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A.I.Suleimenova[1,2]*, M.N.Poshanov[1], A.S. Vyrakhmanova[1]

FROM MECHANISMS TO FIELD APPLICATION: A SYSTEMATIC REVIEW OF SILICON-MEDIATED SALINITY TOLERANCE IN PLANTS

[1]Kazakh Research Institute of Soil Science and Agrochemistry named after U.U. Uspanov, 050060, Almaty, Al-Farabi avenue, 75B, Kazakhstan

[2]Kazakh National Agrarian Research University, 050010, Almaty, Abai Ave., 8, Kazakhstan, e-mail: s.altynai87@mail.ru

Abstract. The study was conducted in accordance with the PRISMA 2020 guidelines. Two complementary searches of the Scopus database identified 746 scientific records, of which 378 studies were included in the analysis after removal of duplicates and assessment against the predefined eligibility criteria. The analysis of the scientific literature showed that silicon-mediated enhancement of plant salinity tolerance is primarily associated with improved regulation of Na^+ ions, stabilization of the K^+/Na^+ ratio, reduction of oxidative damage, maintenance of photosynthesis and water status, as well as recovery of plant growth and biomass. Both conventional silicon sources and silicon nanoparticles can be effective under specific conditions. However, due to the limited number of studies directly comparing these forms, there is insufficient evidence to confirm the overall superiority of nano-silicon over other forms of silicon. Most studies were conducted under controlled conditions, whereas field studies accounted for only 4.6% of the total. Future research should prioritize standardized reporting of silicon doses, direct comparisons of different silicon sources and application methods, investigation of genotype-specific responses, and field experiments conducted across multiple locations and growing seasons. Overall, silicon represents a promising but context-dependent component of salinity management and should not be considered a universally effective solution across all conditions.

Keywords: silicon, salinity stress, salt tolerance, ion homeostasis, oxidative stress, silicon nanoparticles, crop productivity, saline soils, systematic review.

INTRODUCTION

Soil salinity is one of the major factors limiting plant growth and crop productivity. This constraint is particularly pronounced in arid and semi-arid regions, where high evapotranspiration, poor drainage, and saline irrigation contribute to salt accumulation in the root zone [1]. Salinity induces osmotic, ionic, and oxidative stress: reduced water potential restricts water uptake, while excessive accumulation of Na^+ and Cl^- disrupts mineral nutrition and ion homeostasis [2]. As a result, cell membranes are damaged, photosynthesis is impaired, the production of reactive oxygen species (ROS) increases, and plant growth and productivity decline. The severity of these effects varies depending on plant species, genotype, developmental stage, and growing conditions [3-5].

Silicon (Si) has received increasing attention in recent years due to its ability to alleviate salinity stress [6]. Studies have shown that Si can reduce Na^+ accumulation and transport, maintain K^+ uptake and the K^+/Na^+ ratio, mitigate oxidative damage, and improve plant water relations and photosynthetic performance [7-11]. Silicon has been shown to enhance the activity of proton pumps involved in ion homeostasis in aloe [8], affect the expression of the Si transporters Lsi1 and Lsi2 in rice [12], alter the expression of salt-responsive genes in tomato [13], and be associated with changes in DNA methylation in oat [14]. Thus, Si-mediated salinity tolerance involves interacting physiological, biochemical,

and molecular processes. Plant responses to Si vary depending on plant species and genotype, Si source and dose, application method, salinity conditions, developmental stage, and experimental system [5,14,15-19]. Most of the available evidence is derived from controlled NaCl experiments and does not fully represent the conditions of heterogeneous salt-affected soils. In cotton, the effectiveness of Si has been lower under alkaline stress, while field-based evidence remains limited [16].

This systematic review examines how plant species and genotype, salinity type and severity, Si source and dose, application method, developmental stage, and experimental system influence Si-mediated salinity tolerance. The synthesis covers ion homeostasis, oxidative and antioxidant responses, water relations, photosynthesis, growth, productivity, and molecular regulation. We hypothesize that the effectiveness of Si is context dependent and is determined by interactions among plant characteristics, Si treatment, salinity conditions, and the experimental environment.

MATERIALS AND METHODS

Review Design and Search Strategy. This systematic review followed the PRISMA 2020 guidelines [20] and a predefined review protocol [21]. The review examined experimental evidence on Si-mediated plant responses to salinity, with emphasis on the mechanisms involved, sources of variation in Si effectiveness, and translation of physiological responses to growth and yield.

Literature was searched in Scopus using the TITLE-ABS-KEY fields. Two complementary searches were used to capture both general studies of Si-mediated salinity tolerance and studies focused on major physiological and biochemical mechanisms. The searches covered publications from 1992 to 2026 and retrieved 364 and 382 records, respectively. The complete search strings are provided in table 1. Records from both searches were merged and duplicates removed before screening. The final search was conducted on 25 August 2026.

Table 1 - Keyword Combinations and Boolean Syntax Used in the Two-Stage Scopus Search

Database	Search stage	Conceptual dimension	Search terms
Scopus	Stage 1	General Si-mediated salinity tolerance	silicon AND (“salt stress” OR salinity) AND (“plant tolerance" OR “salinity tolerance” OR “salt tolerance”)
	Stage 2	Physiological and biochemical mechanisms	silicon AND (“salt stress” OR salinity) AND plant* AND (“ion homeostasis” OR “Na+/K+” OR “K+/Na+” OR "sodium uptake” OR “oxidative stress" OR “antioxidant defense” OR “osmotic adjustment” OR photosynthesis)

Note: Searches were conducted in the Scopus TITLE-ABS-KEY fields. Records from both searches were merged and deduplicated before screening.

Eligibility and Study Selection. Original experimental articles were eligible if they evaluated Si application under salinity and reported plant responses relevant to salinity tolerance. Studies were excluded if they lacked an experimental Si treatment, did not assess Si-mediated responses, investigated non-Si amendments or stresses other than salinity, or lacked relevant plant responses. Combined treatments were included only when Si-specific effects could be distinguished from those of other

treatments. Where available, comparisons were made between salt-stressed plants treated with Si and corresponding plants without Si.The searches identified 746 records. After removing 181 duplicates, 565 records were screened by title and abstract, with 43 excluded. Of 522 reports assessed for full-text eligibility, eight could not be retrieved and 136 of the remaining 514 articles were excluded. Thus, 378 articles were included in the final synthesis (figure 1). Each article was treated as the primary unit of inclusion, while multiple treatments, genotypes, salinity levels, and experimental conditions within an article were recorded as study characteristics rather than separate publications.

Bibliometric Analysis. Bibliometric analysis was performed using VOSviewer [22] to examine keyword co-occurrence and temporal changes in research themes. Network visualization was used to identify relationships among frequently occurring keywords, while overlay visualization showed changes in their average publication year. Node size represented keyword occurrence frequency, link strength represented co-occurrence, and overlay color indicated the average publication year.

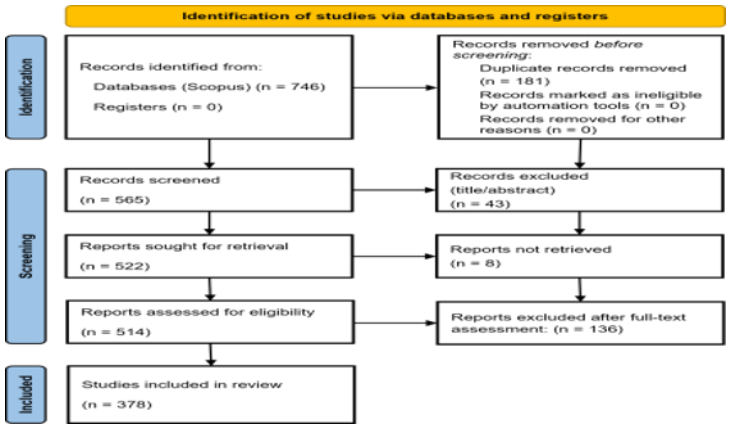


Figure 1 - PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion in the systematic review of silicon-mediated salinity tolerance in plants

RESULTS AND DISCUSSION

Bibliometric Characteristics of Research on Silicon-Mediated Salinity Tolerance. Temporal Dynamics of Publications and Citation Impact. Publication activity increased markedly after 2014-2015 and exceeded 40 records in 2025; 2026 data are partial to 25 August. The field has shifted from early work on growth and ion relations toward oxidative regulation, photosynthesis, molecular mechanisms, Si nanomaterials, and application strategies [23-26]. (figure 2).

Keyword Network and Evolution of Research Themes. The author-keyword network was centered on silicon, salinity, and salt stress, with major clusters related to ion homeostasis, oxidative and antioxidant responses, photosynthesis, water relations, osmotic adjustment, and plant growth (figure 3). The close links among ionic regulation, oxidative defense, photosynthesis, water status, and growth support the view that Si-mediated salinity tolerance involves several interacting processes rather than a single mechanism [27-31]. (figure 4).

General Characteristics of the Included Articles. Dicotyledonous species accounted for 54.6% of records and mono-

cotyledonous species for 40.6%, with 4.8% involving multiple, other, or unclassified groups (figure 5).

Controlled experiments dominated: pots 34.1%, greenhouse/growth chamber 25.3%, hydroponic/nutrient solution 22.3%, field 4.6%, and in vitro 4.0%. NaCl accounted for 74.5% of treatments, followed by saline soil 9.9% and saline irrigation 6.7%; saline-alkaline conditions accounted for only 0.5% (figure 6). NaCl experiments do not fully reproduce field soil complexity [12, 25, 32-37]. Among identified Si sources, nano-Si/nano-SiO_2 accounted for 18.3%, sodium silicate 17.5%, potassium silicate 12.6%, silicic acid 8.3%, calcium silicate 4.6%, and bulk SiO_2 1.9%; 23.9% were other or unspecified. Nutrient-solution application was most common (32.0%), followed by soil/root 26.9%, foliar 16.9%, combined 9.7%, and seed pri ming/soaking 6.5%. These differences limit direct comparison [25,38].

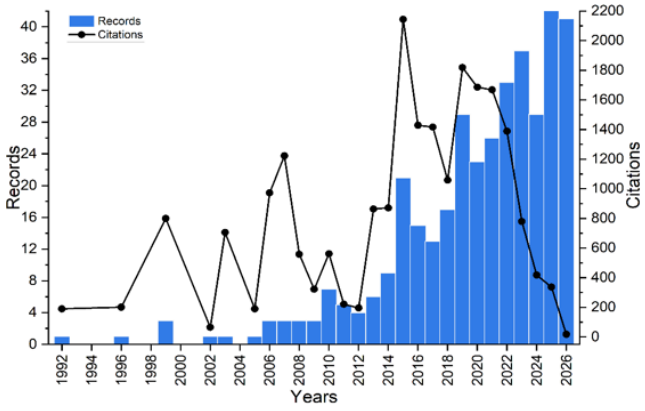


Figure 2 - Temporal dynamics of publication output and citation activity in research on Si-mediated salinity tolerance

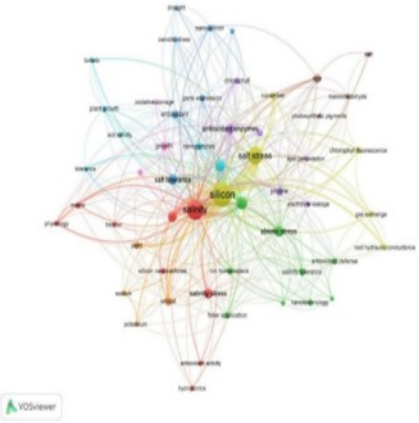


Figure 3 - Author-keyword co-occurrence network of research on Si-mediated salinity tolerance

Recent research increasingly addresses Si nanoparticles, ion homeostasis, antioxidant defense, gene expression, foliar application, and seed priming [12, 13, 31, 32]. However, species, genotype, treatment, salinity, and experimental-system differences limit direct comparison [33-36].

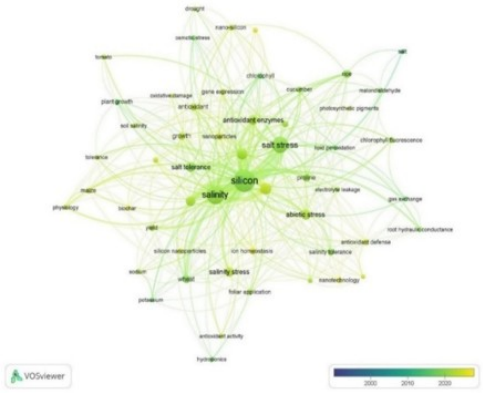


Figure 4 - Temporal overlay visualization of author keywords in research on Si-mediated salinity tolerance

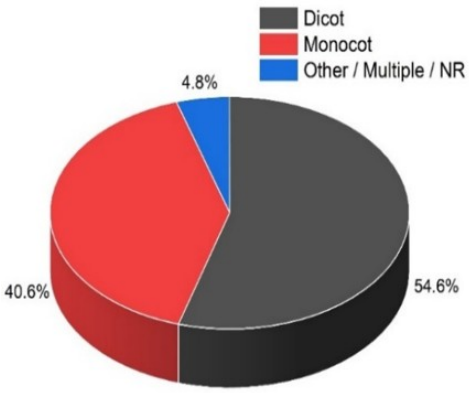


Figure 5 - Distribution of plant taxonomic groups among the articles included in the systematic review

Salinity intensity and Si dose were not pooled because units and experimental systems varied. Overall, the evidence was strongly weighted toward controlled NaCl studies, with limited field and saline-alkaline research; physiological benefits may therefore not translate directly to heterogeneous salt-affected soils [39].

Effects of Silicon on Ion Homeostasis under Salinity. Ion homeostasis was one of the most consistent responses: Si commonly reduced Na^+ uptake/transport, maintained K^+, and improved K^+/Na^+ balance, although effects varied by species, genotype, organ, salinity, and experimental conditions [23-25, 37].

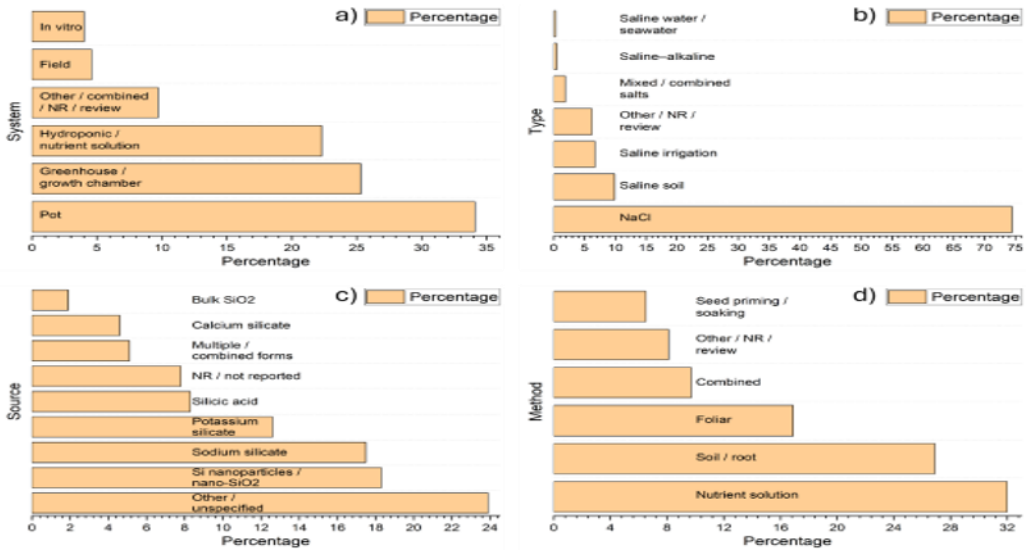


Figure 6 - General characteristics of the included articles: (a) experimental systems, (b) salinity treatments, (c) Si sources and formulations, and (d) Si application methods

Na^+ and K^+ Homeostasis and the K^+/Na^+ Ratio. Reduced Na^+ accumulation was frequently observed, although its extent depended on the plant organ and specific conditions. Such responses were reported in rice, wheat, maize, alfalfa, purslane, and liquorice [5, 40, 41]. In purslane, 1 mM sodium silicate reduced leaf Na^+ concentration and improved the K^+/Na^+ ratio under 120-240 mM NaCl, whereas a similar effect was not observed in the roots [11,42]. In rice, Si deposition in the roots can restrict apoplastic Na^+ movement and bypass flow, thereby reducing its transport to the shoots [40, 43]. Other studies have reported tissue redistribution or vacuolar compartmentation of Na^+ [44, 45], while in some cases shoot transport increased [46]. Thus, Si is better considered a regulator of Na^+ homeostasis rather than a uniform Na^+ exclusion mechanism. Silicon also frequently maintained or increased K^+ concentrations in the roots and shoots of rice, wheat, maize, alfalfa, and liquorice [5, 35, 41, 47].

Overall, Si improves K^+/Na^+ homeostasis by maintaining K^+ and/or restricting or redistributing Na^+. The K^+/Na^+ ratio should therefore be interpreted as a separate indicator from absolute K^+ concentration.

Si frequently maintained or increased K^+ in roots and shoots of rice, wheat, maize, alfalfa, and liquorice [5, 35, 41, 47].

Thus, Si improves K^+/Na^+ homeostasis through K^+ maintenance and/or Na^+ restriction or redistribution; the ratio should be interpreted separately from absolute K^+.

Variation in Ionic Responses: Ionic responses differed by genotype and species. In wheat, Si increased K^+ and reduced Na^+ in contrasting genotypes at 10 dS m^{-1}, but response magnitude differed [48]. Cucumber showed stronger overall responses than bitter gourd in some studies [10, 25, 27, 36, 45].

Treatment conditions also mattered. Nano-Si produced stronger responses than conventional Si in pea under 100-250 mM NaCl, while 50 mg L^{-1} SiO_2 nanoparticles outperformed 100 mg L^{-1} in potato [49-52].

Oxidative Stress and Antioxidant Defense. Reduced oxidative damage was among the most consistent responses: Si frequently decreased MDA, H_2O_2/ROS, and electrolyte leakage. Nano-Si increased CAT, SOD, and APX in chia, while in saline-soil wheat it reduced MDA by 17.3% and EL by 12.4% [53, 54].

Antioxidant enzymes also changed, but less consistently. In wheat, foliar Si increased SOD 50%, CAT 47%, POD 110%, and APX 8%; in Brassica juncea, APX, CAT, GR, and SOD increased while H_2O_2, MDA, and EL declined [48, 55].

Higher enzyme activity was not universally required; lower activity may reflect lower ROS production. Reduced MDA, H_2O_2/ROS, and EL therefore provide more direct evidence of protection than any single enzyme response [56].

Photosynthesis, Water Relations, and Osmotic Adjustment. Si frequently maintained chlorophyll, photosynthesis, stomatal conductance, and RWC. In cucumber and bitter gourd, net photosynthesis and stomatal conductance increased by 12.13% and 30.14%, respectively; foliar Si improved mungbean gas exchange, with the strongest response at 100 mg L^{-1} [51, 57]. Improved photosynthesis was often associated with better water status. Si increased RWC, leaf area, and biomass in safflower at 10 dS m^{-1}, while cotton studies linked improved water status to ABA-aquaporin regulation of root hydraulic conductance [58]. Osmotic responses were less consistent. Nano-Si priming in chia increased proline by 90.1% and carbohydrates by 146%, but proline should be interpreted together with water status, growth, and stress severity [53].

Growth, Biomass, and Yield Responses. Si frequently improved plant height, leaf area, root/shoot growth, and biomass. In safflower, foliar Si performed best at 2.5 mM; in pea under 100-250 mM NaCl, both Si forms improved growth, with a stronger response to nano-Si [49, 58]. Yield evidence was less consistent. Nano-Si seed priming at 200 mg L^{-1} increased chia seed yield by 149% and oil yield by 327%, while both Si forms improved pea yield [49, 53]. However, many studies were shortterm or controlled and did not follow reproductive development, so physiological benefits do not necessarily imply field yield gains.

Sources of Heterogeneity in Silicon Effectiveness. Si effectiveness depended on species/genotype, source and dose, application method, salinity, experimental system, and growth stage. In wheat, silicic acid benefited both salt-sensitive and tolerant genotypes, but magnitude differed among cultivars [48]; cucumber and bitter gourd also differed in response [57]. Both conventional and nano-Si were beneficial, but neither was universally superior. Nano-Si outperformed conventional Si in pea under equivalent concentrations, while 50 mg L^{-1} outperformed 100 mg L^{-1} in potato; application route also altered responses [48-51]. Salinity treatments (NaCl, saline soils, irrigation, mixed salts, saline–alkaline systems) are not directly equivalent. Soil and field experiments additionally vary in Si availability, soil properties, climate, and root–soil interactions. Most studies focused on germination or vegetative growth; fewer followed reproductive development. Early benefits may not persist to yield formation. Overall, no single optimal Si treatment is supported across crops and salinity conditions.

Crop-Specific Responses and Implications for Salt-Affected Agriculture. Evidence

for soybean was more limited and remained largely based on controlled experiments (table 2). Cotton was represented by only five articles but covered responses from ion homeostasis and antioxidant regulation to water relations, gene expression, biomass, yield, and fiber quality [16, 59-62]. Si increased biomass by approximately 50% in one experiment, while under 150 mM NaCl improved water status was associated with ABA-aquaporin regulation of root hydraulic conductance and water uptake. Responses were stronger under neutral salinity than under alkaline stress, where high pH was associated with reduced Si availability and uptake. Field evidence also showed increased emergence (78.3 to 96.3%) and seed-cotton yield (3830 to 4620 kg ha^{-1}; +20.6%), together with improved fiber characteristics. These results are agronomically relevant, but five articles are insufficient to identify an optimal Si formulation, dose, or application method.

Other crops, including barley, sorghum, alfalfa, sugarcane, mungbean, pea, potato, strawberry, pepper, and liquorice, generally showed the same broad response framework (table 2).

Table 2 - Crop-specific evidence for Si-mediated salinity tolerance and agronomic responses across the reviewed literature

Crop	Evidence base	Salinity / Si treatment	Main Si-mediated responses	Agronomic evidence	Main evidence limitation
1	2	3	4	5	6
Rice (Oryza sativa)	37 (9.8%)	Mainly 25-200 mM NaCl; saline soils. Silicates, silicic acid, SiNPs; root/soil, foliar, seed	Reduced Na^+ transport; improved K^+/Na^+ balance, antioxidant defense, photosynthesis and water status	Improved biomass and grain yield; field evidence available	Evidence concentrated in NaCl-based and controlled studies
Wheat (Triticum spp.)	37 (9.8%)	~35–200 mM NaCl; 4-12 dS m^{-1}. Silicates, silicic acid, SiNPs; root/soil, foliar, seed	Reduced Na^+ and oxidative damage; maintained K^+/Na^+ balance; improved photosynthesis and RWC	Improved biomass; grain/ yield responses reported; some field evidence	Strong genotype and application-dependent variation
Maize (Zea mays)	26 (6.9%)	~40-200 mM NaCl; saline soil/ irrigation. Silicates, silicic acid, SiNPs; root/ soil, foliar, seed	Na^+ redistribution/ compartmentation; improved K^+/Na^+ balance, antioxidant defense, photosynthesis and water status	Improved biomass and yield traits; field evidence available	Heterogeneous salinity and treatment systems
Tomato (Solanum lycopersicum)	25 (6.6%)	Mainly 20-250 mM NaCl; saline substrate. Silicates, SiNPs; root/substrate, foliar, seed	Improved ion homeostasis, oxidative protection, photosynthesis, RWC and hydraulic function	Mainly vegetative growth; some fruit/yield responses	Limited field validation
Cucumber (Cucumis sativus)	19 (5.0%)	Mainly 50-100 mM NaCl; up to 300 mM. Silicates, silicic acid, SiNPs; mainly root/ solution	Improved K^+/Na^+ balance and Na^+ sequestration; reduced oxidative damage; improved PSII, RWC and hydraulic function	Improved growth/ biomass; limited yield evidence	Field evidence scarce

Continuation of table 3

1	2	3	4	5	6
Soybean (Glycine max)	9 (2.4%)	Mainly 50-150 mM NaCl. Silicates, SiNPs; root, foliar, seed	Improved ion balance, antioxidant responses, photosynthesis and RWC; reduced oxidative damage	Improved biomass; limited reproductive/ yield evidence	Small, predominantly controlled evidence base
Cotton (Gossypium spp.)	5 (1.3%)	Neutral and alkaline salinity. Soluble Si, biostimulants, SiNPs; soil/root, foliar	Improved ion homeostasis and antioxidant defense; reduced ROS/MDA; enhanced ABA-aquaporin-mediated water regulation	Biomass improvement; field yield (+20.6%) and fiber-quality benefits reported	Only five articles; weaker responses under alkaline stress
Other crops†	-	NaCl, saline soils/ irrigation, mixed salts; diverse Si sources and applications	Improved ion homeostasis, oxidative protection, photosynthesis, water status and osmotic adjustment	Biomass commonly improved; yield/field evidence limited	Highly heterogeneous and individually underrepresented crops

Note: Percentages are based on 378 articles; crop categories are not mutually exclusive. †Other crops include less frequently studied species. SiNPs, silicon nanoparticles; RWC, relative water content; PSII, photosystem II; ROS, reactive oxygen species; MDA, malondialdehyde.

CONCLUSIONS

This systematic review demonstrates that silicon (Si) alleviates salinity stress through interconnected effects on ion homeostasis, oxidative protection, photosynthesis, water relations, and plant growth. Improved K^+/Na^+ balance and reduced oxidative damage were among the most consistent responses, although their magnitude varied with plant species and genotype, Si source and dose, application method, salinity conditions, growth stage, and experimental system.

Both conventional Si sources and silicon nanoparticles (SiNPs) showed beneficial effects, but the available direct comparisons do not establish the general superiority of either formulation or a universally optimal application strategy. The evidence was unevenly distributed among crops and dominated by controlled NaCl experiments, whereas field and Saline–alkaline studies remained scarce. Consequently, improvements in physiological traits and vegetative biomass cannot be assumed to translate into consistent yield benefits under field conditions.

Future research should prioritize standardized Si treatment reporting, direct comparisons of formulations and application methods, genotype-specific responses, and multi-location, multi-season field trials in well-characterized saline and saline-alkaline environments. Overall, Si represents a promising complementary approach to salinity management, but its agronomic effectiveness requires crop- and environment-specific validation.

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ТҮЙІН

А.И. Сулейменова[1,2]*, М.Н. Пошанов[1], А.С. Вырахманова[1]

МЕХАНИЗМДЕРДЕН ДАЛАЛЫҚ ҚОЛДАНУҒА ДЕЙІН: ӨСІМДІКТЕРДІҢ ТҰЗДАНУҒА ТӨЗІМДІЛІГІН КРЕМНИЙ АРҚЫЛЫ АРТТЫРУҒА ЖҮЙЕЛІ ШОЛУ

[1]Ө.О. Оспанов атындағы Қазақ топырақтану және агрохимия ғылыми-зерттеу институты, 050060, Алматы, әл-Фараби даңғылы, 75В, Қазақстан

[2]Қазақ ұлттық аграрлық зерттеу университеті, 050010, Алматы, Абай даңғылы, 8, Қазақстан, e-mail: s.altynai87@mail.ru

Зерттеу PRISMA 2020 нұсқаулығына сәйкес жүргізілді. Scopus дерекқорындағы екі өзара толықтырушы іздеу нәтижесінде 746 ғылыми жазба анықталып, іріктеу үдерісінен кейін 378 зерттеу талдауға енгізілді. Әдебиеттерді талдау кремнийдің тұзға төзімділікті арттыруы Na^+ реттелуінің жақсаруымен, K^+/Na^+ арақатынасының тұрақтануымен, тотығу зақымдануының төмендеуімен, фотосинтез бен су режимінің сақталуымен және өсім мен биомассаның қалпына келуімен байланысты екенін көрсетті. Дәстүрлі кремний көздері мен нанокремний белгілі бір жағдайларда тиімді болғанымен, олардың тікелей салыстырмалы зерттеулері аз болғандықтан, нанокремнийдің жалпы артықшылығы дәлелденбеген. Зерттеулердің басым бөлігі бақыланатын жағдайда жүргізіліп, далалық зерттеулер 4,6%-ды құрады. Болашақ зерттеулерде кремний дозаларын стандарттау, әртүрлі көздері мен қолдану тәсілдерін салыстыру, генотиптік ерекшеліктерді және көпжылдық далалық жағдайларды зерттеу қажет. Жалпы алғанда, кремний тұздануды басқару шараларында перспективалы, алайда оның тиімділігі нақты жағдайларға байланысты.

Түйінді сөздер: кремний; тұздану стресі, тұзға төзімділік, иондық гомеостаз, тотығу стрессі, кремний нанобөлшектері, дақылдардың өнімділігі, тұзданған топырақтар, жүйелі шолу.

РЕЗЮМЕ

А.И. Сулейменова[1,2]*, М.Н. Пошанов[1], А.С. Вырахманова[1]

ОТ МЕХАНИЗМОВ К ПОЛЕВОМУ ПРИМЕНЕНИЮ: СИСТЕМАТИЧЕСКИЙ ОБЗОР КРЕМНИЙ-ОПОСРЕДОВАННОГО ПОВЫШЕНИЯ СОЛЕУСТОЙЧИВОСТИ РАСТЕНИЙ

[1]Казахский научно-исследовательский институт почвоведения и агрохимии имени У.У. Успанова, 050060, Алматы, пр. аль-Фараби, 75В, Казахстан,

[2]Казахский национальный аграрный исследовательский университет, 050010, Алматы, пр., Абая, 8, Казахстан, e-mail: s.altynai87@mail.ru

Исследование проведено в соответствии с рекомендациями PRISMA 2020. В результате двух взаимодополняющих поисковых стратегий в базе данных Scopus было выявлено 746 научных записей, из которых после процедуры отбора в анализ было включено 378 исследований. Анализ литературы показал, что повышение солеустойчивости растений под воздействием кремния связано с улучшением регуляции Na^+, стабилизацией соотношения K^+/Na^+, снижением окислительного повреждения, поддержанием фотосинтеза и водного режима, а также восстановлением роста и биомассы. Традиционные источники кремния и нанокремний могут быть эффективными при определённых условиях, однако из-за ограниченного числа прямых сравнительных исследований общее преимущество нанокремния не подтверждено. Большинство исследований проведено в контролируемых условиях, тогда как доля полевых исследований составила 4,6%. В будущих исследованиях необходимо стандартизировать дозы кремния, сравнивать различные источники и способы его применения, учитывать генотипические особенности и проводить многолетние полевые исследования. В целом кремний является перспективным, но зависящим от условий компонентом управления засолением.

Ключевые слова: кремний, солевой стресс, солеустойчивость, ионный гомеостаз, окислительный стресс, наночастицы кремния, продуктивность сельскохозяйственных культур, засолённые почвы, систематический обзор.

INFORMATION ABOUT AUTHORS

1. Suleimenova Altynay Izteleuovna - Head of the Department of Soil Fertility and Soil Biology, Master's degree, https://orcid.org/0009-0006-2130-7572,
e-mail: s.altynai87@mail.ru

2. Poshanov Maksat Nurbayevich - Head of the Department of Saline Soil Reclamation, PhD, https://orcid.org/0000-0002-8657-953X,
e-mail: maksat_90.okkz@mail.ru

3. Vyrakhmanova Assem Sabitkanovna - Scientific Secretary, PhD, https://orcid.org/0000-0002-6295-653X, e-mail: asem-v80@mail.ru