent rather than a participant in active cellular signaling [6]. This position has prompted continued discussion in the recent literature [7]. For cannabis (*Cannabis sativa* L.), this distinction is especially important. The crop is increasingly produced indoors in intensive soilless systems, where nutrient solutions or substrates can be precisely controlled, but where the natural background supply of plant-available Si is often low [8–12]. Coco coir, rockwool, peat-based propagation plugs, expanded clay, perlite-rich mixes, and recirculating hydroponic solutions generally do not behave like mineral soils that continuously replenish

soluble silicic acid [11,12]. Consequently, Si becomes a management variable rather than a passive environmental input [12,13]. It should be noted, however, that peer-reviewed data quantifying the extent to which silicon is adopted in commercial controlled-environment cannabis production are currently lacking. Statements about the prevalence of silicon supplementation in this sector, therefore, necessarily remain qualitative. The remainder of this introduction moves from silicon's general role in plant nutrition to the specific biology, medicinal value, and production context of cannabis, before identifying the knowledge gaps that motivate this review and outlining the framework it provides.

Throughout this review, the terminology used for *C. sativa* is applied as follows. Industrial hemp, often termed fiber or fiber hemp, denotes low-tetrahydrocannabinol (THC) cannabis grown for stalk fiber, grain, or biomass, typically as dense, often dioecious field stands [14,15], and includes textile cultivars such as 'Santhica 27' and 'Finola' that are prominent in the existing silicon literature [16–19]. Drug-type cannabis denotes high-THC chemovars selected for psychoactive resin production in the female inflorescence [15]. Medicinal cannabis flower production denotes the controlled-environment cultivation of unpollinated female inflorescences, whether high-THC or high-cannabidiol (CBD), for pharmaceutical or therapeutic markets, where dried flower is the marketable organ and is subject to strict residue, microbial, and quality requirements [20–22]. Where a cited study used a specific production category, that category is named explicitly, because conclusions drawn from fiber hemp cannot be assumed to transfer directly to medicinal flower production [15]. These distinctions make cannabis a special case for silicon management. In drug-type and medicinal production, crop value is not determined by biomass alone, but by flower yield, cannabinoid and terpene profiles, absence of visible disease, and low contaminant load [10,15,22–25]. Because the inflorescence may be consumed by inhalation, any input applied late in the production cycle must also be evaluated for residual and sensory consequences as well as agronomic benefit [20,21,26,27]. A silicon decision in cannabis therefore cannot be judged only by growth or stress endpoints, but must ultimately be evaluated in relation to flower yield, secondary-metabolite quality, and consumer safety—criteria that do not constrain silicon use in most other crops to the same extent. The cannabis inflorescence is valued medicinally for cannabinoids such as THC and CBD and for its terpene profile, and is increasingly produced as a pharmaceutical-grade herbal raw material, further raising the stakes of any agronomic input applied to the flower.

The relevance of Si is further amplified by the biology and intensity of controlled-environment cannabis production. Dense canopies, strong lighting, rapid fertigation cycles, intensive vegetative growth, repeated training or pruning, and the later mechanical load of inflorescence biomass all increase the need for stable water movement, strong stems and petioles, balanced mineral nutrition, and resilient epidermal tissues [8–10,28]. These pressures coincide with recurring production risks, including transient water deficit, root-zone salinity or nutrient imbalance, high-humidity episodes, powdery mildew, *Botrytis*-related bud rot, and root pathogens such as *Pythium* and *Fusarium* [29–31]. Studies comparing fertigation strategies in medicinal cannabis further show that the cultivation system itself can alter plant ionome, biomass formation, and cannabinoid outcomes, making Si management inseparable from the broader fertigation context [32,33]. Cannabis-specific evidence for Si has expanded substantially in recent years, but it remains fragmented across different plant types, developmental stages, stress models, and Si sources. Anatomical and genomic studies indicate that *C. sativa* is not a true Si non-accumulator, as candidate nodulin 26-like intrinsic protein 2 (NIP2)-type aquaporins have been identified. Silica deposition has been localized to bast fibers and non-glandular trichomes, supporting the interpretation of cannabis as an intermediate Si accumulator with active, transporter-mediated uptake [34,35]. Agronomic trials have linked root-applied wollastonite or calcium-silicate

amendments with increased foliar Si content and reduced powdery mildew severity [36,37], while studies on hemp exposed to salinity, cadmium, zinc, or water deficit show that Si can reduce stress injury through changes in anatomy, toxic-ion uptake, antioxidant responses, and water-use behavior [18,19,38–40]. More recent work also indicates that Si-containing biostimulant formulations can raise tissue Si approximately 2.1-fold and increase inflorescence yield by roughly 1.2-fold without changing volatile or color quality. However, the yield effect was only marginally significant, and because Si was supplied along with a phosphite-containing component, the observed response could not be attributed solely to Si [41]. Information on Si in industrial hemp under soilless culture has also expanded, with recent deep-water-culture work showing that 10 mg L⁻¹ Si maximized fiber content and cellulose yield compared with non-Si controls [42].

Despite this growing evidence base, no simple universal recommendation can yet be made for cannabis Si supplementation. The literature spans soluble monosilicic acid, potassium silicate, calcium silicate, wollastonite, diatomaceous earth, nano-Si formulations, and organic or bio-based carriers; it also spans root-zone fertigation, substrate incorporation, and foliar application. These approaches differ not only in bioavailability but also in pH effect, precipitation risk, potassium or calcium contribution, compatibility with concentrated fertilizers, and suitability for propagation, vegetative growth, flowering, or post-harvest quality targets [12,13]. A further complication is that findings from fiber hemp, short-term stress assays, and related horticultural crops are often extrapolated to medicinal cannabis flower production, where genotype, substrate, legal residue requirements, and the intended marketable organ may strongly alter the risk-benefit balance [11,24,43]. To date, no peer-reviewed study has isolated the effects of Si supplementation on cannabinoid or terpene biosynthesis under standardized medicinal flower-production conditions. Direct cannabis evidence on Si-mediated disease management remains limited to powdery mildew, leaving a clearly defined and pressing evidence gap. This review provides a novel cannabis-tailored fertigation framework for silicon, spanning the entire production cycle from uptake and source selection to stage-specific deployment, abiotic-stress resilience, disease management, and practical fertigation integration, while clearly distinguishing direct cannabis evidence from cross-crop extrapolation. The objective of this review is therefore to synthesize the available evidence on Si in cannabis fertigation and to translate it into a stage-specific and system-aware framework that distinguishes direct cannabis findings from cross-crop extrapolation, identifies where the evidence supports selected agronomic decisions, and defines the priority research gaps.

To support this synthesis, the evidence reviewed here was identified through a structured literature search of Scopus, Web of Science, PubMed, and Google Scholar covering publications up to May 2026. Search strings combined silicon-related terms (silicon, silica, silicic acid, monosilicic acid, silicate, potassium silicate, calcium silicate, wollastonite, nanosilicon, nano-SiO₂) with cannabis-related terms (*Cannabis sativa*, cannabis, hemp, marijuana) and, where appropriate, topic terms (fertigation, hydroponics, soilless, drought, salinity, heavy metal, powdery mildew, *Botrytis*, cannabinoid, terpene, yield, trichome). Studies were eligible if they were peer-reviewed primary investigations or reviews reporting silicon uptake, physiology, agronomy, stress tolerance, disease management, or product quality in *C. sativa*. Selected mechanistic studies in model crops, notably cucurbits, cereals, and strawberries, were retained only where direct cannabis evidence was lacking and are explicitly labeled as cross-crop extrapolation. Non-peer-reviewed material was excluded, except for two clearly identified theses cited only for qualitative context. Retrieved records were classified according to plant category, developmental stage, stress model, silicon source and form, and delivery route; this classification structures the synthesis that follows. The search was restricted to English-language publications, and records were screened first

by title and abstract and then by full text. Because the cannabis literature remains limited and methodologically heterogeneous, the evidence was synthesized narratively rather than assessed using a formal quality or risk-of-bias instrument.

2. Forms, Sources, and Availability

The agronomic value of silicon depends strongly on its chemical form, plant availability, and compatibility with fertigation systems. Silicon sources differ in bioavailability, ease of handling, effects on solution pH and ionic balance, and risk of incompatibility with concentrated fertilizers. Therefore, the most appropriate choice for cannabis production depends on both the developmental stage and the technological setting [3,4,41]. To ensure comparability across studies and product labels, silicon doses must be expressed on a common basis [44]. On a mass basis, elemental Si is converted to silicon dioxide (SiO_2) by multiplying by 2.14, corresponding to the SiO_2/Si molar-mass ratio of 60.08/28.09, and to monosilicic acid (H_4SiO_4) by multiplying by 3.42, corresponding to 96.11/28.09. Conversely, SiO_2 and H_4SiO_4 are expressed as elemental Si by multiplying by 0.47 and 0.29, respectively. On a molar basis, 1 mM Si corresponds to 28.1 mg L⁻¹ elemental Si, 60.1 mg L⁻¹ SiO_2 , or 96.1 mg L⁻¹ H_4SiO_4 . Unless stated otherwise, doses in this review are expressed as elemental Si, and concentrations reported in sources as SiO_2 , H_4SiO_4 , or product percentages are recalculated to elemental Si where the declared Si basis is clear.

2.1. Mono-Silicic Acid and Stabilized Formulations

The most readily available form is monosilicic acid [H_4SiO_4 , also written as $\text{Si}(\text{OH})_4$; commonly referred to as monosilicic acid], a soluble species present in aqueous solution that is directly absorbable by roots and is therefore particularly useful when rapid physiological effects are desired. Stabilized monosilicic acid formulations are often considered especially suitable for sensitive developmental stages, including propagation and early vegetative growth. Their main advantages are rapid uptake and minimal effects on electrical conductivity; in practical use, they may increase EC only marginally. Their main disadvantages are higher cost and the formulation challenges associated with maintaining silicon in soluble and plant-available form. Such products are therefore best stored according to the manufacturer's instructions and diluted shortly before use, because dilution, pH adjustment, and prolonged standing can favor gradual repolymerization or precipitation into non-available silica forms [3,5]. Above approximately 2 mM at pH above 9, H_4SiO_4 spontaneously polymerizes to amorphous silica, which is no longer accessible to roots. However, this threshold is approximate and shifts with pH, temperature, ionic strength, and dissolved salt concentration; therefore, the practical onset of polymerization should be confirmed for each specific working solution. This constraint means that the total silicon content declared on a product label can be misleading; the agronomically relevant quantity is the fraction maintained as monomeric H_4SiO_4 in the working solution [2,45]. Silicon content in the dry matter of above-ground organs varies considerably across plant species, from approximately 0.1 to 10%, reflecting differences in uptake capacity and transporter expression [2,4]. In cannabis cultivated in soilless media, where background plant-available Si is naturally low, this variability underlines the importance of targeted supplementation [41,45,46]. Among stabilized formulations, choline-stabilized orthosilicic acid represents a well-defined product category in which silicon is maintained in monomeric form through a molecular carrier; experimental work in tomato grown on rockwool demonstrated that this formulation influenced photosynthetic activity and improved marketable yield under specific Mn-stress conditions, providing supporting evidence for the functional effectiveness of stabilized monosilicic acid across crops beyond cannabis [47]. Root uptake of H_4SiO_4 is mediated by membrane-localized transporter

proteins belonging to the low-silicon 1 (Lsi1; influx) and low-silicon 2 (Lsi2; efflux) families. In monocot crops, these transporters are typically strongly polarized within root cells, whereas in dicotyledonous species, including cannabis, this polarity appears to be less pronounced. Nevertheless, transporter-mediated uptake remains important for acquisition beyond passive uptake from the external solution [4,34]. Even within cannabis, reported tissue-Si concentrations vary with cultivar, plant organ, substrate, silicon supply, and the analytical method used for silicon determination [34,37,48]. Therefore, the description of cannabis as an intermediate silicon accumulator should be read as an approximation rather than as a fixed, cultivar-independent property [34,49].

2.2. Potassium Silicate

By contrast, potassium silicate remains the most common silicon source in horticultural practice [5,50]. Silicates were originally regarded as non-bioactive, but subsequent work has shown otherwise [41]. It is widely available, inexpensive, and effective in strengthening plant tissues and supporting repeated supplementation [13,46]. However, potassium silicate is strongly alkaline, and its use requires careful pH management. It may substantially raise solution pH and, if mixed incorrectly with concentrated fertilizers or calcium-containing products, readily form precipitates or gel-like deposits. These compatibility issues are among the principal reasons why silicon, despite its agronomic promise, is not yet universally integrated into cannabis fertigation systems [5,50]. The practical risk of precipitation with potassium silicate is better appreciated with quantitative reference points. Technical data commonly express soluble silicon concentrations as SiO_2 equivalents; concentrations above approximately 100–130 ppm silicon dioxide (SiO_2), corresponding to about 47–61 ppm elemental Si, indicate conditions under which polymerization becomes increasingly likely [2,46]. At a pH around 6, common for cannabis fertigation, the transition to insoluble silica gel can occur rapidly. In a hydroponic experiment with sweet basil, 75 ppm Si was identified as the practical maximum before Ca_2SiO_4 precipitate began to form, illustrating how quickly this threshold is reached in calcium-containing nutrient solutions. Commercial liquid potassium silicate products typically contain 10–17% potassium oxide (K_2O) and 20–27% SiO_2 by weight, with the working solution pH ranging from 11 to 13. The additional potassium supplied by potassium silicate should be factored into the overall fertigation recipe, as inadvertent potassium excess can interfere with calcium and magnesium uptake through cationic competition [51]. Sodium silicates, occasionally offered as lower-cost alternatives, are generally less suitable for high-value flower production because they introduce sodium, which, at elevated concentrations, can impose ionic stress and interfere with potassium and calcium nutrition [5,38]. When used as a foliar spray, potassium silicate should be diluted to a concentration that contributes a conductivity of approximately $0.1\text{--}0.2\text{ mS cm}^{-1}$ and applied during cooler periods of the photoperiod or just before lights-off to minimize phytotoxic surface alkalization [52,53].

2.3. Calcium Silicate and Wollastonite

Additional silicon may be delivered through solid or slowly available materials such as calcium silicate, wollastonite, silica-rich minerals, diatomaceous earth, and silicon-enriched substrate amendments. These forms are generally less suitable for direct liquid fertigation but may provide longer-term supplementation when incorporated into the growing medium. In purely recirculating hydroponic systems without a solid substrate, they are impractical as the primary silicon source. They are better suited to substrate-based or container production, where they can be mixed into the medium before planting [3,45]. Calcium silicate is particularly noteworthy because it supplies both Si and Ca, thereby linking silicon nutrition to cell wall integrity and disease resistance [1,36]. Wollastonite

is a naturally occurring calcium silicate mineral (CaSiO_3 ; calcium metasilicate) with a reported silicon content of approximately 21–25% Si by weight, making it a concentrated yet slowly released Si source when incorporated into a substrate [45]. A cannabis-specific study in which calcium silicate was mixed into a 70:30 peat:perlite medium at rates of 1.04 and 2.07 kg m^{-3} demonstrated that substrate-level supplementation can reduce the accumulation of micronutrients in leaves, roots, and inflorescence material after 12 weeks of cultivation, without adverse effects on growth parameters or cannabinoid concentrations [37]. This is an agronomically meaningful result for production focused on flower quality: calcium silicate additions can serve a dual role, supporting silicon supply while simultaneously moderating micronutrient excess in intensive fertigation systems. A further practical benefit is that calcium silicate and wollastonite exert a modest liming effect, moderating pH decline that occurs in peat- or coco-based substrates under intensive irrigation management [45]. The combined nutritional roles of silicon and calcium warrant closer examination, as they underscore the unusually strong disease-suppressive effect of calcium-bearing silicate sources. Once translocated to evaporative tissues such as leaves and trichomes, silicon polymerizes in situ into hydrated amorphous silica, a polymerized Si–O network with no fixed number of Si atoms, within the cell wall matrix and cuticle, mechanically reinforcing the outer surface against fungal hyphal penetration [1,54]. Calcium contributes independently by forming calcium pectate in the middle lamella, thereby strengthening cell-to-cell adhesion and participating in pathogen-related signaling [55,56]. Calcium silicate and wollastonite, by supplying both elements simultaneously, support these mechanisms in a complementary manner, providing a biochemical explanation for the consistently strong protective effect observed in wollastonite-amended cannabis trials [36]. By contrast, industrial slag-derived silicate products, although chemically comparable to wollastonite in their Si and Ca content, require careful evaluation in the context of medicinal cannabis production, as some slag materials carry residual heavy-metal loads that may be incompatible with the strict purity standards of flower destined for therapeutic use [57].

2.4. Diatomaceous Earth and Silica-Rich Minerals

Diatomaceous earth, rich in SiO_2 , is only slowly plant-available and is often more relevant as a mechanical aid against insects than as a rapid silicon source. Diatomaceous earth, while containing approximately 38–42% Si by weight, dissolves so slowly under typical growing-media conditions that its contribution to the pool of plant-available Si within a single crop cycle remains limited [5,46]. Its primary agronomic value is as a mechanical insecticide acting against soft-bodied pests, including fungus gnats and certain mite species, rather than as a silicon nutritional input [58,59]. A further category of materials sometimes promoted as silicon sources comprises naturally occurring silica-rich minerals such as zeolites, silica sand, crystalline quartz, pumice, and perlite. Although these contain approximately 23–35% elemental Si by mass, their crystalline or amorphous structure is highly stable under cultivation conditions, and their dissolution to plant-available H_4SiO_4 proceeds far too slowly to provide a meaningful nutritional contribution within a single cannabis crop cycle [13,57]. In growing media, these materials are therefore valued primarily for their physical contributions to porosity, drainage, and structural stability. At the same time, any silicon nutritional benefit is incidental and should not be relied upon when designing a silicon supplementation program [57,60]. Other silicon-bearing materials occasionally encountered in horticulture include colloidal silica (silica sol), magnesium silicates such as talc, zeolitic aluminosilicates, rice-husk-derived biosilica, silica fume, and silicate-bearing industrial slags [50,61,62]. Like diatomaceous earth and crystalline minerals, however, most of these materials either dissolve too slowly to supply meaningful plant-available silicon within a crop cycle or raise compositional and purity concerns.

They are therefore not suitable as the primary fertigation silicon source for high-value cannabis [12,50,61].

2.5. Organic and Bio-Based Silicon Sources

Organic or semi-organic materials such as horsetail-based extracts and silicon-rich organic fertilizers may also contribute to plant silicon status, especially in biologically managed systems. However, their performance is generally less predictable than that of defined mineral formulations [3,5,46]. Among organic silicon sources, *Equisetum arvense* (common horsetail) has the most documented supporting data [49,63,64]. Its aerial biomass may contain approximately 22% Si in dry matter. However, the silicon released in a usable form depends critically on the method of preparation. Boiling the ground-dried plant material increased Si release approximately ten-fold relative to a cold-water control, and the addition of sodium bicarbonate elevated it up to forty-fold, demonstrating that the processing protocol is at least as important as raw silicon content when evaluating the practical value of plant-based Si extracts. A further bio-based option is alginite, a bituminous rock rich in silicon together with phosphorus, potassium, and numerous trace elements; in a foliar trial on fiber hemp (cv. 'Finola'), suspension applications increased plant height and dry biomass yield, and raised inflorescence CBD content from 2699.78 mg kg⁻¹ in the untreated control to 2882.77, 3295.11, and 3190.75 mg kg⁻¹ after foliar applications of 20, 30, and 60 g L⁻¹ alginite suspension, respectively. However, the highest dose produced a lower CBD response than the moderate 30 g L⁻¹ dose, indicating a non-linear dose response rather than a simple dose-dependent increase [65]. More generally, organic and bio-based silicon sources can vary markedly in composition depending on species, plant part, harvest, and processing [66–68]. Because these products are rarely standardized for soluble silicon content, their bioavailability is difficult to predict, making batch-level quality control advisable before use in high-value production [61,62].

2.6. Nano-Silicon Formulations

Nano-silicon (nano-Si) and nano-silica (nano-SiO₂) formulations constitute a distinct class of engineered silicon inputs that should not be treated as interchangeable with the soluble silicates or solid amendments described above. Engineered nanoparticles are conventionally defined by having at least one dimension between 1 and 100 nm. Their agronomic and biological behavior is governed not only by dose but also by particle composition, primary and hydrodynamic size, agglomeration state, surface chemistry and charge, specific surface area, and dissolution kinetics [69]. For nanomaterials, size, surface area, particle number, and surface chemistry may be more informative than mass-based concentration alone [69,70]. Such formulations are often proposed for efficient, low-dose foliar delivery. Still, their comparability across studies is weak whenever this characterization is missing, and blanket claims of high solution stability or low polymerization cannot be made for the category as a whole. The nanostructure itself, rather than the “nano” label, governs efficacy. Among SiO₂ nanoparticles, dissolution to silicic acid and the resulting gain in shoot silicon can vary markedly with particle architecture, with hollow and porous structures generally outperforming solid and bulk forms [71]. A second, often overlooked, point is mechanistic. The canonical pathway of silicon permeability in plants is mediated by silicic-acid-permeable aquaporins, including NIP2-type channels identified in *C. sativa*, rather than by the uptake of intact particles [34,35,72]. Any nano-Si response must therefore be interpreted with care. It may reflect dissolution to plant-available silicic acid, a surface or particulate effect at the leaf or root interface, altered leaf-surface retention, or the action of co-formulants such as carriers, surfactants, or loaded actives, rather than the nanoparticle itself [16,73]. Direct, peer-reviewed evidence on cannabis remains sparse and heteroge-

neous and spans more than drought alone. It includes foliar nanosilicon trials on fiber-type hemp under water deficit, in which 0.5–1.5 mM increased antioxidant-enzyme activity and modified essential-oil and cannabinoid composition, with 1.5 mM the most effective concentration overall [39,40], and salinity experiments using a silicon-particle “phyto-courier” nanobiostimulant. Porous Si nanoparticles below 100 nm, with a specific surface area of approximately $34.8 \text{ m}^2 \text{ g}^{-1}$ and a zeta potential of approximately -30 mV , loaded with a flavonoid and stabilized with trehalose, reduced stress symptoms in *C. sativa* [16,73]. These reports are not directly comparable: the hemp drought studies did not fully characterize nanoparticle composition or primary particle size, whereas the salinity work used a well-characterized, flavonoid-loaded carrier whose benefits cannot be attributed solely to silicon nutrition. Across this small literature, chemical identity, primary and in-suspension size, agglomeration state, surface charge, dissolution behavior, formulation additives, and even whether doses are expressed on a Si or SiO_2 basis are frequently unreported, fundamentally limiting reproducibility [69].

Evidence from models and crop species is more developed and broadly supportive. Still, it must be extrapolated with caution because cannabis appears to be an intermediate Si accumulator, and cuticular barriers constrain foliar uptake. Foliar-, root-, or seed-applied nano-Si has improved drought and salinity tolerance and yield in wheat, rice, tomato, strawberry, and several aromatic or medicinal plants, chiefly by improving water relations, increasing antioxidant-enzyme activity, protecting photosynthetic pigments, and reinforcing ion homeostasis [74–78]. However, the dose-response is often hormetic: stimulation is usually confined to a narrow low-dose window, whereas higher doses can become ineffective or inhibitory [79]. Critically, in direct comparisons, nano-silica is not consistently superior to stabilized silicic acid or potassium silicate at equivalent applied silicon, so its theoretical surface-area advantage does not necessarily translate into greater agronomic efficacy. Finally, nano-formulations raise safety and regulatory questions that are unusually acute for cannabis. Airborne nanoparticles can be inhaled and deposited in the respiratory tract, and liquid suspensions are generally lower risk than dry powders, except when aerosolized, which is precisely the scenario created by foliar spraying [69,80]. Although crystalline silica is a recognized human lung carcinogen, whereas amorphous silica is not classified as such [81], manufactured amorphous silica nanoparticles can nonetheless elicit dose-dependent pulmonary inflammation in toxicological studies [69,80]. Because the European Pharmacopeia cannabis-flower monograph covers dried female inflorescences that may be administered by inhalation and sets strict limits for elements such as arsenic, cadmium, and lead [20], late-flower foliar application of silica nanoparticles must be judged not by agronomic endpoints alone, but also by whether particulate residues or co-formulants persist on the marketable inflorescence [20,21,82,83]. Nano-Si should therefore be regarded as a promising but still poorly standardized and largely experimental category. In cannabis, its use should be conditional on explicit particle characterization, on distinguishing dissolved-silicon effects from particulate and co-formulant effects, and, for inflorescences intended for inhalation, on caution pending residue, sensory, and regulatory data.

2.7. Source Selection

In practical terms, the most appropriate silicon source depends on the production stage and cultivation system [5,13]. Mono-silicic acid is often preferable where rapid uptake and ease of use are priorities [4,46]. In contrast, potassium silicate may be more suitable for routine supplementation in vegetative fertigation programs, provided that mixing order and pH are carefully controlled [5,50]. Solid amendments such as calcium silicate or wollastonite can serve as complementary long-term sources of silicon in silicon-poor media [36,37] (Table 1).

Table 1. Comparative overview of silicon sources for cannabis fertigation.

Silicon Source	Available Si Form	Solubility/pH Effect	Primary Application (Dose)	Main Advantages/Limitations	References
Stabilized mono-silicic acid	H ₄ SiO ₄ (monomeric)	High; minimal pH shift	Root-zone fertigation; propagation (low dose, ~0.25–0.5 mM Si)	Rapid uptake; EC-stable; broadly compatible. Higher cost; finite shelf life. Foliar use at 2.4 mL/L gave variable powdery-mildew control in cannabis.	[4,46,53]
Potassium silicate (liquid)	Silicate species converted toward H ₄ SiO ₄ after dilution and pH adjustment	Highly water-soluble; concentrated stock solutions are strongly alkaline and can markedly increase nutrient-solution pH	Root-zone fertigation; foliar spray (root 0.5–1.7 mM Si; foliar ≥ 17 mM Si for mildew)	Inexpensive and concentrated Si source; requires careful pH adjustment and separate mixing; polymerization/precipitation risk increases above ~47–61 ppm elemental Si (equivalent to 100–130 ppm SiO ₂)	[5,41,50,52]
Sodium silicate	Silicate species converted toward H ₄ SiO ₄ after dilution and pH adjustment	Similar to K-silicate	Generally not recommended for cannabis fertigation	Introduces sodium load; risk of ionic stress in high-value flower production.	[5,38]
Calcium silicate (CaSiO ₃)	Slow H ₄ SiO ₄ release	Low solubility; mild liming effect	Substrate incorporation (~1–2 kg/m ³ CaSiO ₃)	Dual Si and Ca supply; reduces micronutrient excess in cannabis substrate trials. Long-term Si and Ca reservoir; documented mildew suppression in cannabis	[37]
Wollastonite (CaSiO ₃ , 21–25% Si)	Slow H ₄ SiO ₄ release	Very low solubility; near-neutral	Substrate amendment (300–900 kg Si/ha; optimum ~600)	(root-applied, ~300 kg Si/ha for the upper canopy and ~600 kg Si/ha for the mid-canopy). Useful as a mechanical insecticide (fungus gnats, mites). Limited nutritional Si supply.	[36,57]
Diatomaceous earth (~38–42% Si)	Very slow H ₄ SiO ₄ release	Very low; minimal pH effect	Substrate additive; surface dusting (~600 kg/ha)	Improves porosity and drainage; not a reliable Si nutritional input.	[46,58,59]
Silica-rich minerals (zeolite, quartz, perlite)	Negligible bioavailability	Effectively insoluble at agronomic pH	Physical media component	~22% Si in dry matter; release ≈10× with boiling, up to 40× with NaHCO ₃ ; variable efficacy.	[46,57,60]
Horsetail extract (<i>Equisetum arvense</i>)	Mixed soluble Si species	Variable; depends on processing	Foliar spray; root drench in organic systems (non-standardized)	Promising low-dose source and nanocarrier, but poorly standardized, often hormetic, not consistently superior to conventional Si sources at equivalent Si, and problematic for late-flower use because of particle-residue, co-formulant, sensory, and inhalation-safety concerns	[49,63,64]
Nano-silicon/nano-silica (nano-Si, nano-SiO ₂)	Engineered particulate SiO ₂ or Si-based carriers; plant-available Si likely depends mainly on dissolution to H ₄ SiO ₄	Dissolution and efficacy depend on particle size, agglomeration, surface area, charge, structure, and coating/loading	Foliar or root-applied; low-dose range, typically ≈0.5–1.5 mM in cannabis studies		[16,20,69,73]

Abbreviations: CaSiO₃, calcium silicate; EC, electrical conductivity; H₄SiO₄, monosilicic acid; Si, silicon; SiO₂, silicon dioxide.

In summary, the choice of silicon source for cannabis fertigation should be guided by three criteria operating in concert: the required speed of silicon delivery, chemical compatibility with the existing nutrient program, and the production stage being addressed [5,13,50]. Stabilized monosilicic acid is preferable during propagation and early vegetative growth, where rapid uptake and EC-neutral chemistry are decisive [4,46]. Potassium silicate remains the most economical option for routine vegetative supplementation, provided that the silicon-first mixing sequence and pH management are respected [5,50]. Calcium silicate and wollastonite, incorporated into the substrate before planting, provide a long-term Si reservoir together with the secondary benefits of dual Si–Ca nutrition and modest pH buffering [36,37]. The cannabis-specific literature on silicon sources, while still less extensive than for major horticultural crops, increasingly converges with the

broader silicon-in-horticulture evidence base and supports these source-selection principles [36,37,41,42].

3. Effects Across the Cannabis Growing Cycle

While silicon is not generally recognized as an essential element, several studies have reported its benefits for plant growth, especially in soilless culture [5,13,50]. The effects of silicon-enriched fertigation vary across growth cycle phases, with most benefits occurring during early growth stages [5,84]. The cannabis-specific evidence base has consolidated rapidly since 2019; the principal cannabis studies, together with key cross-crop references, are summarized in Table 2 before the stage-by-stage discussion that follows.

Table 2. Summary of silicon studies in cannabis and, for a mechanistic context, related crops.

Material/System	Si Source & Application/Dose	Stage/Context	Main Findings	Limitations	Ref.
<i>C. sativa</i> ; genomic & anatomical	endogenous Si (no supplementation)	vegetative/anatomy	Two candidate NIP2 Si channels; Si in bast fibers and non-glandular trichomes	No dosing or agronomic response	[34]
‘Copenhagen Kush’; indoor	Silamol (2.5% Si(OH) ₄), 2.4 mL/L foliar, weekly ×4	vegetative/powdery mildew	Severity reduced in 2 of 3 trials (~25–73%); preventive, not curative	High inter-trial variability; no yield data	[53]
Textile hemp; leaf stress assay	2 mM silicate; 200 mM NaCl	vegetative/salinity	Milder symptoms in old leaves; wider xylem lumen; Lsi2 induced	Small scale; anatomical/gene endpoints	[38]
‘Santhica 27’; hydroponics	2 mM Si; 20 µM Cd	young plants/Cd stress	Lower Cd in all organs; better water-use efficiency; no growth stimulation	Short-term stress model	[18]
‘Santhica 27’; hydroponics	2 mM Si; 100 µM Zn	young plants/Zn stress	Reduced Zn uptake; lower lipid peroxidation; higher antioxidant capacity	Mechanistic; no flowering data	[19]
‘Finola’, ‘Purple Kush’; SEM-EDX	sodium silicate (Pro-Silicate)	leaves, bracts, mildew sites	Si in non-glandular (not glandular) trichomes; concentrates at infection sites	Localization study; no yield	[17]
‘HK’, ‘Victoria’; peat substrate	wollastonite 300–900 kg Si/ha	greenhouse/powdery mildew	~82–83% severity reduction; optimum 600 kg/ha; 900 no further benefit	Disease endpoint only	[36]
‘BaOx2’, ‘Sweetened’; greenhouse	Sil-Matrix (K silicate) 1% v/v ×3	vegetative/powdery mildew	~88% mildew reduction; no phytotoxicity	Fungicidal context; no nutrition data	[52]
‘Auto CBG’; peat:perlite	CaSiO ₃ 0–2.07 kg/m ³	12 wk/non-stress	Lower Fe, B, Mn, Zn, Cu load; growth & cannabinoids unchanged	No stress; not hydroponic	[37]
‘BaOx’; peat-perlite vs. peat-biochar	CaSiO ₃ 0× vs. 1×	12 wk/non-stress	Higher foliar Si; biochar did not limit Si; biomass/cannabinoids unchanged	Dose not fully specified	[37]
Cannabis; fertigation	silicate + phosphite complex	flowering/yield	Leaf Si 2.1×; inflorescence ~1.2×; volatile & color unchanged; branches slightly shorter	Pure-Si effect not separated from phosphite	[41]
Hemp; potted drought	nano-Si 0–1.5 mM foliar; 40–100% FC	veg-flower/drought	1.5 mM improved morphology; EO content & composition shifted; CBD-in-EO peaked under stress	EO/CBD-in-EO not standard flower chemotyping	[39]
Several genotypes; in vitro	sodium metasilicate	propagation/rooting	Improved leaf appearance and rooting rate	Dose/replication unspecified (thesis)	[85,86]
Cucumber/melon/zucchini (cross-crop)	K silicate; root 1.7 mM, foliar 1.7–34 mM	powdery mildew	Root & foliar effective; foliar effects from ≥17 mM	Cross-crop; foliar ‘fungicidal’ dose far above fertigation	[87]
Wheat (cross-crop)	soluble Si; root 1.7 mM	powdery mildew	Root reduced severity up to 80%; foliar inconsistent	Cross-crop; supports the root zone for systemic effect	[88]
Cucumber (cross-crop)	root & foliar Si (comparative)	powdery mildew	Foliar = surface barrier; root = induced defense	Cross-crop; supports a combined strategy	[89]
Barley (cross-crop)	K ₂ SiO ₃ ; 0–1.5 mM	hydroponic vegetative	Peak metabolic activity at 0.5 mM; ionome shifts	Cross-crop; favors low-mid test doses	[84]

Abbreviations: CaSiO₃, calcium silicate; CBD, cannabidiol; CBG, cannabigerol; EO, essential oil; FC, field capacity; K₂SiO₃, potassium silicate; nano-Si, nanoparticulate silicon; NIP2, nodulin 26-like intrinsic protein 2; SEM-EDX, scanning electron microscopy with energy-dispersive X-ray spectroscopy; Si, silicon; Si(OH)₄, silicic acid.

3.1. Silicon Uptake, Transport, and Tissue Deposition

Silicon is absorbed from the root-zone solution as monomeric silicic acid, and in cannabis, the molecular basis of this uptake has begun to be resolved [3,4]. Analysis of the

C. sativa genome identified two aquaporins of the NIP2 subfamily that carry the glycine-serine-glycine-arginine (GSGR) aromatic/arginine selectivity filter and the 108-amino-acid spacing between the two asparagine-proline-alanine (NPA) motifs diagnostic of the rice silicic-acid channel Lsi1, and secondary-ion mass spectrometry confirmed that silicon is indeed deposited in planta, principally in the gelatinous layer of the bast fibers and in silicified non-glandular trichomes—not the glandular, capitate-stalked trichomes in which cannabinoids and terpenes are produced [34,72]. Independent phytolith analysis corroborates this, having recovered five distinct silica morphotypes from the leaves, stem, and inflorescence of *C. sativa*, confirming that biogenic silica is laid down throughout the plant body rather than confined to a single organ [34,72,90]. Functionally, this positions cannabis between true non-accumulators and high-accumulating grasses, as an intermediate species capable of active, transporter-mediated uptake rather than purely passive accumulation; consistent with an active system, a putative ortholog of the efflux transporter Lsi2 is transcriptionally induced in hemp roots under stress [34,38]. These observations refine the earlier, largely cereal-derived picture of silicon transport [4] and confirm that the root system, rather than the foliage, is the principal route of entry in cannabis. It should nonetheless be noted that the substrate specificity of NIP2 channels for silicic acid continues to be debated, and definitive loss-of-function evidence in cannabis is not yet available. Thus, transporter-mediated silicic acid uptake in cannabis is currently inferred from sequence homology and tissue-localization data rather than demonstrated by direct functional assays [72,91]. This mechanistic picture provides the foundation for the stage-specific effects discussed below. Because uptake is root-mediated and silicon is deposited in cell walls and surface structures, its agronomic value depends on delivering available silicic acid to the root zone at developmental stages when wall reinforcement and surface defense are most needed [34,38]. A critical review of the evidence on cannabis uptake is therefore warranted. Current support for active, transporter-mediated silicon accumulation rests on the genomic identification of candidate channels, silica localization by secondary-ion mass spectrometry and independent phytolith analysis, and analogy with functionally validated silicon transporters in other species. However, the most recent cannabis studies continue to characterize deposition patterns rather than transport kinetics, leaving uptake rates, channel substrate specificity, and genotype-dependent accumulation as open questions.

3.2. Propagation

Among the most practically relevant applications of silicon in cannabis is its use during propagation (a stage central to drug-type and medicinal cannabis, which are clonally propagated from cuttings rather than sown from seed like fiber hemp) [3,5]. Unrooted cuttings are physiologically fragile, lack a functional root system, and are highly vulnerable to water loss, tissue collapse, transplant shock, and infection by opportunistic pathogens. Under these conditions, silicon may improve propagation success by strengthening cell walls, reducing wilting, limiting infection by pathogens such as *Pythium* and *Botrytis*, reducing shock after separation from the mother plant, and accelerating the formation of strong, well-developed roots [1,30,92]. This is possible because silicon interacts with polyphenols and pectins, which are mainly present in the cell wall [93,94]. This interaction triggers silicon polymerization, which, in turn, causes structural rigidity, primarily in the cuticle and vasculature [1,93]. A practical propagation strategy is to include silicon in a mild starter solution with an electrical conductivity of approximately $0.6\text{--}0.8\text{ mS cm}^{-1}$ and a pH around 5.8–6.0. This solution may be used for soaking rockwool cubes, wetting propagation media, or lightly misting cuttings. Importantly, silicon should be added to water first, followed only afterward by Ca/Mg products and other nutrients, with pH adjustment performed at the end. This sequence minimizes precipitation and helps preserve nutrient

compatibility [5,46,50]. In this context, stabilized monosilicic acid is especially advantageous because it acts rapidly and increases EC only minimally. In contrast, potassium silicate, although effective, requires more rigorous pH correction due to its strong alkalinity [5,46]. Once cuttings have rooted, continued silicon supplementation during early vegetative growth may support chlorophyll formation, improve photosynthetic activity, strengthen stems and branches, and reduce the variability commonly observed during canopy establishment [5,13,42].

Silicon may therefore serve as a bridge between propagation management and full vegetative fertigation, enhancing both transplant success and subsequent crop uniformity. Mechanistically, these propagation benefits follow from the chemistry of silicic acid. Once the apoplastic concentration of monomeric H_4SiO_4 exceeds approximately 2 mM, it polymerizes in situ into amorphous silica, which becomes complexed with cell wall pectins and phenolic monomers, forming the cuticle–silica double layer that reduces cuticular water loss and locally reinforces penetration-prone tissues [91,93]. Closely analogous work in vegetatively propagated ornamentals is also informative: in stem cuttings of poinsettia, a potassium silicate drench increased root number, the length of the longest root, and both fresh and dry root mass, while up-regulating the expression of silicon-transporter genes, indicating that silicon can act on adventitious-root initiation and not merely on shoot tissues [95]. The protective effect against opportunistic root pathogens is similarly supported by experimental evidence. In cucumber colonized by *Pythium*, silicon supplied through the nutrient solution stimulated the activity of chitinases, peroxidases, and polyphenoloxidases, along with the deposition of phenolic material at infection sites, significantly reducing seedling mortality [92]. For unrooted cannabis cuttings, which combine an open wound, high humidity, and the absence of a functional root system, this combination of accelerated rooting and primed chemical defense is the most plausible basis for the empirically reported gains in propagation success. A preliminary in vitro study lends some direct support, reporting improved leaf appearance and higher rooting rates in cannabis explants supplied with sodium metasilicate. However, the dose and replication were not fully specified [85,86]. Direct cannabis evidence for improved propagation therefore rests essentially on a single methodologically limited report. The propagation rationale is otherwise based on analogy with other vegetatively propagated species and on mechanistic plausibility rather than on a consistent body of cannabis-specific trials.

3.3. Early Vegetative Growth and Canopy Development

The vegetative stage is characterized by rapid biomass accumulation, increasing transpiration, and high nutrient demand [51,96]. During this phase, silicon often produces some of its clearest agronomic effects [5,13]. Silicon-treated plants typically develop thicker stems, firmer petioles, stronger branches, and a more stable canopy architecture [1,42]. These structural benefits are particularly important in drug-type and medicinal cannabis, where the later development of large inflorescences places considerable load on stems and lateral branches. Stronger tissues may reduce breakage, improve tolerance to training, and support more productive canopy management strategies [41,97]. Silicon also appears to support vegetative vigor by increasing Si accumulation in above-ground tissues, with potential downstream effects on chlorophyll content and photosynthetic performance. For example, Si-treated plants showed substantially higher leaf Si concentrations than untreated controls, increasing from approximately 6% to 15.5% SiO_2 in dry matter, equivalent to about 2.8% to 7.2% elemental Si. Such Si accumulation may contribute to the greener and more robust appearance often reported in plants supplied with adequate silicon [38,41,42]. The positive effects of silicon on vegetative development may be associated not only with structural reinforcement but also with improved photochemical performance. Similar

responses have been reported in woody species supplied with potassium silicate, in which silicon enhanced photochemical efficiency and morphological development under varying environmental conditions [98]. At the same time, silicon may improve nutrient relations. Available evidence indicates that it can stabilize the uptake or utilization of N, P, K, Ca, Mg, and S, while also helping plants tolerate certain nutrient imbalances or transient stresses associated with fertigation management [5,41,84]. In practice, this means that silicon should not be regarded as a substitute for balanced nutrition, but rather as an element that may improve the efficiency and resilience of the nutritional program. It also highlights substrate-based approaches to silicon delivery during vegetative growth. Silicon-amended substrate components, including silicon-coated perlite or calcium silicate additions, may offer a useful complementary strategy in media inherently poor in available silicon [36,37]. Such approaches are especially attractive where frequent liquid addition is chemically difficult or where long-term root-zone supplementation is desired. Because vegetative silicon is most often delivered as potassium silicate, its use cannot be considered in isolation from the crop's cation balance. In medical cannabis, a potassium supply of about 15 mg L⁻¹ is clearly deficient and depresses inflorescence yield, whereas a range of roughly 60–175 mg L⁻¹ sustains optimal function. However, higher potassium levels simultaneously lower leaf and inflorescence calcium and magnesium concentrations [51]. Magnesium nutrition displays reciprocal interaction, with high magnesium restricting calcium and potassium uptake and translocation [99], and a vegetative response-surface analysis showed that raising phosphorus and potassium together depressed leaf magnesium [100]. The practical consequence is that a potassium-silicate program must be monitored not only for its silicon dose but also for these indirect shifts in the potassium–calcium–magnesium equilibrium. This effect is amplified in recirculating systems where such changes accumulate over successive top-ups [32,33]. It should be noted that, with the exception of the silicate–phosphite biostimulant trial, evidence for stem- and branch-strengthening responses is still largely inferred from other crops rather than measured directly in cannabis under defined silicon dosing.

3.4. Yield and Biomass Quality

The practical significance of silicon depends on whether it improves final crop performance [5,41]. The strongest cannabis-specific yield evidence comes from a biostimulant trial combining silicate-form Si with phosphite. This treatment raised leaf silicon roughly 2.1-fold and increased inflorescence yield by approximately 1.2-fold, although the yield effect was only marginally significant. Branch length was also marginally reduced, an architecture consistent with sturdier, more compact growth rather than elongation, while volatile and color quality remained unchanged [41]. Because this treatment was not a pure silicon source, the observed yield response cannot be attributed solely to silicon, but rather to the combined effect of the applied silicate–phosphite formulation. A separate substrate trial with calcium silicate likewise reported no effect on cannabinoid concentration despite clear changes in tissue mineral status [37]. Because the approximately 1.2-fold inflorescence-yield increase and the approximately 2.1-fold tissue-silicon rise both derive from a single biostimulant study, and the calcium-silicate substrate trial that found no cannabinoid change is likewise a single study, these specific figures should be regarded as provisional pending independent replication. Taken together, these results indicate that silicon may influence cannabinoid output mainly through biomass gain rather than by increasing cannabinoid concentration. Silicon may contribute to yield formation by strengthening the vegetative framework, supporting sustained photosynthetic function, reducing stress-related losses, and improving the plant's capacity to carry reproductive biomass [1]. Stronger branches and stems allow plants to support heavier flowers, while

healthier leaves may remain functionally active for longer during crop development. These effects are particularly relevant in intensive controlled-environment production, where rapid vegetative growth, repeated training or pruning, dense canopies, and the later mechanical load of inflorescence biomass can place high structural demands on the crop. Such effects are also relevant for fiber hemp, where higher Si availability may contribute to stronger and more resilient fibers [42,101,102]. For fiber-type cannabis, the quality response appears more direct: supplying silicate during primary fiber formation favored fiber quality, whereas application during secondary thickening favored total fiber yield, with measurable increases in the thickness of the secondary fiber layer [103].

3.5. Secondary Metabolism

In cannabis grown for inflorescences, silicon must also be evaluated in relation to secondary-metabolite quality, including cannabinoid and terpene concentration, profile stability, and total metabolite yield. At the same time, any potential quality concern is most relevant when silicon is applied excessively or too late in the production cycle, because the harvested flower is the marketable and often inhaled product [3]. Experimental observations suggest that silicon may increase dry flower yield and, in some contexts, total cannabinoid output [41]. However, these benefits appear to arise primarily through indirect mechanisms. Silicon does not directly replace core yield drivers, but by reducing stress and improving plant architecture, it may enable the crop to express its genetic potential more fully. In some cases, silicon may also help preserve or stimulate the production of secondary metabolites under mild stress, including terpenoid or essential-oil components. However, the evidence remains less uniform than for structural and protective effects [39,40]. Aside from strengthening cell walls and cuticles, silicon has been reported to deposit in trichomes, which constitute a significant portion of cannabis inflorescences [17,34,103]. This point should be interpreted with care. Elemental mapping by scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) and secondary-ion mass spectrometry (SIMS) shows that silicon silicifies the non-glandular, covering trichomes and accumulates at sites of fungal infection, but provides no evidence that it increases the density of the glandular, capitate-stalked trichomes in which cannabinoids and terpenes are actually synthesized [17,34]. These complementary imaging approaches, and their interpretation in cannabis as an intermediate accumulator, have been reviewed in detail [35]. The effect of silicon on the secondary-metabolite profile appears to be largely conditional on plant stress. Whereas Wise et al. (2025) found terpene profiles unchanged under well-watered conditions, foliar nano-silicon applied to hemp under water deficit markedly increased essential-oil content and reorganized its composition, shifting the relative proportions of major mono- and sesquiterpenes such as β -myrcene, β -ocimene, β -caryophyllene, and limonene [39,41]. This reconciles the apparently divergent reports: under non-stress cultivation, silicon tends to preserve the baseline profile, an advantage for product consistency, whereas under stress it can modulate terpene biosynthesis through the same defensive signaling that underlies its protective role. A thesis study applying silica-nanoparticle fertilizers to several hemp varieties directly illustrates this variability, reporting inconsistent, formulation-dependent effects on growth and tetrahydrocannabinol and cannabidiol concentrations, with some treatments raising and others lowering these compounds [39,40,104]. Quality responses must therefore be interpreted with caution. On the positive side, silicon-supported crops may produce healthier, more uniform, and less disease-affected flowers [36,41]. On the other hand, excessively prolonged or heavy use late in flowering is sometimes viewed critically by growers, who report excessive tissue hardness or concern over mineral hardness. Although such observations are not universally confirmed experimentally in cannabis, they are consistent with the broader point that silicon management should be stage-specific. Its value

is clearest during propagation, vegetative growth, early crop strengthening, and preventive health management, whereas late-flowering programs may benefit from more moderate use [3,41]. Finally, the grower's concern over harshness following heavy late-season use, although not yet verified experimentally in cannabis, has a plausible analog in tobacco, where excessive silicon altered the leaf sugar-to-nicotine balance and was associated with harsher smoke [3]. This consideration strengthens rather than contradicts the case for stage-specific, moderated late-flower dosing. These cannabis-specific responses must, moreover, be read against the strong influence of macronutrient supply on flower chemistry, which has direct implications for how silicon trials should be designed and interpreted. Increasing nitrogen from 30 to 320 mg L⁻¹ raises yield but lowers tetrahydrocannabinolic acid (THCA) and cannabidiolic acid (CBDA) concentrations by roughly 69% and 63%, respectively [105]. Phosphorus above approximately 5 mg L⁻¹ depresses THCA and CBDA by up to 25%, even though inflorescence biomass peaks near 30–90 mg L⁻¹ P [106]. Elevated root-zone phosphorus and overall nutrient concentration confer no additional yield or cannabinoid benefit [107]. Because potency expressed as concentration can thus be raised by mild nutrient deficit or stress, but only at the expense of total yield, any rigorous evaluation of silicon must report the total cannabinoid and terpene yield per plant or per unit area rather than concentration alone. This methodological requirement is essential for distinguishing a genuine agronomic gain from a mere dilution or a stress artifact [28,105,106,108,109].

4. Abiotic Stress Tolerance and Resilience

This section evaluates the cannabis-specific abiotic-stress evidence in detail. The cannabis literature is currently most coherent for salinity, water deficit, and toxic-metal exposure. At the same time, support for silicon-mediated heat, high-light, and oxidative-stress protection remains heavily dependent on mechanistic extrapolation from the wider plant-Si literature [18,19,38–40]. The subsections that follow are organized by stressor according to the strength of direct evidence in cannabis.

4.1. Salinity Tolerance

Salinity is currently the most coherently documented abiotic stress in the cannabis silicon literature, and the available data point to a primarily indirect, prophylactic mode of action [16,38]. In textile hemp, root-applied silicate alleviated visible stress symptoms in the older fan leaves. This response was accompanied by xylem vessels with a wider lumen, an anatomical adjustment consistent with improved hydraulic function under salt exposure. The same work showed that silicon accumulated in the fan leaves and that salinity induced expression of a putative low-silicon 2 (Lsi2) efflux transporter orthologue, indicating that hemp actively regulates silicon transport under ionic stress rather than passively accumulating it. These findings are mechanistically consistent with earlier evidence that *C. sativa* possesses aquaporin family members orthologous to known silicon transporters and that it deposits silica in stem and leaf tissues [34,38]. More recent work extends this evidence beyond conventional silicate supplementation to silicon-based nanocarriers. A foliar porous-silicon “phyto-courier” loaded with the flavonoid quercetin reduced macroscopic stress symptoms in salt-stressed hemp, with the best-performing formulations modulating soluble sugars and lowering the expression of stress-marker genes relative to salt-stressed controls [16]. A subsequent study showed that a root-applied phyto-courier loaded with rutin translocated to aerial tissues and induced protective molecular and anatomical changes under salinity, including effects on xylem and sclerenchyma development [73]. These nanocarrier studies should not be directly equated with standard reservoir dosing of monosilicic acid or potassium silicate, because in these systems, silicon also acts as a carrier for bioactive flavonoids. Nonetheless, they strengthen the cannabis-specific case

that silicon-containing interventions can reduce the severity of osmotic and ionic stress. Mechanistically, this prophylactic benefit is expected to involve reduced Na^+ influx and improved K^+/Na^+ and Ca^{2+} balance, but the cannabis studies available so far have not resolved these ion-balance and nutrient-interaction details, which remain to be quantified under realistic fertigation conditions. This salinity response is agronomically relevant because saline irrigation in hemp has been shown to reduce biomass at higher salinity levels and to alter phytocannabinoid composition, including a relative predominance of cannabidiol under stronger saline treatments [110]. Because recirculating hydroponic and indoor systems are prone to gradual salt accumulation, a prophylactic silicon supply is mechanistically well matched to the salinity range most relevant to commercial cultivation [32,33]. However, the direct demonstrations to date derive largely from fiber-type hemp rather than drug-type cultivars [16,38,73].

4.2. Water Deficit and Drought Tolerance

Evidence for water-deficit tolerance in hemp has also strengthened appreciably and now rests on direct cannabis experiments rather than extrapolation from cereals or cucurbits alone [39,40]. Under controlled mild-to-severe drought, foliar nanosilicon—applied to the foliage as a nanoparticulate-silicon suspension at 0.5–1.5 mM in 0.01% Tween 20, sprayed every ten days—improved drought tolerance by preserving photosynthetic pigments and increasing the activities of superoxide dismutase, peroxidase, and ascorbate peroxidase relative to droughted controls, with 1.5 mM nanosilicon identified as the most effective concentration overall; notably, the highest cannabidiol and tetrahydrocannabinol contents occurred under moderate stress combined with nanosilicon, indicating that silicon may influence both stress physiology and secondary metabolism [40]. A subsequent study confirmed that nanosilicon modified growth, essential-oil composition, and cannabidiol representation under water deficit, while partially mitigating the severe-drought penalty on aerial biomass and essential-oil output [39]. These results justify discussing silicon explicitly in relation to transient drought, irregular irrigation, and excessive transpiration in cannabis. Interpretive discipline is nonetheless warranted: both key drought studies used fiber-type hemp, foliar nanosilicon, and relatively short, controlled experiments at early developmental stages, thereby substantiating a cannabis-specific drought benefit without yet establishing a definitive protocol for full-cycle medical flower production. Moreover, neither report specified the precise chemical form (elemental nano-Si versus nano- SiO_2) or the primary nanoparticle size (agronomic silica nanoparticles are typically below 100 nm), which limits reproducibility and direct comparison with ionic silicon sources [39,40]. The decline in proline at the higher silicon dose, rather than its accumulation, is consistent with reduced stress injury and with the dose-dependent, non-linear behavior observed elsewhere with silicon [5,40]. The observed benefits of silicon for plant water relations should therefore be interpreted within the broader framework of irrigation and fertigation management. Although evidence from field production systems is not cannabis-specific, it shows that management practices can affect crop water productivity as strongly as environmental constraints [111]. This reinforces a practical point: silicon supplementation should be integrated with irrigation scheduling, root-zone salinity control, substrate water-holding capacity, and nutrient management rather than treated as an isolated solution to drought or transpiration stress.

4.3. Heavy Metals and Toxic Ions

Some of the most mechanistically detailed cannabis silicon studies concern toxic-metal exposure, particularly cadmium and zinc [18,19,112]. In hydroponically grown hemp exposed to cadmium, silicon reduced cadmium accumulation in all organs and improved

water-use efficiency through reduced transpiration; the reported effect on cadmium distribution among organs was, however, only marginal, so strong claims about pronounced silicon-driven root-to-shoot redistribution should be made cautiously [18]. Under zinc exposure, silicon reduced zinc absorption, lowered membrane lipid peroxidation, and increased total antioxidant capacity, even as root silicon rose markedly, by roughly 3.6-fold relative to untreated controls and roughly 7.4-fold in zinc-exposed plants relative to zinc alone, while reducing the accumulation of phytochelators and total glutathione, yet without a measurable short-term improvement in growth [19]. The suppression of intracellular chelators when silicon is present is itself informative, suggesting that by restricting metal entry at the apoplast, silicon lowers the demand on internal detoxification machinery rather than enhancing it. Complementary stem-focused work showed that cadmium and zinc altered bast-fiber diameter and the expression of cell-wall-related genes, whereas exogenous silicon modified part of the cadmium-associated protein response, suggesting a stabilizing role in cell-wall metabolism [112]. Taken together, these findings indicate that in hemp, much of silicon's protective action against ionic and metal stress is indirect, operating through reduced toxic-ion entry, improved hydraulic behavior, attenuation of oxidative damage, and stabilization of cell-wall-associated processes, rather than through direct detoxification of the stressor [18,19,112]. This interpretation is consistent with the wider view of silicon as an extracellular, apoplastic agent rather than an intracellular signaling molecule [1,91]. However, these cadmium and zinc findings come from short-term hydroponic exposure studies using fiber hemp and a single 2 mM silicon dose. Therefore, their applicability to substrate-based or field phytoremediation systems, other genotypes, and longer exposure periods remains to be demonstrated.

4.4. Flooding and Waterlogging

Flooding and waterlogging represent a further abiotic stress of practical relevance to both soilless and field cannabis, particularly where drainage is poor or irrigation is mismanaged. Physiologically, this stress is best understood as root-zone oxygen deficiency rather than simply as excess water [113]. However, no peer-reviewed study has yet tested silicon supplementation against flooding, waterlogging, or experimentally imposed root-zone hypoxia in *C. sativa*. In other crops, silicon has been reported to alleviate waterlogging injury by supporting root function, antioxidant capacity, and limiting reactive oxygen species accumulation under hypoxia [114–117]. For cannabis, however, any such benefit remains a mechanistic extrapolation, and flooding tolerance should therefore be treated as a clear research gap rather than as an established application of silicon. In the absence of cannabis data, the mechanistic rationale rests largely on the rice model, in which silicon is deposited in the root apoplast and can modify the barriers that govern gas and ion movement. Under waterlogged, oxygen-poor conditions, flood-tolerant species restrict radial oxygen loss from the basal root zone so that oxygen transported internally through aerenchyma can reach the growing root tip [113]. In rice, silicon has been reported to promote suberization and lignification of the exodermis and the formation of Casparian bands, thereby reinforcing this barrier and helping to sustain internal aeration [118–120]. However, this interpretation is not entirely settled. A more recent study reported the opposite effect, with silicon weakening and delaying the formation of the outer apoplastic barrier in rice roots and thereby increasing sodium and chloride fluxes to the shoot [121]. Whether silicon strengthens or weakens root-zone apoplastic barriers remains unresolved, even in the most intensively studied model species. Moreover, rice is a flood-tolerant, high-silicon-accumulating monocot with root anatomy that differs markedly from that of cannabis, making it an imperfect template for extrapolation. More generally, current models of waterlogging tolerance place aerenchyma formation, apoplastic barriers to

radial oxygen loss, ethylene-mediated acclimation, metabolic adjustment, and reactive-oxygen-species control at the center of plant survival under root-zone hypoxia [113]. The antioxidant dimension of this potential benefit is supported by a small number of trials in which silicon was supplied directly under root-zone oxygen deficit. In muscadine grapes under waterlogging, silicon and more strongly silicon nanoparticles increased the activities of superoxide dismutase, peroxidase, catalase, and ascorbate peroxidase, increased ascorbate and glutathione pools, and reduced lipid peroxidation [114]. A companion study in southern highbush blueberry reported a similar pattern, again with nanoparticulate silicon producing stronger responses than the conventional silicate treatment [115]. In maize exposed to oxygen deficiency, supplementary silicon at 1.0 mM reduced hydrogen peroxide, malondialdehyde, and membrane injury while improving chlorophyll content and plant water status [117]. In buckwheat, foliar silicon lessened waterlogging-induced declines in photosynthesis, relative water content, and membrane integrity and accelerated post-stress recovery [116]. Across these systems, the response is broadly consistent: silicon reduces oxidative damage and helps maintain root and canopy function under hypoxia, with several studies suggesting stronger responses to nano-scale formulations than to conventional silicates. Two limitations temper the transfer of these findings to cannabis. First, the direct evidence for silicon under hypoxia comes from a small, taxonomically narrow set of non-cannabis crops, and some of the most detailed datasets originate from the same research group. Second, the anatomical component of the response is not fully resolved even in rice, where silicon has been reported both to reinforce and to delay outer apoplastic barrier formation [118–120]. The mechanistic case for silicon in flooded cannabis therefore remains plausible but unverified.

4.5. Temperature and High-Light Stress

Direct cannabis-specific evidence for silicon-mediated protection against temperature and high-light stress remains weak. The available cannabis literature shows that elevated temperature can alter biomass and cannabinoid outcomes, including genotype-specific reductions in inflorescence dry matter and specialized-metabolite yield [122,123]. However, trials demonstrating silicon-mediated thermotolerance specifically in *C. sativa* are scarce. Any expectation of heat protection should therefore be treated as a cautious mechanistic extrapolation rather than as an established cannabis-specific result [1,5]. A similar limitation applies to light-related stress. No cannabis-specific studies yet address whether silicon mitigates ultraviolet stress or stress caused by supraoptimal photosynthetic photon flux density. Because both thermal and high-light stress can act, at least in part, through reactive oxygen species accumulation, silicon's antioxidant-supporting effects in other cannabis stress contexts provide a plausible mechanistic rationale [1,5,74]. However, this remains an inference rather than direct evidence, leaving temperature, ultraviolet radiation, and high-light stress as clear research priorities for controlled-environment cannabis production [124].

4.6. Oxidative Stress

A unifying thread across the salinity, drought, and metal-stress studies is the reinforcement of antioxidant defense: silicon has repeatedly been associated with increased enzymatic antioxidant activities and total antioxidant capacity, together with lower markers of membrane lipid peroxidation [19,39,40]. These findings indicate that a substantial part of silicon's protective value lies in buffering the oxidative component common to many abiotic stresses [5]. Because this response appears across several stress models, oxidative stress is best understood in the current cannabis literature as a shared downstream component of salinity, drought, and metal toxicity rather than as an independent stressor. No cannabis study has yet manipulated oxidative stress in isolation. Consequently, although

the antioxidant-supporting role of silicon is among the better-supported themes in the cannabis stress literature, it has not been tested as a primary endpoint. Its magnitude relative to the apoplastic, ion-exclusion, hydraulic, or cell-wall-mediated components of silicon action, therefore, remains to be resolved [5,6,19]. This interpretation connects to a broader, still unresolved debate over whether silicon acts directly on plant redox metabolism or only indirectly. One influential view holds that silicon functions largely as an extracellular, apoplastic agent, so that the improved antioxidant status recorded under stress is chiefly a downstream consequence of relieving the primary stressor rather than evidence of direct defense priming [6]. Strong transcriptomic support for this view comes from unstressed *Arabidopsis*, in which silicon altered only 2 of roughly 40,000 transcripts. In contrast, thousands responded when stress was imposed, implying that the molecular footprint of silicon is largely stress-conditional [125]. Set against a strictly passive account are reports of silicon effects that are difficult to explain by reduced uptake of the primary stressor alone, including modulation of the ascorbate–glutathione cycle [126] and benefits under stressors such as glyphosate or aluminum toxicity, where limiting ion uptake cannot readily account for the improvement. This question has been contested directly in the literature [1,7]. On balance, the evidence is most consistent with oxidative stress acting primarily as a shared downstream node, but a strictly passive model is probably incomplete. At the same time, claims that silicon directly activates antioxidant defense are often stronger than the experimental designs that support them, because many studies lack an unstressed silicon-only control [6,125]. For cannabis, the decisive experiment is clear: pairing an unstressed silicon-only treatment with a stressed silicon treatment, while profiling enzymatic and non-enzymatic antioxidants together with redox-related gene expression, would help separate direct redox modulation from the indirect consequences of stress relief. Until such data exist, the antioxidant contribution of silicon in cannabis is best described as real but mechanistically unresolved.

5. Disease and Pest Management

Building on the general motivation established in the Introduction, this section grades the cannabis-specific evidence for Si in crop protection, target by target. In greenhouse and indoor production, the pathogens that most consistently threaten crop continuity and inflorescence quality are powdery mildew, bud rot caused by *Botrytis cinerea*, and the root-infecting *Pythium* and *Fusarium* spp. [29–31]. Silicon does not act as a conventional fungicide; rather, it contributes through deposition of hydrated silica in epidermal cell walls that raises the barrier to penetration, priming of defense responses that accelerate the accumulation of phenolics, phytoalexins, and pathogenesis-related proteins, and, after foliar application, a thin surface layer that physically impedes spore germination [1,5,46]. Powdery mildew is currently the only disease for which direct cannabis Si trials provide a coherent evidence base. In contrast, claims for *Botrytis*, root pathogens, and arthropod pests should be treated as biologically plausible but not yet experimentally demonstrated in cannabis [29,36,52,53].

5.1. Powdery Mildew: The Strongest Direct Evidence

Powdery mildew is the best-supported disease target for silicon in cannabis, with three independent peer-reviewed studies providing direct evidence [36,52,53]. The causal agent is currently recognized as *Golovinomyces ambrosiae* (treated as synonymous with *G. spadicus* and reported in older work as *G. cichoracearum* sensu lato) [52,53]. For root-applied silicon, one study grew two hemp cultivars in a peat-based soilless medium amended with wollastonite. They monitored both leaf-tissue silicon and mildew severity over six weeks, demonstrating a negative linear relationship between leaf-tissue silicon

and the proportion of leaf area affected. The response was canopy-position dependent: mildew in the upper canopy was significantly reduced at approximately 300 kg Si/ha, whereas roughly 600 kg Si/ha was required to suppress mid-canopy mildew, and the dose response saturated beyond that level. This is the strongest evidence that root-supplied silicon acts systemically, linking disease suppression to tissue silicon loading and to the spatial silicon gradient within the canopy [36]. Two further studies document foliar efficacy. In greenhouse hemp, plants (cultivars ‘BaOx2’ and ‘Sweetened’) were inoculated with *G. ambrosiae* conidia standardized to 2×10^5 conidia mL⁻¹ and applied treatments three times at seven-day intervals to both leaf surfaces, with the first, prophylactic application one day before inoculation; the potassium-silicate product Sil-Matrix reduced disease by approximately 88% on a disease-index area under the disease progress curve (AUDPC) basis, placing it in the authors’ “very good” efficacy class [52]. On drug-type cannabis, foliar treatments were evaluated under naturally developing mildew pressure across three repeated trials with four replicates each; stabilized silicic acid (Silamol, ~2.5% available Si as Si(OH)₄) at 2.4 mL L⁻¹ reduced the area under the disease-progress curve by 24.77%, 73.19%, and 69.26% across the three trials. These reductions are biologically meaningful but highly variable, and silicon was not ranked among the most consistently effective treatments, which were instead potassium bicarbonate, *Reynoutria sachalinensis* extract, *Bacillus subtilis* QST713, neem oil, and fluopyram. Foliar silicon is therefore best read as a useful preventive adjunct whose performance depends strongly on disease pressure, timing, and environment rather than as a stand-alone or curative control [53]. Whether this suppression is driven primarily by silicon deposition at infection sites, silicon-primed host defenses, or indirect nutritional effects cannot be fully separated from the current cannabis data. However, the cytological localization of silica at attempted-penetration sites, together with the systemic response to root application, points to a combination of physical surface reinforcement and primed defense rather than to a purely nutritional effect.

5.2. Bud Rot and Root Pathogens: Evidence Gaps in Cannabis

In contrast to powdery mildew, direct evidence for silicon against bud rot and root pathogens in cannabis is currently absent, and claims for these targets must be framed as extrapolations [29,31]. For *Botrytis cinerea*, cannabis-specific work establishes epidemiological relevance rather than silicon efficacy: bud rot is among the most destructive flowering-stage diseases, with infection favored by dense inflorescences, relative humidity above roughly 70%, and temperatures of about 17–24 °C [127], and it is consistently listed among the principal greenhouse diseases of the crop [29,31]. No published study has tested silicon directly against *Botrytis* on cannabis. Because the infection court of this necrotroph (senescing floral tissues and the dense bud microclimate) differs fundamentally from the epidermal penetration route of biotrophic powdery mildew, extrapolation from grey-mould suppression in strawberry and other crops is biologically reasonable but mechanistically weaker, and a controlled trial on cannabis inflorescences remains an important research gap [1,5]. The same caution applies to root pathogens. Surveys of hydroponically grown marijuana have documented the importance of *Pythium dissotocum*, *P. myriotylum*, *P. aphanidermatum*, *Fusarium oxysporum*, and *F. solani*, including dissemination of *F. oxysporum* through recirculating nutrient solution and on rooted cuttings. This biology provides a strong rationale for a preventive, root-directed silicon strategy, but no direct cannabis study has shown that silicon reduces *Pythium* or *Fusarium* severity on cannabis roots [30,128]. The transferable evidence comes from hydroponic cucumber, where soluble silicon in the recirculating solution reduced damping-off and root rot caused by *Pythium*, and where silicon-amended roots responded to infection with accelerated activation of chitinase, peroxidase, and polyphenoloxidase and with accumulation of fungistatic glycosy-

lated phenolics [92,129]. For cannabis, this supports testing root-zone silicon in propagation and vegetative root-health programs, but not yet the stronger claim that efficacy has been demonstrated. No primary cannabis study has yet demonstrated silicon-specific suppression of arthropod pests such as the cannabis aphid (*Phorodon cannabis*), hemp russet mite (*Aculops cannabicola*), or two-spotted spider mite (*Tetranychus urticae*). However, root-zone silicon has reduced *T. urticae* in other protected crops, so a contribution to pest resilience in cannabis is plausible but unverified [29,130,131].

5.3. Mechanisms: Foliar Surface Barrier Versus Root-Induced Priming

The mechanistic literature consistently supports a two-pathway model that aligns with the cannabis observations above [1,5]. After foliar application, soluble silicate forms a surface deposit that physically and osmotically impedes conidial germination and appressorial penetration; foliar potassium silicate has been shown to reduce powdery-mildew colony numbers on cucurbits, an essentially local effect on the treated surface [87]. After root application, silicic acid is loaded into the xylem, polymerized as silica at apoplastic deposition sites, and coupled to a primed defense state in which pathogen attack triggers faster accumulation of pathogenesis-related proteins and antifungal phenolics [1,5]. This asymmetry has been demonstrated directly in cucumber, where root-applied but not foliar-applied silicon enhanced systemic powdery-mildew resistance and pathogenesis-related enzyme activity, while the flavonol aglycone rhamnetin has been identified as a silicon-induced phytoalexin [89,132]. In wheat, root applications reduced powdery mildew by as much as 80%, whereas foliar applications were inconsistent [88]. In cannabis specifically, silica has been localized by elemental mapping to non-glandular trichomes and to sites of attempted powdery mildew penetration [17,34], providing a cannabis-level cytological counterpart to these cucurbit and cereal mechanisms. The convergence of these lines supports interpreting root-zone silicon as the more rational route when durable, systemic resistance is the objective, and foliar silicon as a preventive surface treatment best applied to vegetative foliage rather than to maturing inflorescences [36,52,53]. It should be emphasized that the cucurbit and cereal experiments cited here are invoked solely to explain the mechanism, not to imply direct disease control in cannabis. The primary economic diseases of concern in cannabis are powdery mildew, Botrytis-related bud rot, and the root pathogens *Pythium* and *Fusarium*, as discussed above [29–31]. The central research priority is therefore to confirm these silicon mechanisms directly in *C. sativa* rather than to rely on analogy with other crop systems.

6. Practical Integration into Fertigation Programs

Successful integration of silicon into cannabis fertigation programs is best framed around the route of delivery, verifiable tissue uptake, and compatibility with the cultivation system rather than around a single universal recipe [5,41,50]. Because uptake in cannabis is root-mediated through NIP2-type aquaporins (Section 3) and the underlying chemical-handling rules (the silicon-first mixing sequence, pH control, and the potassium–calcium–magnesium balance of potassium–silicate programs) have already been established for the propagation and vegetative stages, the present section concentrates on what those constraints imply for choosing among delivery routes, for managing different fertigation systems, and for verifying that a program has actually reached the plant [13,34,51]. The three available routes (root-zone fertigation, substrate incorporation, and foliar spraying) are not equivalent in cannabis, and the evidence supports a clear hierarchy among them [36,37,41,53].

6.1. Route of Delivery: A Cannabis-Specific Hierarchy

Root-zone delivery is the principal, best-supported route for building sufficient plant silicon status in cannabis [36,41]. In hemp, root-applied silicon raised leaf-tissue silicon from approximately 0.39% to about 1.10% of dry weight at the highest tested rate of 600 kg Si/ha. It reduced powdery mildew severity in a dose-dependent manner, with significant suppression in the upper canopy at roughly 300 kg Si/ha and in the mid-canopy at roughly 600 kg Si/ha [36]. Cannabis studies on salinity and metal stress reinforce this conclusion, because the protective effects of silicon in those systems followed root supply and acted systemically on tissues, water relations, and stress metabolism [18,19,38]. Continuous low-to-moderate root-zone supplementation is therefore the most evidence-based strategy for vegetative support and resilience building, and it has the practical advantage that its success can be verified through leaf-tissue silicon and canopy-position responses rather than inferred solely from the dose added to the reservoir. Substrate incorporation is the second route, and it deserves more emphasis in cannabis than general horticultural guidance usually gives it. In greenhouse-grown *C. sativa* 'Auto CBG', calcium-silicate amendment of a peat-based substrate reduced excessive accumulation of micronutrients in foliage, roots, and floral material without negative effects on growth or cannabinoid concentration, and related work in 'BaOx' showed that calcium-silicate amendment raised foliar silicon [36,37]. These direct cannabis findings make pre-planting incorporation of a slow-release silicon source a scientifically justified option in intrinsically silicon-poor media such as peat or coco, particularly where a chemically sensitive shared reservoir makes continuous dosing of soluble silicates difficult. Foliar application should be treated as a complementary rather than an equivalent route. In a cannabis salinity study using a silicon-based phyto-courier, repeated leaf spraying mitigated visible stress symptoms, yet leaf silicon did not increase significantly. The authors noted that leaves are not the principal organs of silicon absorption because the cuticle acts as a diffusion barrier and estimated that a single foliar application delivered only about 6.4 ppm Si [16]. This value, however, should not be directly compared with the earlier increase in leaf silicon from 0.34% to 0.66% dry weight achieved through root-zone application of sodium metasilicate, because the two approaches differed in application route, formulation, applied Si dose, and exposure duration. Overall, foliar Si may be useful for rapid local protection or stress priming. Still, it should not be presented as a substitute for sustained root uptake or as a route for establishing systemic silicon sufficiency in cannabis [16,52,53]. In practical fertigation terms, the evidence therefore supports a clear route hierarchy: silicon is most justifiably supplied through the root zone or incorporated into the substrate during propagation and vegetative growth, the stages at which uptake, deposition, and cannabis-specific evidence are strongest [34,36,37,41]. Foliar silicate is better reserved as an occasional preventive treatment of vegetative foliage and should be used cautiously, if at all, on developing inflorescences, where residue and sensory considerations dominate [20,21,52,53]. Because this routing question is central to integrating silicon into cannabis fertigation, it is treated here as a major practical recommendation of the review rather than as an incidental technical detail.

6.2. Fertigation System as a Modifier of Strategy

The type of fertigation system is a major modifier of any silicon program. In medicinal cannabis, the fertigation system alone has been shown to alter the plant ionome and production outcomes, with recirculating and drain-to-waste systems differing clearly in agronomic behavior [32,33]. Silicon programs should therefore not be transferred uncritically between systems. In drain-to-waste or discrete-event substrate irrigation, routine root-zone supplementation is comparatively easy to standardize, because each irrigation event delivers a defined dose and residues are flushed rather than accumulated [5,50]. In recirculating

hydroponics, by contrast, silicon is best introduced conservatively and evaluated alongside the broader behavior of the reservoir, since the system is chemically dynamic and indirect shifts in the potassium–calcium–magnesium equilibrium discussed in Section 3 accumulate over successive top-ups [32,33,51]. A defensible recirculating protocol, therefore, validates silicon in the specific stock-solution architecture in use, monitors dissolved silicon, pH drift, and the saturation status of calcium, magnesium, and phosphorus between top-ups, and seeks to separate a genuine physiological effect of silicon from an indirect effect of altered reservoir chemistry [5,13,50].

6.3. Verifying Uptake and Stage-Specific Dosing

Because the dose added to a tank is only a proxy for what reaches the plant, periodic analysis of leaf-tissue silicon is the most reliable way to make a silicon program verifiable [36,41]. Tissue analysis is already the established basis for managing other cannabis nutrients, for which foliar survey and sufficiency ranges have been characterized against documented deficiency and toxicity symptoms [133], and silicon can be incorporated into the same most-recently mature leaf sampling routine. Cannabis data show that effective root application elevates foliar silicon content well above untreated background values, with leaf silicon rising from about 0.39% to above 1.0% of dry weight at the higher incorporation rates [36]. Such values are best read not as a universal sufficiency threshold for all cannabis, but as a practical internal benchmark confirming that silicon supplied to the root zone has genuinely entered the plant; pairing tissue testing with records of source, dose, and growth stage then allows growers to detect both under-supply and the earliest signs of over-application before they appear in crop quality [36,41,133]. Stage-specific management is best expressed in evidence-based rather than calendar-based terms. The cannabis literature supports silicon most clearly during propagation, vegetative development, early crop strengthening, and preventive health management. Still, it does not yet establish a universal rule requiring silicon withdrawal at a defined flowering week across genotypes and systems [36,37,41]. Late-cycle management is therefore better guided by verified tissue uptake, genotype response, substrate type, and the intended marketable organ than by a fixed cut-off schedule. Working doses should likewise be treated as a research-derived starting range rather than a fixed prescription. As with the tissue-silicon benchmarks above, these doses should be regarded as provisional given the current evidence base. For root-zone application, an initial bracket of roughly 0.25–0.5 mM available silicon is reasonable during vegetative growth and into early flower. This corresponds to approximately 7–14 mg L⁻¹ elemental Si, or 15–30 mg L⁻¹ expressed as SiO₂, the unit most commonly used on commercial product labels. As a rule of thumb, 1 mM Si ≈ 28 mg L⁻¹ Si ≈ 60 mg L⁻¹ SiO₂ ≈ 96 mg L⁻¹ H₄SiO₄. Extension toward about 1.0 mM may be justified only where solution stability has been confirmed, and no antagonism toward calcium, magnesium, or potassium is observed. This range is consistent with the saturating low-dose response reported in barley at 0.5 mM [84] and remains below the approximately 1.7 mM associated with stronger protective effects in wheat and cucumber [88,89]. Because silicon supplementation does not replace appropriate irrigation management, its implementation should be integrated with crop-specific water and fertigation strategies. Although the supporting evidence is not cannabis-specific, previous studies have shown that irrigation criteria and water-allocation decisions can substantially affect crop performance and resource-use efficiency [134]. This reinforces the practical point that silicon should be managed as part of an integrated root-zone strategy rather than as an isolated input.

7. Limitations

Despite its promise, silicon is not a universally simple input. The main practical constraints relate to chemistry, compatibility, and incomplete crop-specific optimization [5,13,50]. Soluble silicates can destabilize nutrient solutions, sharply raise pH, and generate precipitates if mixed improperly. Because silicon is generally more stable under highly alkaline conditions, whereas fertigation solutions are typically managed at mildly acidic pH, formulation, dilution order, and handling are critical [5,46]. Moreover, when solution pH rises above neutral levels, micronutrient availability may decline, creating secondary nutritional problems [50]. The principal limitation of this review is that the cannabis-specific evidence base for silicon, although consolidating rapidly since 2019, is still considerably smaller than for staple field and horticultural crops, so a substantial portion of the mechanistic and practical framework presented above is derived by extrapolation from cucurbits, cereals, strawberry, and other model species, with the transferability to high-potency medicinal chemovars plausible but not yet fully quantified [34,36,38,41]. A further limitation is that several grower-relevant concerns remain only indirectly supported. No direct molecular evidence of silicon–phosphorus competition has yet been obtained in cannabis. The prudent inference from the wider literature and from cannabis phosphorus trials is therefore not that silicon blocks phosphorus, but simply that aggressively high phosphorus should not be combined with high silicon during flowering without direct ionome and quality monitoring, since adequate phosphorus is in any case safer than luxury phosphorus [84,106,108]. Equally, growers' concern about the potential for harsh late-season silicon may be better addressed through an evidence-based post-harvest approach than through dosing changes alone. Controlled drying and curing are documented to reduce harsh smoke and microbial load [135,136] and thus represent a better-supported lever for inhalation quality than speculative late-flower silicon restriction, particularly given the recent observation that non-glandular cannabis trichomes can excrete mineral salts under excessive fertilization and might thereby contribute surface residue [17]. A related and largely unaddressed constraint is regulatory rather than agronomic. Because cannabis inflorescence is frequently consumed by inhalation, agronomic efficacy must be separated from residual and regulatory acceptability. Under the Canadian Good Production Practices framework issued by Health Canada, only pest-control products registered for cannabis are permitted, and residue testing is required. In contrast, the good agricultural and collection practice guidance issued by the European Medicines Agency requires documentation of chemical inputs and testing of herbal raw material for pesticide residues, heavy metals, and microbial contaminants [83,137–139]. The practical consequence is that an agronomically rational silicon product cannot automatically be justified for medicinal cannabis without jurisdiction-appropriate registration. Late-flower foliar applications of alkaline silicates or formulations containing non-validated adjuvants, whose inhalation toxicology is uncharacterized, should therefore be treated with high caution rather than as routine practice until residue and sensory data are available [17,80].

8. Future Research Directions

Within the cannabis literature itself, the principal open needs are cultivar- or genotype-resolved dose–response work, source comparison under identical conditions, defined interactions with Ca and P nutrition across substrates, and quantitative endpoints linking silicon nutrition to cannabinoid and terpene yield rather than concentration alone [37,41]. At the mechanistic level, candidate silicon-transporting aquaporins in cannabis have been identified by sequence and tissue localization but not yet validated by loss-of-function or heterologous expression studies, leaving their precise transport roles and substrate specificities unresolved [34,72]. Finally, there is currently almost no peer-reviewed evidence on how

late-flower silicon dosing affects the mineral load, combustion behavior, or sensory quality of the finished product, even though this is precisely the stage about which growers express the greatest concern [17,41]. These needs can be ordered by priority. In the short term, the field most urgently requires standardized source- and dose-comparison trials, routine leaf-tissue-silicon verification, and commercial controlled-environment studies that couple silicon uptake with flower yield, cannabinoid and terpene output, and flowering-stage disease control. In the medium term, genotype- or chemotype-resolved experiments should test whether responses differ among fiber hemp, CBD-dominant chemovars, and high-THC medicinal genotypes, and should define interactions with substrate type, Ca–Mg–K balance, phosphorus supply, irrigation regime, and salinity. The most critical unresolved questions for commercial implementation are the residual, sensory, combustion, and regulatory consequences of late-flower silicon applications, as well as the functional validation of the candidate cannabis silicon transporters using loss-of-function or heterologous expression approaches.

9. Conclusions

Silicon is not essential for cannabis, yet the evidence assembled in this review suggests that it can function as a genuine agronomic resource rather than an inert additive. Cannabis behaves as an intermediate silicon accumulator, taking up silicic acid through an apparently active, transporter-mediated pathway and depositing it mainly in bast fibers and non-glandular trichomes. This biology supports a stage-structured approach to Si fertigation. The most dependable benefits occur during propagation and vegetative growth, when Si reinforces cell walls and vascular tissues, supports the establishment of cuttings, and improves canopy resilience. Under abiotic stress, the strongest cannabis-specific evidence concerns salinity, water deficit, and toxic-metal exposure, where Si restricts the entry of harmful ions, modifies root and vascular anatomy, and strengthens antioxidant defense rather than acting as a direct detoxifier. In crop protection, powdery mildew is the only disease currently supported by direct cannabis evidence, with root-zone Si providing systemic, dose-dependent suppression and foliar Si serving as a preventive complement. For yield and quality, Si appears to increase biomass and tissue-Si accumulation while leaving cannabinoid concentrations and volatile profiles largely unchanged under non-stress conditions. Its contribution to yield is therefore best understood as biomass-driven rather than concentration-driven. Overall, the current evidence supports the use of Si as a resilience-enhancing, stage-specific input supplied primarily to the root zone, complemented by substrate incorporation in Si-poor media and by cautious preventive foliar use. Uptake should be verified by leaf tissue analysis, and dosing should be matched to the genotype, substrate, and fertigation system. Silicon should therefore be regarded as one deliberate component of an integrated cultivation program rather than a stand-alone or universal solution. The principal unresolved questions concern flowering-stage disease control, genotype- and chemotype-specific dose–response relationships, functional validation of candidate cannabis silicon transporters, and the residual, sensory, combustion, and regulatory consequences of late-flower application. These questions need to be addressed before broad, unqualified recommendations can be made for medicinal cannabis production.

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Abbreviations

The following abbreviations are used in this manuscript:

AUDPC	Area under the disease progress curve
BC	Biostimulant complex
CaSiO ₃	Calcium silicate
CBD	Cannabidiol
CBDA	Cannabidiolic acid
CBG	Cannabigerol
EC	Electrical conductivity
EO	Essential oil
FC	Field capacity
GSGR	Glycine-serine-glycine-arginine (aquaporin selectivity filter)
H ₄ SiO ₄	Monosilicic acid
K ₂ O	Potassium oxide
K ₂ SiO ₃	Potassium silicate
Lsi1	Low-silicon 1 (influx transporter)
Lsi2	Low-silicon 2 (efflux transporter)
NIP2	Nodulin 26-like intrinsic protein 2 (aquaporin subfamily)
NPA	Asparagine-proline-alanine (aquaporin pore motif)
SEM-EDX	Scanning electron microscopy with energy-dispersive X-ray spectroscopy
Si	Silicon
SIMS	Secondary-ion mass spectrometry
SiO ₂	Silicon dioxide
THC	Tetrahydrocannabinol
THCA	Tetrahydrocannabinolic acid

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