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RELACIÓN ENTRE SILICIO Y RESPUESTA DEL PEPINO SOMETIDO A DÉFICIT HÍDRICO

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Presenta:

GEORGY FAROUTINE

Bajo la supervisión de:

DIRECTOR: RAMÓN ARTEAGA RAMÍREZ, D.Sc.

CODIRECTOR: JOEL PINEDA PINEDA, D.Sc.

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Tesis realizada por **Georgy Faroutine** bajo la supervisión del Comité Asesor indicado, aprobada por el mismo y aceptada como requisito parcial para obtener el grado de:

DOCTOR EN INGENIERÍA

DIRECTOR: ______________________

Dr. Ramón Arteaga Ramírez

CODIRECTOR: ______________________

Dr. Joel Pineda Pineda

ASESOR: ______________________

Dr. Mario Alberto Vázquez Peña

LECTOR EXTERNO: ______________________

Dr. Manuel Sandoval Villa

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INFORMACIÓN BIOGRAFICA

Información personal

Nombre:	Georgy Faroutine
Fecha de nacimiento:	29 de Julio
Lugar de nacimiento:	Thomassique, Centre, Haití
Educación:	Ingeniero Agrónomo
	Maestría en Agronomía

RESUMEN GENERAL[1]

RELACIÓN ENTRE SILICIO Y RESPUESTA DEL PEPINO SOMETIDO A DÉFICIT HÍDRICO

El silicio (Si) es benéfico para las plantas debido a su capacidad para mitigar diferentes situaciones desfavorables, entre las cuales está el estrés por déficit hídrico. Se realizaron 3 ensayos en condiciones de invernadero en la Universidad Autónoma Chapingo para evaluar los efectos de la aplicación del Si para atenuar los impactos del estrés hídrico en pepino. Se realizaron en un periodo concomitante 2 ensayos, usando un diseño completamente al azar de dos factores, donde se evaluaron los efectos de 9 tratamientos constituidos por 3 dosis de Si (0, 50, 100 mg L^{-1} SiO_2) y 3 niveles de humedad del sustrato (55-65 %, 75-85 % y 90-100 % de la capacidad de contenedor CC) en el crecimiento, producción de frutos y absorción de nutrimentos del híbrido de pepino 'Braga F1'. Los efectos individuales del Si aumentaron la producción de frutos del hibrido ‘Braga F1’ sin afectar el contenido de sólidos solubles totales. La interacción entre las dosis de Si y el contenido de humedad en el sustrato aumentó la producción de biomasa seca aérea, biomasa seca de raíz y área foliar del hibrido ‘Braga F1’ en condiciones de déficit hídrico. La dosis 50 mg L^{-1} de SiO_2 aumentó la biomasa seca aérea en 36.5 % y 38.8 %, el área foliar en 17.3 % y 29.3 %, y la biomasa seca de raíz en 46.5 % y 48.9 %, respectivamente, en relación con 100 mg L^{-1} de SiO_2 y el tratamiento sin silicio. Las concentraciones de N, P, K y Mg en frutos, P y K en hojas y N y K en tallos del pepino hibrido ‘Braga F1’ también mejoraron. En un segundo ensayo con un diseño completamente al azar, se evaluaron 15 tratamientos formados por 5 dosis de Si (0, 50, 100 mg L^{-1} de SiO_2, 2 g L^{-1} y 3 g L^{-1} de Wollastonita) y 3 niveles de humedad (50-60 %, 75-85 % y 90-100 % de CC) en el sustrato, sobre parámetros biométricos, fisiológicos y atributos nutricionales del híbrido de pepino 'Vitaly'. El rendimiento del pepino hibrido ‘Vitaly’ aumentó 24.9 % con la aplicación de 3 g L^{-1} de wollastonita en comparación con las plantas no tratadas, con humedad de 75-85 % a CC en el sustrato. Con el nivel de humedad entre 90-100 % de CC y 50 mg L^{-1} de SiO_2 se incrementó 9.3 % la biomasa seca aérea, y en el nivel de humedad entre 50-60 % de CC y 100 mg L^{-1} de SiO_2 la biomasa seca aérea aumentó 11.8 % más que las plantas no tratadas con Si. Igualmente, el Si mejoró los contenidos de clorofila

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[1] Tesis de Doctorado en Ingeniería, Posgrado en Ingeniería Agrícola y Uso Integral del Agua, Universidad Autónoma Chapingo.
Autor: Georgy Faroutine
Director: Dr. Ramón Arteaga Ramírez

a, b y total de las hojas. También, la interacción del Si con la humedad del sustrato incrementó las concentraciones de N, P, K, Ca, Mg y Si en los diferentes órganos de la planta. El rendimiento y atributos fisiológicos y nutricionales, como masa seca aérea y de raíces, área foliar, contenido de clorofila a, b y total, contenido de N, P, K, Ca, Mg y Si en tejidos foliares, del pepino mejoran con la aplicación del Si bajo condiciones deficitarias de agua.

Palabras clave: agua, *Cucumis sativus*, déficit hídrico, estrés hídrico, fertilización silícica, planta estresada, sequía.

GENERAL ABSTRACT[2]

RELATIONSHIP BETWEEN SILICON AND RESPONSE OF CUCUMBER SUBJECTED TO WATER DEFICIT

Silicon (Si) is beneficial for plants due to its ability to mitigate different unfavorable situations, including stress due to a water deficit. Three trials were carried out under greenhouse conditions at the Chapingo Autonomous University to evaluate the effects of Si application to attenuate water stress impacts on cucumbers. Two trials were carried out in a concomitant period, using a completely randomized two-factor design, where the effects of 9 treatments consisting of 3 doses of Si (0, 50, 100 mg L^{-1} SiO_2) and 3 substrate humidity levels were evaluated (55-65 %, 75-85 % and 90-100 % of the container capacity (CC)) on the growth, fruit production and nutrient absorption of the 'Braga F1' cucumber hybrid. The individual effects of Si increased fruit production of the 'Braga F1' hybrid without affecting the total soluble solids content. The interaction between the doses of Si and the moisture content in the substrate increased the production of aerial dry biomass, root dry biomass and leaf area of the 'Braga F1' hybrid under water deficit conditions. 50 mg L^{-1} SiO_2 increased aerial dry biomass by 36.5 % and 38.8 %, leaf area by 17.3 % and 29.3 %, and root dry biomass by 46.5 % and 48.9 % in relation, respectively, to 100 mg L^{-1} SiO_2 and the treatment without silicon. Also, the concentrations of N, P, K and Mg in fruits, P and K in leaves and N and K in stems of the hybrid cucumber 'Braga F1' also improved. Subsequently, another trial was carried out where, in a completely randomized design, 15 treatments consisting of 5 Si doses (0, 50, 100 mg L^{-1} SiO_2, 2 g L^{-1} and 3 g L^{-1} Wollastonite) and 3 substrate humidity levels (50-60 %, 75-85 % and 90-100 % CC) were evaluated on biometric, physiological parameters and nutritional attributes of the 'Vitaly' cucumber hybrid. The yield of the hybrid cucumber 'Vitaly' increased by 24.9 % with the application of 3 g L^{-1} of wollastonite compared to untreated plants, under 75-85 % CC in the substrate. With a humidity level between 90-100 % CC, 50 mg L^{-1} SiO_2 increased aerial dry biomass by 9.3 %. In the humidity level between 50-60 % CC, 100 mg L^{-1} SiO_2 enhanced the aerial dry biomass by 11.8 % than the plants not treated with Si. Likewise, Si improves the chlorophyll a, b and total contents of the leaves. Also, the interaction of Si with the substrate humidity increases the concentrations of N, P, K, Ca, Mg and Si in the different

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[2] Doctoral thesis, Postgraduate in Agricultural Engineering and Integrated Use of Water, Universidad Autónoma Chapingo.
Author: Georgy Faroutine
Advisor: Dr. Ramón Arteaga Ramírez

components of the plant. Cucumber performance and physiological and nutritional attributes, such as aerial and root dry mass, leaf area, chlorophyll a, b and total content, N, P, K, Ca, Mg and Si content in leaf tissues, improve with Si application even under water deficit conditions.

Keywords: water, *Cucumis sativus*, water deficit, water stress, silicic fertilization, stressed plant, drought.

1. INTRODUCCIÓN GENERAL

Prácticas insostenibles, como la sobreexplotación de los recursos naturales, afectan negativamente la disponibilidad del agua que está cada vez más presionada debido a la tendencia creciente de la población mundial y mayores necesidades de recursos para proporcionar suficientes alimentos a la sociedad. El aumento de la demanda de agua para el riego y las consecuencias nefastas del cambio climático provocan escasez hídrica en muchas regiones geográficas del mundo. Según el Instituto Mexicano para la competitividad (IMCO), los fenómenos de sequias en México fueron recurrentes durante la última década ya que han ido aumentando en frecuencia, intensidad y duración. Un total de 8491 fenómenos de sequías fueron reportados en México en 2021, incluyendo 71 % sequías severas, causando pérdidas de cultivos, 26 % sequías extremas, causando mayores pérdidas de cultivos y riesgo de incendios forestales, y 3 % de los casos fueron sequías excepcionales, donde el agua en los embalses, arroyos y pozos se agotaron por completo (IMCO, 2023). A medida que las necesidades de recursos aumentan, es fundamental encontrar métodos sostenibles de producción que permiten enfrentar a las limitaciones impuestas por la escasez hídrica y reducir sus impactos en los sistemas de producción agrícola.

Cerca del 28 % de la corteza terrestre está compuesta de Si (Liang et al., 2015). Después del oxígeno, es el segundo elemento más abundante en el suelo (Epstein, 2009; Liang et al., 2015). Se han utilizado fertilizantes de silicato a base de escoria en Europa desde la época medieval (Liang et al., 2015), pero no ha recibido atención de los fisiólogos de plantas debido a que históricamente no se ha considerado esencial para las plantas superiores, excepto los miembros de la familia *Equisetaceae* (Epstein, 1994), y está predominantemente presente en el suelo como aluminosilicatos cristalinos, que no están directamente disponibles para las plantas (Richmond y Sussman, 2003). Se han logrado en las últimas décadas progresos significativos en la comprensión de la absorción del Si por las plantas y cómo mejora la resistencia de estas a los estreses bióticos. Sin embargo, aún se necesitan más estudios sobre sus beneficios contra los estreses abióticos, por el ejemplo el estrés hídrico en las plantas ya que es un factor importante que limita el crecimiento y rendimiento de los cultivos, siendo una amenaza para la sostenibilidad agrícola.

En la solución del suelo, el ácido monosilícico (H_4SiO_4) es la forma de Si disponible para las plantas y se encuentra en concentraciones entre 0.1 y 0.6 mM (Gunnarsson y Arnórsson, 2000), aproximadamente el doble de las concentraciones de P (Epstein, 1994). Las plantas absorben y transportan al Si por procesos tanto activo como pasivo (Liang et al., 2006). Principalmente en los sitios de máxima transpiración, el Si absorbido por las plantas se polimeriza y forma fitolitos amorfos (SiO_2–nH_2O) (Ma y Yamaji, 2006). Las concentraciones de Si en las plantas, en base seca, varía entre 0.1 a 10 %, lo que cambia de una especie a otra (Liang et al., 2015).

A pesar de las divergencias sobre la esencialidad del Si desde un punto de vista metabólico y fisiológico en las plantas, varios estudios han demostrados sus beneficios para la agricultura y lo han presentado como alternativa para el manejo de estreses bióticos y abióticos en diferentes cultivos. Se ha reportado que el Si es benéfico en estimular el crecimiento y desarrollo vegetal (Menegale *et al*., 2015; Kaushik y Saini, 2019). Además de tener efectos metabólicos y estructurales (Thakral et al., 2021), demuestra efectos mecánicos y fisiológicos positivos, promueve la tolerancia a la sequía, mejora la absorción de K y Ca (Guntzer et al., 2012; Savvas y Ntatsi, 2015). Su deposición en la pared celular de la planta ayuda a reducir el estrés hídrico disminuyendo la transpiración y mejorando las características de interceptación de luz (Kaya et al., 2006). Además de estimular el sistema de defensa antioxidante (Savvas y Ntatsi, 2015) ayuda en la regulación y acumulación de carbohidratos y azúcares solubles (Peris-Felipo et al., 2020). La tolerancia al estrés hídrico y mejora en las características de absorción y del uso del agua debido al Si fueron observada en varios cultivos, por ejemplo: tomate (*Solanum lycopersicum*) (Shi et al., 2016), canola (*Brassica napus*) (Habibi, 2014), arroz (*Oryza sativa*) (Ming et al., 2012), sorgo (*Sorghum bicolor* L.) (Hattori et al., 2009; Ahmed et al., 2011a, b; Liu et al., 2014; Liu et al., 2015), maíz (*Zea mays*) (Kaya et al., 2006), trigo (*Triticum aestivum*) (Gong et al., 2005) soya (*Glycine max*) (Shen et al., 2010), mango (*Mangifera indica*) (Helaly et al., 2017), girasol (*Helianthus annuus*) (Gunes et al., 2008) y pepino (*Cucumis sativus*) (Ma, 2004).

Las plantas de las familias cucurbitáceas, como el pepino, son consideradas plantas de acumulación media de Si (Ma et al., 2001). De acuerdo con el Servicio de Información Agroalimentaria y Pesquera (SIAP, 2019), entre los mayores productores de Pepino a nivel mundial, México se encuentra en la sexta posición, siendo que 72.3 % de la producción tiene destino internacional, principalmente los Estados Unidos. En 2018, el pepino fue parte de los productos agroalimentario más exportados de México, siendo el decimoséptimo producto, por un valor de 538 millones de dólares aproximadamente (SIAP, 2019). Los eventos recurrentes de sequía afectaran negativamente a los cultivos, entre los cuales, al Pepino, ya que es una planta altamente demandante en agua. Así, se propuso evaluar el uso del silicio como una solución alternativa para contrarrestar los impactos perjudiciales del déficit hídrico en el cultivo de Pepino (*Cucumis sativus* L.) en condiciones de invernadero.

1.1 Objetivo General

Evaluar el efecto del silicio como una solución alternativa para contrarrestar los impactos perjudiciales del déficit hídrico en el cultivo de Pepino (*Cucumis sativus* L.) en condiciones de invernadero.

1.2 Objetivos específicos

- Estudiar los efectos de diferentes dosis de Si y niveles de humedad en el sustrato sobre el crecimiento, productividad y absorción de nutrimentos del pepino en condiciones de invernadero.

- Investigar si la fertilización silícica, usando dos fuentes diferentes de Si, reduce los impactos negativos del déficit hídrico en el rendimiento, parámetros biométricos, fisiológicos y nutricionales de plantas de pepino.

1.3 Hipótesis

El uso de silicio como fuente de fertilizante puede reducir los impactos del déficit hídrico sobre los parámetros de productividad, rendimiento, biométricos, fisiológicos y nutricionales de pepino al disminuir la lámina de agua aplicada.

1.4 Breve presentación de la estructura de la tesis

La tesis está organizada en 5 apartados, donde el primer apartado incluye una introducción general que abarca la justificación, antecedentes, objetivo general y específicos, e hipótesis. En el segundo apartado se presenta una revisión de literatura con informaciones breves sobre el cultivo de pepino y su importancia, cómo el déficit hídrico puede afectar a las plantas, principalmente al cultivo de pepino, y también los impactos del silicio contra estrés hídrico en pepino y otras plantas.

En el tercer apartado se presenta los resultados de la primera parte experimental de la investigación, donde se estudiaron los efectos de diferentes dosis de Si y niveles de humedad en el sustrato sobre el crecimiento, productividad y absorción de nutrimentos del pepino en condiciones de invernadero. Se presentaron los resultados en formato de un artículo publicado en el volumen 83, serie 03, junio de 2023 de "*Chilean Journal of Agricultural Research*".

En el cuarto apartado se presenta los resultados de la segunda parte de la investigación enfocada en los impactos de la fertilización silícica, usando dos fuentes de Si, para reducir los efectos negativos del déficit hídrico en el rendimiento, parámetros biométricos, fisiológicos y nutricionales de plantas de pepino. Se presentaron los resultados en formato de un artículo en el "*Journal of Agricultural Science*", volumen 15, número 06, mayo de 2023.

Finalmente, el quinto apartado es la conclusión general del trabajo que abarca las conclusiones de las dos partes experimentales de la investigación y una conclusión general.

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2. REVISIÓN DE LITERATURA

2.1 Cultivo de pepino y su importancia

El pepino (*Cucumis sativus* L.) es una de las 960 especies de la familia Cucurbitaceae (Schaefer et al., 2009). Desde la India, el pepino se extendió hacia el Oeste (Valcárcel et al., 2018). Luego de que los Romanos lo diseminaron por Europa, los Españoles lo introdujeron en América y se popularizó no solo como alimento sino también por sus propiedades medicinales (Valcárcel et al., 2018). De origen asiático (Schaefer et al., 2009), detrás del subcontinente indiano (Sebastian et al., 2010), China ha sido identificada como un centro secundario de diversidad para el pepino (Valcárcel et al., 2018). Actualmente, el cultivo se encuentra distribuido alrededor del mundo.

El pepino es un cultivo de clima cálido (Kapuriya et al., 2017), de raíces poco profundas y de poca tolerancia al estrés hídrico (Fan et al., 2014). Es muy sensible a condiciones desfavorables, y el menor estrés puede perjudicar su crecimiento y su productividad (Papadopoulos, 1994). Un suministro adecuado de agua es imprescindible para garantizar buena producción del cultivo (Edgar et al., 2009). Se cultiva principalmente bajo condiciones tropicales y subtropicales (Kapuriya et al., 2017). Prefiere altas temperaturas, alta humedad (65 % – 85 %) e iluminación intensa, así como un suministro constante de agua y nutrimentos (Papadopoulos, 1994). Temperaturas entre 23.9 y 29.4 °C son ideales para los pepinos (Westerfield, 2013). Se presenta mayor producción de frutos cuando la temperatura se encuentra entre 20 y 22 °C durante el día y entre 19 y 20 °C durante la noche (Haifa, 2014). Puede ser cultivado en campo abierto, bajo invernadero en suelo, en macetas o bolsas de polietileno usando algún tipo de sustrato, como, por ejemplo, corteza de pino, turba, fibra de coco, perlita, vermiculita, grava, arena o lana de roca (Zamora, 2017).

El pepino es de mucha importancia en México, con una superficie sembrada en 2018 de 19597 ha, una producción de 1072048 toneladas y un rendimiento de 54.7 toneladas ha^{-1} (SIAP, 2019). El país se encuentra entre los mayores productores de pepino a nivel mundial (SIAP, 2019). Aproximadamente el 72.3 % de los pepinos producidos se exportan, principalmente a Estados Unidos (SIAP, 2019). La vocación de producción del cultivo tanto para el mercado interno como externo lo permite posicionar entre las hortalizas más importantes producidas y exportadas por el país (SIAP, 2019).

Nutricionalmente, el pepino contiene 95 % de agua y electrolitos importantes lo que lo convierte en una excelente fuente de hidratación (Dilonardo y Juber, 2022). También, ayuda a controlar la ganancia y pérdida de peso debido a su baja densidad energética (Zelman, 2021). Igualmente, es muy rico en nutrimentos como las vitaminas B, C, K y minerales como Cu, P, K y Mg (Zelman, 2021). Además, los pepinos tienen antioxidantes, que incluyen flavonoides, lignanos y triterpenos (Zelman, 2021). Su actividad antioxidante disminuye o detiene la progresión de enfermedades cardiovasculares (Olsen y Ware, 2019). De la misma manera, su buena cantidad de fibra ayuda a controlar el colesterol y prevenir problemas cardiovasculares (Olsen y Ware, 2019). Por su alto contenido de cucurbitacinas, ayuda a prevenir el cáncer al impedir la reproducción de las células cancerosas (Olsen y Ware, 2019). Las semillas de pepino contienen una mezcla de nutrimentos que pueden mejorar los niveles de colesterol, lo que afecta positivamente la salud del corazón (Zelman, 2021). Igualmente, el pepino tiene propiedades anti-inflamatorias y antidiabéticas (Dilonardo y Juber, 2022).

2.2 Impactos del déficit hídrico en el cultivo de pepino

Ante condiciones desfavorables, por ejemplo, el déficit hídrico, las plantas desarrollan ciertos mecanismos de tolerancia y de adaptación. En este contexto se producen cambios anatómicos, morfológicos, metabólicos, bioquímicos y fisiológicos como consecuencia del estrés hídrico (Bouchelha y Djebbar, 2020). Entre los cuales se pueden mencionar la reducción del crecimiento, cierre estomáticas (Reddy et al., 2004), inhibición de la fotosíntesis (Mooussa, 2011), aclimatación, reducción del área foliar, mayor crecimiento radical (Potters et al., 2007), entre otros. También, los procesos celulares y moleculares de las plantas pueden ser interrumpidos (Potters et al., 2007). La actividad de las acuaporinas y el gradiente osmótico juegan un papel importante en la regulación de la absorción de agua por parte de las raíces, principalmente en condiciones de estrés hídrico (Liu et al., 2014). El aumento de la absorción de agua por la raíz mediante la regulación de la superficie y la anatomía de la raíz es importante para la tolerancia de la planta al estrés (Javot y Maurel, 2002). El grado de sensibilidad de las plantas al déficit hídrico varía según su estado de desarrollo, la severidad y la duración del estrés (Bouchelha y Djebbar, 2020). Enseguida se presentan algunas respuestas morfológicas, fisiológicas y bioquímicas de las plantas bajo condiciones de estrés hídrico.

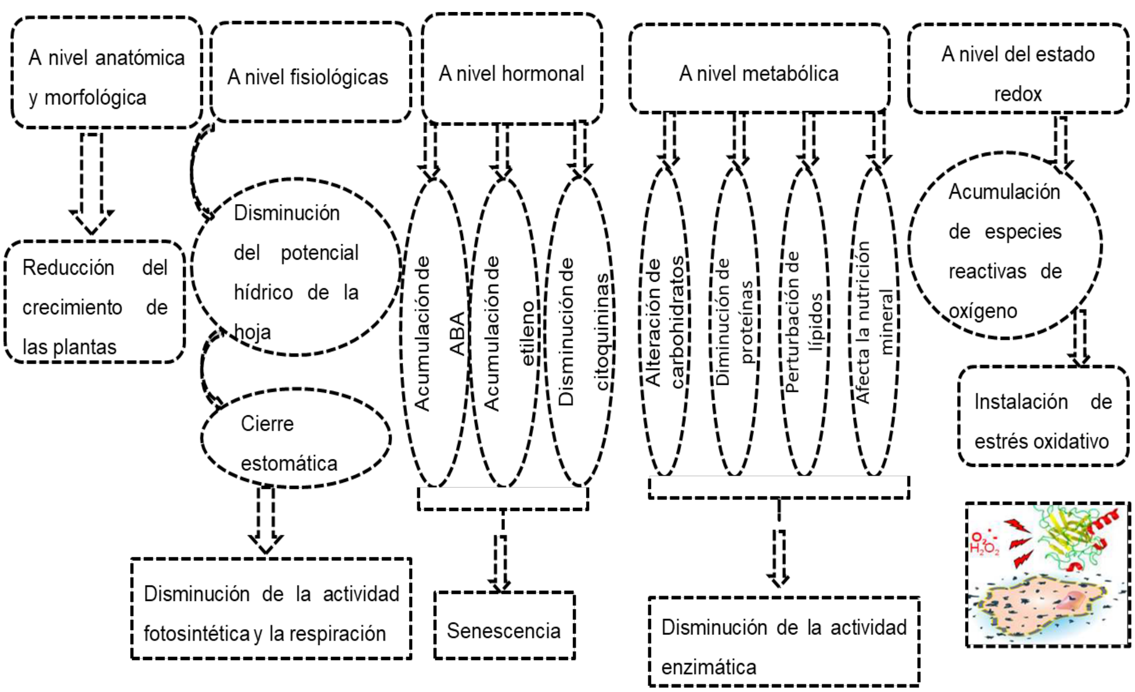

Figura 2. Respuestas morfológicas, fisiológicas y bioquímicas de plantas bajo condiciones de estrés hídrico. Adaptado de Travaux pratiques : En relation avec la physiologie des stress (p. 3), por L. Bouchelha y R. Djebbar, 2020. Université des Sciences et de la Technologie Houari Boumediene (USTHB).

La demanda hídrica del pepino es superior a la de los cereales (Li y Wang, 2000; Mao et., 2003), pero su umbral de índice de estrés hídrico es inferior a lo de otros cultivos (Şimşek et al., 2005). De acuerdo con Janoudi et al. (1993), el pepino puede recuperarse rápidamente de un leve déficit hídrico sin impactos perjudiciales a largo plazo. No obstante, las plantas deben adaptarse a los eventos de déficit hídrico, principalmente cuando ocurren lentamente, los cuales perjudican al cultivo (Potters et al, 2007; Shao et al., 2008).

El nivel de riego aplicado puede afectar múltiples parámetros del cultivo de pepino, incluso su rendimiento. En un estudio de Mao et al. (2003), el volumen de riego aplicado afectó el rendimiento de frutos de pepino, resultando en una menor producción de frutos en el tratamiento con menor nivel de riego. La eficiencia en el uso del agua aumentó desde el establecimiento del cultivo hasta la maduración del primer fruto, pero desde la fructificación hasta el final del ciclo del cultivo se disminuyó con el incremento del riego (Mao et al., 2003). Igualmente, Şimşek et al. (2005) reportaron mejores producciones de frutos de pepino con la aplicación del 100 % de la lámina de riego requerida y disminución notable del rendimiento al reducir la lámina aplicada. La aplicación del 100 % del requerimiento hídrico en pepino generó mayores rendimientos, aunque disminuyó la eficiencia del uso de agua de las plantas (Tüzel et al., 2009).

En invernadero, Rahil y Qanadillo (2015) analizaron el rendimiento, parámetros de crecimiento y la eficiencia del uso del agua de plantas de pepino bajo diferentes regímenes de riego y encontraron mayor rendimiento, plantas más altas, mayor producción de masa seca y mayor eficiencia en el uso del agua empleando un 70 % ETc en comparación con el riego tradicional de los agricultores, riego basado en tensiómetro y riego completo (100 % ETc).

Wang y Zhang (2004) estudiaron los efectos de la humedad del suelo sobre la tasa fotosintética neta, la resistencia estomática y la estructura de los estomas y cloroplastos en pepino y encontraron reducción de la tasa fotosintética neta y aumento de la densidad y la resistencia estomática con la disminución de la humedad del suelo. También, la disminución de la humedad del suelo redujo la cantidad de cloroplastos por célula y el número de amiloides por cloroplasto (Wang y Zhang, 2004).

2.3 Impactos del silicio contra estrés hídrico en pepino y otras plantas

Dentro de la planta, el Si se distribuye a través de los tejidos y forma una capa continúa entre la cutícula y la epidermis (Bernal, 2015; Pathak et al., 2019). Esta capa está formada por dos subcapas, un gel de silicona y un complejo silico-celulósico (Bernal, 2015; Pathak et al., 2019). La reducción de la pérdida de agua en las plantas debido a la disminución de la transpiración generada por el Si contribuye a su turno en reducir el estrés por déficit hídrico en las mismas (Datnoff, 2017; Pathak et al., 2019). La deposición de Si en las paredes celulares de las hojas, tallos y raíces de las plantas aumenta su resistencia y rigidez, lo que reduce los efectos del estrés hídrico (Crusciol et al., 2009). Entre los estudios del uso de Si para reducir los impactos del estrés por déficit hídrico en especies como trigo (Bukhari et al., 2015), arroz (Mauad et al., 2016), maíz (Amin et al., 2018), tomate (Zhang et al., 2018), soya (Teodoro et al., 2015), y entre otros, han demostrado efectos positivos del elemento sobre parámetros relacionados con tolerancias a estrés por sequía. Han reportado aumento de la tasa fotosintética, estado hídrico en hojas, ajuste osmótico, actividades de las enzimas antioxidantes, mayor contenido de proteínas solubles, reducción de la transpiración, fuga de electrolitos, contenido de malondialdehído y peróxido de hidrógeno, entre otros.

Jafari et al. (2015) reportaron que el Si o su combinación con el ácido salicílico aumentaron el área foliar, masa fresca y seca del tallo, contenido relativo de agua, compuestos fenólicos totales, antocianinas, flavonoides, contenido de K en el tallo y actividad de fenilalanina amonio-liasa en plantas de pepino bajo estrés osmótico. Górecki y Danielski-Busch (2009) han encontrado que los silicatos de Ca y de NH_4 de liberación lenta aumentaron el rendimiento y el contenido de Si en las hojas y frutos de pepino. La fertilización con Si, vía raíz, de plantas de pepino generó frutos con mayor masa seca, contenido de sólidos solubles totales, concentración de Si, pero menos contenido de Zn y Cu en comparación con plantas no fertilizadas (Jarosz, 2013). La aplicación de Si, vía foliar y suelo, en pepino cultivado en invernadero aumentó el rendimiento de frutos comercializables, su firmeza, contenido de Si, P y K en hojas y frutos y con efectos variables cuanto al contenido de sólidos solubles totales y ácido ascórbico (Abd-Alkarim et al., 2017).

Después de la evaluación de diferentes dosis de K_2SiO_3 (0, 120 y 240 mg SiO_2 kg^{-1} de suelos) y diferentes grados de estrés hídrico (80-90% CC; 55-70% CC y 35-50% CC) sobre parámetros de producción, fisiológicas y bioquímicas del cultivo de pepino, Ma et al. (2004) reportaron, tanto en presencia como en ausencia de estrés hídrico, efecto positivo del silicio al mejorar la resistencia de las plantas a la sequía actuando sobre el metabolismo de estas. Bajo estrés hídrico, los autores reportaron aumento de la tasa fotosintética neta de las plantas debido a la aplicación del Si (Ma et al., 2004). Mientras en ausencia de estrés, la aplicación del Si mejoró ligeramente la tasa fotosintética neta y disminuyó significativamente la transpiración y la conductancia estomática (Ma et al., 2004). También, bajo estrés hídrico, el Si aumentó la producción de biomasa y el contenido de agua en las hojas, redujo la descomposición de la clorofila en las plantas (Ma et al., 2004).

El estrés hídrico aumentó el contenido de malondialdehído (MDA) en las hojas de pepino y además dañó la membrana plasmática volviéndola más permeable (Ma et al., 2004). En plantas de pepino sometidas a estrés hídrico y fertilizadas con Si, Ma et al. (2004) observaron menor permeabilidad de la membrana plasmática con relación a plantas deficientes en silicio, lo que permitió concluir que el Si disminuye la permeabilidad de la membrana plasmática en pepino afectado por estrés hídrico.

Según Ma et al. (2004) el estrés hídrico en pepino favorece la actividad de la enzima peroxidasa (POD) y la acumulación de radicales libres como superóxido dismutasa (SOD) y disminuye la actividad de la catalasa (CAT). Bajo diferentes grados de estrés hídrico, se encontraron que el Si disminuyó la actividad de la peroxidasa (POD) y de la acumulación del superóxido dismutasa (SOD) y aumentó la actividad de la catalasa (CAT) en el cultivo de pepino (Ma et al., 2004).

El estrés por sequía simulado en semillas de Pepino (cv. New Spring 4) usando glicol de polietileno (PEG) al 10 % fue perjudicial al inhibir la germinación, redujo el vigor de las plántulas, disminuyó la longitud y el peso fresco de las plántulas (Jin et al., 2020). El PEG también aumentó el contenido de malondialdehído (MDA), de prolina libre y las actividades de las enzimas antioxidantes (Jin et al., 2020). El Si contrarrestó el efecto del estrés osmótico generado por el PEG en las plántulas de pepino al mejorar la germinación de las semillas, aumentó el vigor, la longitud y el peso fresco de las plántulas (Jin et al., 2020). También, el Si aumentó las actividades de las enzimas antioxidantes y redujo los contenidos de MDA y prolina en los tallos de las plántulas (Jin et al., 2020). Bajo estrés hídrico, el silicio mitiga el daño por peroxidación lipídica en semillas de pepino y aceleró la conversión de carbohidratos al aumentar las actividades de las enzimas antioxidantes, la actividad de la hidrolasa del almidón, redujo la acumulación de MDA y reguló al alza los niveles de expresión de los genes AMY y BMY (Jin et al., 2020).

El estrés hídrico inhibe el crecimiento de brotes y raíces y disminuye las concentraciones de clorofila y carotenoides en plantas de tomate (Zhang et al., 2018). Por el contrario, el Si mejoró el crecimiento de las plantas y aumentó las concentraciones de clorofila y carotenoides (Zhang et al., 2018). También, el Si alivió el estrés hídrico modulando genes relacionados con la fotosíntesis y regulando el proceso fotoquímico, estimulando la fotosíntesis (Zhang et al., 2018). Shi et al. (2014) encontraron que la aplicación exógena de Si (0.5 mM) incrementó la germinación de semillas, redujo el estrés oxidativo en etapa de plántulas y mejoró la defensa antioxidante en cuatro cultivares de tomate en germinación y en plántula bajo estrés hídrico simulado por glicol de polietileno. En otro estudio, Shi et al. (2016) concluyeron que la aplicación del K_2SiO_3 (2.5 mM de Si) aumentó la tolerancia del tomate al estrés hídrico inducido por glicol de polietileno, al mejorar la conductancia hidráulica de la raíz y la absorción de agua. El Si promueve la concentración de azúcar soluble, proteína soluble y mejora la absorción y el estado hídrico en la raíz del tomate (Cao et al., 2017). Asimismo, ayudó a la tolerancia a la sequía mediante la inducción de enzimas, la desintoxicación de las especies reactivas del oxígeno y el mantenimiento de la estabilidad de la membrana de las raíces del tomate (Cao et al., 2017).

Farouk y Omar (2020) mostraron impactos significativos en los parámetros de crecimiento y los atributos bioquímicos (pigmento fotosintético, porcentaje de iones, solutos antioxidantes y osmolitos orgánicos) de la albahaca dulce con aplicaciones de metasilicato de sodio y Zeolita, tanto en condiciones suficiencias de riego y de sequía. Bajo condiciones de sequía, se observaron aumento notable en el crecimiento de las plantas, porcentaje y rendimiento del aceite esencial con efectos positivos sobre su composición, siendo más efectivo a dosis de 250 mg L^{-1} (Farouk & Omar, 2020).

El pretratamiento con Si (1.5 mM K_2SiO_3) redujo los efectos adversos de la sequía y mejoró la calidad del rendimiento de dos cultivares de arroz sometidos a déficit hídrico al aumentar los niveles de amilosa, compuestos fenólicos, flavonoides y aceites, y al mismo tiempo redujo la absorción de agua en los granos durante la cocción (Emmam et al., 2014). Igualmente, el Si aumentó los contenidos de lignina, celulosa y pectina de la paja del arroz y también incrementó los niveles totales de carbohidratos, proteínas, fitatos, e iones de Ca y P en el grano (Emmam et al., 2014). Mauad et al. (2016) observaron reducción del contenido de prolina en el tejido, tanto en fases vegetativas como reproductivas, e incremento en la actividad de peroxidasa en la fase reproductiva, en dos cultivares de arroz expuestas a estrés hídrico y fertilizadas con Si (350 kg ha^{-1}).

En plantas de maíz sometidas a diferentes regímenes de riego y fertilizadas con Si, Sirisuntornlak et al. (2019) observaron mayor longitud de mazorca, peso de 100 granos y rendimiento de grano que el tratamiento testigo, siendo más efectivas las dosis 1 mM (cebado de semillas) y 300 kg ha^{-1} (incorporación al suelo). En otro estudio, plantas de maíz afectadas por déficit hídrico (60% CC) y fertilizadas con Si (100 mg kg-1), demostraron mejora en los atributos de crecimiento y rendimiento, así como aumento en la tasa fotosintética y reducción de la transpiración (Amin et al., 2018). El Si es eficaz en aumentar la altura, rendimiento, índice de área foliar, tasa fotosintética, estado hídrico de la hoja, ajuste osmótico, y menor transpiración en plantas de maíz en condiciones de sequía (Amin et al., 2016).

En dos variedades de maíz cultivadas con diferentes regímenes hídricos, tratamientos silícicos incrementaron significativamente los atributos de crecimiento y pigmentos fotosintéticos, redujeron los contenidos de malondialdehído y peróxido de hidrógeno, así como mejoraron las actividades de superóxido dismutasa, peroxidasa y catalasa, mitigando los efectos perjudiciales del estrés hídrico (Parveen et al., 2019). Igualmente, Sayed y Gadallah (2014) afirmaron que el Si mejoró los atributos de crecimiento, mitigó los efectos adversos de la sequía y el anegamiento, y aumentó la tolerancia de plantas de maíz al estrés hídrico. También, Zargar y Agnihotri (2013) encontraron efectos positivos del Si sobre el número de granos por mazorca, contenido relativo de agua, densidad estomática y temperatura del dosel en 15 genotipos de maíz cultivados bajo estrés hídrico.

Maghsoudi et al. (2015) observaron repuestas positivas de varias variedades de trigo con aplicación foliar de Si, demostrando mejoras en los parámetros de crecimiento, concentración de clorofila, y reducción de los efectos desfavorables del déficit hídrico sobre la fluorescencia de la clorofila. Estudio de Bukhari et al. (2015) sobre dos genotipos de trigo con condiciones contrastantes de tolerancia a la sequía y bajo condiciones opuestas de riego demostraron mejora notable en la tolerancia de las plantas a déficit hídrico con mayor absorción de Si y actividad de ascorbato peroxidasa, peroxidasa y catalasa. La aplicación foliar del Si en la etapa de macollamiento favoreció la turgencia de las plantas y una mejor acumulación de nutrimentos en ambos genotipos de trigo (Bukhari et al., 2015). También, Tale Ahmad y Haddad (2011) observaron mayores impactos del Si en la etapa de macollamiento de plantas de trigo bajo estrés hídrico. Igualmente, bajo estrés hídrico, Ali et al. (2013) observaron mayor crecimiento y rendimiento de plantas de trigo fertilizadas con Si debido al aumento del estado hídrico, aceleración del proceso fotosintético y mayores contenidos de clorofila en las hojas de las plantas. Igualmente, bajo diferentes niveles de riego (50%, 75% y

100% CC) y dosis de Si (150 y 200 mg kg^{-1} K_2SiO_3) aplicada vía suelo, Morsy y Mohamed (2013) reportaron mayor crecimiento y mejora del estado nutricional de plantas de trigo cv. Sids-12, sobretodo en condición de déficit hídrico. Ahmed et al. (2016) encontraron que el cebado de semillas de trigo con distintas concentraciones (0.5 %, 1.0 %, 1.5 %) y fuentes de Si (ácido silícico, silicato de sodio y gel de sílice), fue efectivo en potencializar la resistencia de las plantas al estrés hídrico, mejorando los componentes de rendimiento del cultivo.

Teodoro et al. (2015) encontraron que el déficit hídrico es responsable entre 60-70 % de la variabilidad en el cultivo de soja y que la aplicación de Si, vía foliar, generó una mayor acumulación de masa seca aérea (tallo, ramas, hojas, pecíolos, vainas y semillas) en soja cultivada en condiciones de déficit hídrico. Los efectos del Si en los componentes de producción y productividad del cultivo de soya mostraron resultados heterogéneos (Teodoro et al., 2015). Ruppenthal et al. (2016) encontraron que la aplicación de Si en suelos con contenido medio de Si no incrementó la producción de materia seca de las plantas afectadas por estrés hídrico, y en condiciones óptimas de riego la producción de materia seca se redujo. Bajo estrés hídrico, Ruppenthal et al. (2016) observaron reducción del contenido de N en las plantas y concluyeron que el Si no estimuló suficientemente los mecanismos de defensa de las plantas de soja para mitigar los efectos del estrés por sequía en el contenido relativo de agua de las hojas y la producción de materia seca.

Eneji et al. (2008) observaron respuestas positivas al K_2SiO_3, $CaSiO_3$ y en un menor grado al gel de sílice, en cuatro especies de gramíneas. Se observaron una mayor respuesta al Si en condiciones de déficit hídrico, mejorando el crecimiento de las plantas (Eneji et al., 2008). También, la absorción de K fue altamente correlacionada con el Si (Eneji et al., 2008). Independientemente del nivel de humedad del suelo la correlación entre la absorción de Si, N y P fue positiva (Eneji et al., 2008).

En plantas de sorgo, Ahmed et al. (2011) reportaron que la absorción y acumulación de Si aumentó el potencial hídrico de las hojas, el crecimiento, la transpiración, la tasa fotosintética neta y disminuyó la relación tallo/raíz de las plantas. Ahmed et al. (2011) concluyeron que la fertilización del sorgo con Si tuvo un efecto sinérgico tanto bajo sequía como en condiciones óptima de riego.

En plantas de Castaña, Zhang et al. (2013) reportaron aumentó del crecimiento de la planta y de los rasgos fotosintéticos, como el contenido de clorofila y la relación clorofila a/b, mayor intercambio de gases y tasa de evolución de oxígeno, debido a la aplicación foliar del Si.

Helaly et al. (2017) encontraron que la fertilización de cultivares de mango con K_2SiO_3 aumentó el crecimiento vegetativo, así como el rendimiento y sus atributos, tanto en condiciones normales como de estrés hídrico. Fisiológicamente, Helaly et al. (2017) indicaron que el K_2SiO_3 podría estar involucrado en la actividad metabólica de las plantas de mango expuestas al estrés por sequía, sugiriendo así su aplicación para aumentar la tolerancia de los cultivares a condiciones de estrés hídrico.

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CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

3. EFFECT OF CALCIUM SILICATE AND MOISTURE CONTENT OF THE SUBSTRATE ON THE GROWTH AND PRODUCTIVITY PARAMETERS OF CUCUMBER

Georgy Faroutine[1], Ramón Arteaga-Ramírez[2*], Joel Pineda-Pineda[3], and Mario Alberto Vázquez-Peña[2]

[1]Universidad Autónoma Chapingo, Instituto de Ingeniería Agrícola y Uso Integral del Agua, 56230, Texcoco, Estado de México, México.
[2]Universidad Autónoma Chapingo, Departamento de Irrigación, 56230, Texcoco, Estado de México, México.
[3]Universidad Autónoma Chapingo, Departamento de Suelos, 56230, Texcoco, Estado de México, México.
[*]Corresponding author (rarteagar@taurus.chapingo.mx).

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ABSTRACT

Water deficits can be mitigated by silicon in plants. Two greenhouse experiments were conducted at the Universidad Autónoma Chapingo to determine whether Si affects the growth, nutrient absorption, and fruit production of a ‘Braga F1’ hybrid cucumber under water deficit. A completely randomized design was used with two factors, substrate moisture (55-65%, 75-85%, and 90%-100% of container capacity) and Si dose (0, 50, 100 mg L^{-1} SiO_2) applied to the substrate, resulting in nine treatments with four replicates. After transplanting, moisture content was determined on days 30 to 60 (Experiment I) and 60 to 90 (Experiment II). Accumulated fruit production (AFP), total soluble solids (TSS), aerial (ADB) and radical dry biomass (RDB), leaf area (LA), and concentrations of N, P, K, and Mg in fruits, leaves, and stems were determined. ANOVA and Tukey tests ($P \leq 0.05$) were performed. For AFP and TSS, ADB and LA (experiment II), the interaction between Si concentration and moisture in the substrate was nonsignificant in either experiment. Individual Si effects increased fruit production without affecting TSS content. ADB, RDB, and LA production increased under water stress because of the interaction between Si concentration and moisture content. Application of 50 mg L^{-1} SiO_2 resulted in 36.5% more ADB, 17.3% more LA, and 46.5% more RDB than 100 mg L^{-1} SiO_2 and 38.8%, 29.6% and 48.9% more than

silicon alone. The concentration of N, P, K, and Mg in fruits, P and K in leaves, and N and K in cucumber stems also improved.

Key words: *Cucumis sativus*, drought, hydric deficit, silica fertilization, water.

INTRODUCTION

The cucumber (*Cucumis sativus* L.) is, after the watermelon, the second most cultivated cucurbit in the world (Pal et al., 2020). The crop has shallow roots and is not tolerant to water stress (Fan et al., 2014), so proper irrigation management is essential for high yields and quality of the fruit (Pal et al., 2020). Cucumber cultivation does better with drip irrigation in greenhouses (Pal et al., 2020). Water stress is a common situation the crop faces during its growth and development stages. Appropriate water management is essential to the crop due to its high susceptibility to unfavorable conditions, where stress situations like water shortage can harm its physiological and biochemical processes (Yuan et al., 2016).

Consequently, its photosynthetic capacity is affected, affecting its growth and eventually reducing its productive capacity (Sharma et al., 2019). As well, membrane integrity, osmotic balance, and plant water states are all negatively affected by water shortage (Jafari et al., 2015). Also, plant cellular and molecular processes can disrupt (Potters et al., 2017). Therefore, it is critical to include alternative sustainable approaches to manage plants' water stress in agronomic practices.

Despite the benefits of Si usage in agriculture and its abundance in the terrestrial layer, its essentiality remains not yet accepted or confirmed. Although it is an abundant element, its poor solubility implies that only a tiny amount of it is available for uptake by plants as H_4SiO_4 (Toresano et al., 2012). The extraction and accumulation of Si in plant tissues differ by species (Savvas and Ntatsi, 2015) but also by dosage and soil conditions (Ouellette et al., 2017). Cucurbitaceous plants do not consider Si accumulators, although they show selective assimilation of the element, which can differ between species or even at the cultivar level (Toresano et al., 2012). Although Si absorption is low in some plants, its presence can substantially benefit under stress conditions (Toresano et al., 2012). The cucumber is an intermediate Si accumulator plant (Liang et al., 2015; Savvas and Ntatsi, 2015; Dorais and Thériault, 2018). Its foliar Si concentration ranges from 1.8% to 2.9% (Liang et al., 2015). Si positively influences photosynthetic activity, biomass accumulation in fruits, tolerance to salinity, and environmental stressors such as drought and low and high temperatures (Liang et al., 2015; Savvas and Ntatsi, 2015).

Furthermore, Si protects plants from nutritional imbalance and mineral toxicity (Liang et al., 2015; Savvas and Ntatsi, 2015). The yield of cucumber fertilized with Si can vary according to the element's form and application rate. According to Abd-Alkarim et al. (2017), via the soil or leaves Si enhanced the yield and quality of greenhouse-grown cucumber fruit. Abd-Alkarim et al. (2017) observed that applying Si to the soil increased the yield of marketable cucumber fruit. Si nanoparticles in cucumber under water shortage and salt stress increased crop production, especially in plants watered up to 85% of their ETc, plant height, chlorophyll content, and fruit output increased by 20%, 51%, and 156%, respectively, compared to untreated plants (Alsaeedi et al., 2019). Alsaeedi et al. (2019) found that high Si content in cucumber leaves aids in regulating water loss through transpiration and mitigates the effects of water shortage and salt stress. Research on cucumber's response to Si under water stress remains scarce. Based on the above, in this work, the effects of different Si dosages and moisture levels in the substrate on the growth, productivity, and nutritional absorption of cucumber under greenhouse conditions were studied.

MATERIALS AND METHODS

Condition and location of the experiment

The experiment was conducted from May to August 2021 in a greenhouse of the Soils Department at the Universidad Autónoma Chapingo (UACh) (19º29' N, 98º53' W).

Two assays were carried out in black perforated polyethylene bags, with 10 L substrate made up of a mixture of peat moss and tezontle in a 3:1 v:v ratio, with the respective chemical compositions described in tables 1 and 2. The water holding parameters of the substrate were determined according to the De Boodt et al. (1974) approaches. Table 3 presents some physical parameters, and Figure 1 the moisture retention. Figure 2 presents the average temperature, relative humidity, and luminosity recorded inside the greenhouse during the experiment.

Table 15. Chemical properties of Peat moss (ProMix®) according to the provider (Premier Tech Horticulture). SME: Saturated medium extract; EC: electrical conductivity.

Parameter (S.M.E.)	Peat moss (ProMix®)
pH	5.2 – 6.2
EC (dS m^{-1})	1.0 – 1.8
$N\text{-}NO_3$ (mg L^{-1})	70 – 130
$P\text{-}PO_4$ (mg L^{-1})	5 – 40
K (mg L^{-1})	50 – 130
Ca (mg L^{-1})	100 – 180
Mg (mg L^{-1})	20 – 45
$S\text{-}SO_4$ (mg L^{-1})	30 – 100
Fe (mg L^{-1})	0.8 – 2.2
Zn (mg L^{-1})	0.1 – 1.2
Cu (mg L^{-1})	< 0.3
Mn (mg L^{-1})	0.3 – 1.0
B (mg L^{-1})	< 0.6

Table 16. Chemical properties of tezontle according to Trejo-Téllez et al. (2013). EC: Electrical conductivity.

Parameter	Tezontle
pH	7.35
EC (dS m^{-1})	0.15
N (%)	0.61
P (mg kg^{-1})	0.31
K (mg kg^{-1})	2.74
Ca (mol m^{-3})	22.0
Mg (mol m^{-3})	10.09
Na (mg L^{-1})	Not detected

Table 17. Physical and water retention characteristics of the substrate mixture.

Apparent density (D_{ap}), g cm^{-3}	0.43
Water holding capacity (WHC), %	72.97
Total pore space (TPS), %	89.89
Aeration capacity (AC), %	16.91
Readily available water (RAW), %	21.54
Buffering capacity water (BCW), %	11.25
Hardly available water (HAW), %	40.18
Total available water (TAW), %	32.80

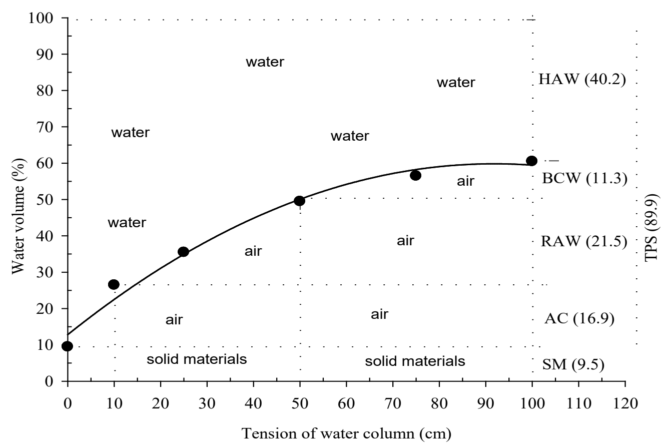

Figure 18. Water release curve of the substrate (peat moss and tezontle in a 3:1 v:v ratio) from 0 to 10 kPa (based on De Boodt et al., 1974). HAW: Hardly available water; BCW: buffering capacity water; RAW: readily available water; AC: air capacity; SM: solid materials; TPS: total pore space.

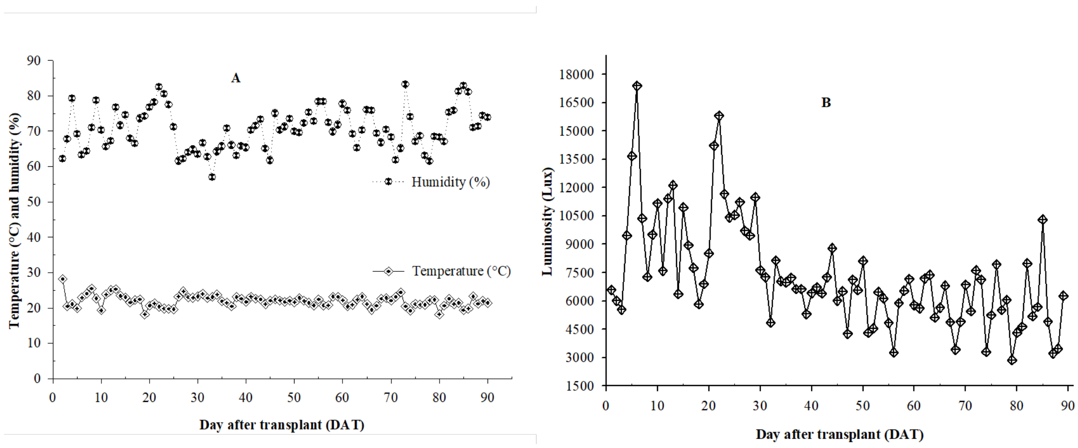

Figure 19. Daily average temperature, relative humidity, and luminosity inside the greenhouse throughout the experiment.

Experimental design, treatments, nutrition, and crop management

Cucumber (*Cucumis sativus* L.) seedlings were grown on seedbeds using 'Braga F1' hybrid seeds and transplanted into the bags of each treatment 22 d later. A completely random design (CRD) was formed from a factorial arrangement with two factors, each with three levels: Moisture in the substrate (55-65%; 75-85% and 90%-100% of container capacity (% CC) combined with Si dosages (0, 50, 100 mg L^{-1} SiO_2), which generated nine treatments replicated four times each, in total 36 experimental units (3 × 3 × 4 = 36) where each bag with a plant represented an experimental unit.

The plants were evenly watered before and after the timeframes indicated for applying the moisture levels. Controlled watering regimes were performed according to each treatment when applying the moisture levels. The varying moisture levels were applied in the first assay from 30 to 60 d after transplantation (DAT) (Figure 3A) and in the second assay from 60 to 90 DAT (Figure 3B). The moisture levels have been measured using HOBOnode Wireless Soil Moisture Sensors (W-SMC, Onset Computer Corporation, Bourne, Massachusetts, USA) inserted into the substrate at a depth of 10 cm in the root environment. Regarding the Si dosages (0, 50, 100 mg L^{-1} SiO_2), 300 mL solution were applied in each bag every 8 d, from the 8th day until the 75th day after transplanting. As Si input, a liquid source of $CaSiO_4$ (Barrier, Cosmocel, Nuevo León, Mexico), with a w/w concentration of 10% Ca, 24% SiO_2, and 66% conditioners and diluents, was employed.

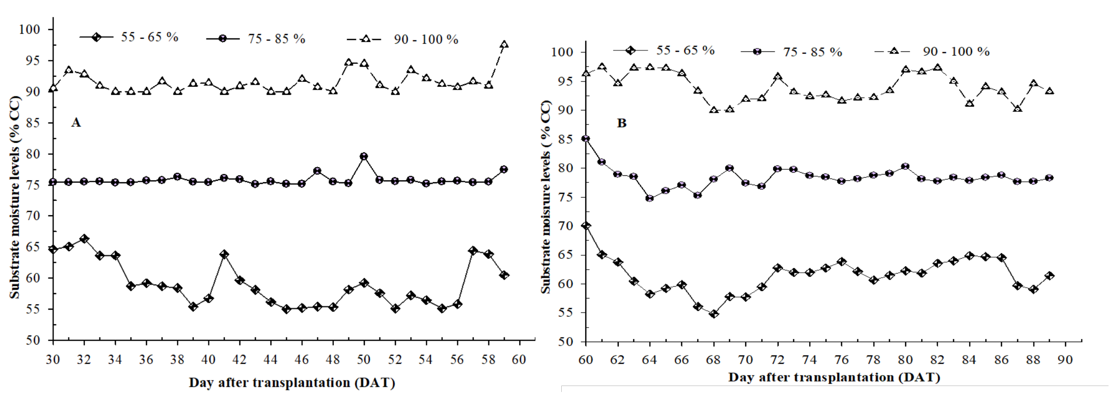

Figure 20. Distribution of the substrate's average moisture levels, trial I (A) and trial II (B).

Plant nutrition has been managed through a fertigation system, preparing the solution according to the recommendations in Table 2. The pH and electrical conductivity (EC) of the nutrient solution used to irrigate the plants, including the control treatment, were maintained between 5.5 to 6.5 and 1 to 2 mS cm^{-1}, respectively. Traps were installed to control the prevalence of insect vectors and the occurrence of diseases that may harm the plant's development. Cultural practices such as tutoring, training, and maintenance pruning were carried out, managing the plants to one stem until the cycle's conclusion (90 d after transplantation).

Table 18. Chemical composition of the nutrient solution used to irrigate the plants.

Nutrient (mg L^{-1})	Seedling to 1st fruit	1st fruit- final
N	133	240
P	62	62
K	150	150
Ca	130	260
Mg	50	50
S	70	70
Fe	2.50	2.50
Zn	0.09	0.09
Cu	0.10	0.10
Mn	0.62	0.62
B	0.44	0.44
Mo	0.03	0.03

Variables analyzed

Cumulative fruit production. Progressively as the fruits matured, they were harvested and weighted. At the end of the trial, the accumulated fruit production (AFP) per plant was calculated.

Total soluble solids of the fruit. A digital sucrose refractometer (HI96801, Hanna Instruments, Woonsocket, Rhode Island, USA), with a sugar content range of 0% to 85% °Brix, was used to determine the total soluble solids (TSS) percentage. One fruit from the middle part of each plant was selected, cut in half, and squeezed to extract drops of juice where the TSS percentage was determined.

Aerial and root dry biomass. At the end of the experiment, the plant's aerial part was cut at the base of the stem to assess the plant's production of aerial dry biomass (ADB). Plant samples were placed in paper bags and dried in a forced ventilation oven at 70 °C until constant weight. After drying, to determine the biomass on a dry basis, dried plant samples were weighted. The roots of each plant were collected and dried under the same conditions described above, and later the root-dried biomass (RDB) was determined.

Leaf area. After the crop cycle, all leaves from each plant were collected, and the total leaf area (cm^2) per plant was determined using a leaf area integrator (LI-3100C, LI-COR Biosciences, Lincoln, Nebraska, USA).

Analysis of nutrients in fruits and leaf tissue. At the end of the assay, N, P, K, and Mg concentrations in the plant's fruits, leaves, and stems were determined in the Plant Nutrition Laboratory of the Soil Department of the UACh. Nitrogen in foliar tissues by the Kjeldahl method and P by the molybdovanadate colorimetric method, both cases as described by Alcántar and Sandoval (1999). Foliar K determination uses a flame photometer (410, Sherwood Scientific, Cambridge, UK), and Mg uses an atomic absorption spectrophotometer (GBC 932 plus, GBC Scientific Equipment, Braeside, Victoria, Australia).

Statistical data analysis

After verifying the fulfillment of the statistical assumptions of variances normality and residuals homogeneity of the data, they were processed through the statistical program Sisvar 5.6 (Ferreira, 2011) using procedures associated with the ANOVA and followed by Tukey tests ($P \leq 0.05$) for means comparison.

RESULTS AND DISCUSSION

Cumulative fruit production and total soluble solids of the fruit

In both trials, the interaction of the Si doses with the substrate moisture levels was nonsignificant in the accumulated fruit production (AFP) and the content of total soluble solids (TSS) of the fruits (Table 5). In the first trial, silica fertilization did not affect the AFP. However, it influenced fruit yield in the second trial since the applications of 50 and 100 mg L^{-1} SiO_2 increased significantly by 7.89% and 15.56% AFP per plant compared to plants without Si applications. In the first trial, the reduction in water availability to the plant harmed the yield of cucumber fruits, with a significant decrease of 15.24% and 22.23%, respectively, in the lowest moisture level compared to the intermediate and high humidity levels. Similarly, fruit production decreased by 7.79% and 14.05% in the second trial at the lowest moisture level, respectively, compared to the substrate's intermediate and highest moisture levels.

Table 19. Silicon dosage and moisture levels on accumulated fruit production (AFP) and total soluble solids (TSS) of 'Braga F1' hybrid cucumber. Different letters in the same column show significant differences between treatments by Tukey's test ($P \leq 0.05$). % CC: Container capacity

Treatments	Trial I		Trial II	
	AFP	TSS	AFP	TSS
	g plant^{-1}	%	g plant^{-1}	%
SiO_2, mg L^{-1}				
0	1675.67 ± 78.0a	3.08 ± 0.11a	1524.33 ± 40.0c	2.93 ± 0.08a
50	1796.25 ± 49.5a	3.18 ± 0.18a	1654.92 ± 48.1b	3.18 ± 0.12a
100	1739.83 ± 67.1a	3.45 ± 0.13a	1805.33 ± 50.8a	3.28 ± 0.13a
Humidity, % CC				
55-65	1503.83 ± 45.6c	2.80 ± 0.09b	1534.67 ± 24.4c	3.02 ± 0.1a
75-85	1774.25 ± 152.6b	3.46 ± 0.11a	1664.33 ± 151.6b	3.23 ± 0.1a
90-100	1933.67 ± 76.3a	3.45 ± 0.12a	1785.58 ± 74.9a	3.14 ± 0.1a

Regarding TSS content in the fruits, the Si dosage's separate effects did not affect this variable since all doses of Si generated significantly similar TSS content in both trials. Nor did the moisture levels of the substrate affect the content of TSS in the fruits in the second trial. In the first trial, the two higher moisture levels favored a higher concentration of TSS in the fruits and a 19% decrease in TSS content in the treatment fruits with the lowest moisture level in the substrate.

In the second trial, a favorable response of cucumber to Si was observed regarding AFP, which coincides with the positive effects of Si reported by Wang et al. (2007) and Dorais and Thériault (2018) on the growth and productivity parameters of cucumber crops. Applying a dose of 8 g L^{-1} wollastonite in cucumber plants, Dorais and Thériault (2018) reported a 6.5% increase in plant growth compared to the control treatment. Cucumber fertilization with variable doses of Si increased crop yield between 5.1% and 10.2% (Wang et al., 2007), while in an experiment carried out by Voogt and Sonneveld (2001) in a hydroponic system, cucumber produced its highest yield response in fruit yield to the application of 0.5 mM Si in the plant's root environment. Also, in cucumber plants fertilized with low doses of $(NH_4)_2SiO_3$ or K_2SiO_3, Górecki and Danielski-Busch (2009) reported increased crop yield. Information reported by Jarosz (2013) and Abd-Alkarim et al. (2017) on the yield of cucumber fertilized with diatomite as a Si source corroborated this experiment's results, mainly from the second trial, on the positive influence of Si on increasing yield in cucumber fruit. The accumulated fruit yield per plant in this experiment is much lower than the data reported by Zamora (2017) and Alejo-Santiago et al. (2021). Probably because of the varieties used, the cycle harvest duration since that cucumber is a staggering production crop, as well as the management technologies and environmental conditions under which the plants were developed. Also, the yield reduction observed, in both trials, with the low humidity level coincides with that reported by Grasic et al. (2021). They observed decreased growth and yield of cucumber due to insufficient water supply.

The decrease in soluble sugar concentration observed with the lowest moisture level in the substrate could be due to the plant's water deficit, which has not favored the concentration of soluble organic solutes in the fruits. However, this behavior did not observe in the second trial. Cucumber is not known for having high contents of soluble sugars in their fruits (Moreno et al., 2013). This variable can change between genotypes or fruit quality categories (Chacón-Padilla and Monge-Pérez, 2017). In this experiment, the TSS values range from 2.80% to 3.46% in assay I and 2.93% to 3.18% in assay II. These values are comparable to those obtained by López-Elías et al. (2015) at 3.3%, higher than those obtained by Alejo-Santiago et al. (2021) at 2.48% and 2.72%, and Galindo-Pardo et al. (2014) with 2.5%; and lower than those obtained by Barraza-Álvarez (2015) with values of 3.60% and 4.07% and Chacón-Padilla and Monge-Pérez (2017) with a variation between 3.38% to 3.67% of soluble solids in fruits of six cucumber genotypes grown under greenhouse conditions.

Aerial and root dry biomass

In the first trial, the interaction between the Si doses and the moisture levels in the substrate was significant in the production of aerial dry biomass (ADB) of the cucumber crop (Figure 4A). Under limited water supply, compared to treatments without silicon and 100 mg L^{-1} SiO_2, ADB increased mainly with 50 mg L^{-1} SiO_2, 38.8% and 36.5% higher, respectively. The ADB generated at the intermediate moisture level reduced considerably for the 100 mg L^{-1} SiO_2 compared to the treatments without Si and 50 mg L^{-1} SiO_2. Under the higher humidity level, the absence of Si has not interfered with the plant's ADB production. In the absence of Si, the two highest humidity levels produced similar amounts of ADB but higher than the treatment with the highest water deficit. This tendency is in line with Grasic et al. (2021), who also indicated a reduction in the aerial biomass produced in cucumber cultivation owing to decreased soil water availability. When there is no water limitation and 100 mg L^{-1} SiO_2 is applied, these plants presented higher ADB than those treated with a similar Si dosage and intermediate or low humidity. Water deficit significantly reduces the growth and production of cucumber (Grasic et al., 2021). In this experiment, the dose of 50 mg L^{-1} SiO_2 counteracted the negative effect of water deficit by favoring higher production of ADB in plants with lower humidity levels compared to plants grown with higher humidity levels. The second assay showed that the effect of silicon's interaction with the substrate's humidity levels did not affect the production of ADB of the crop. The presence or absence of Si and variations in moisture levels in the substrate did not affect the production of ADB of the plant.

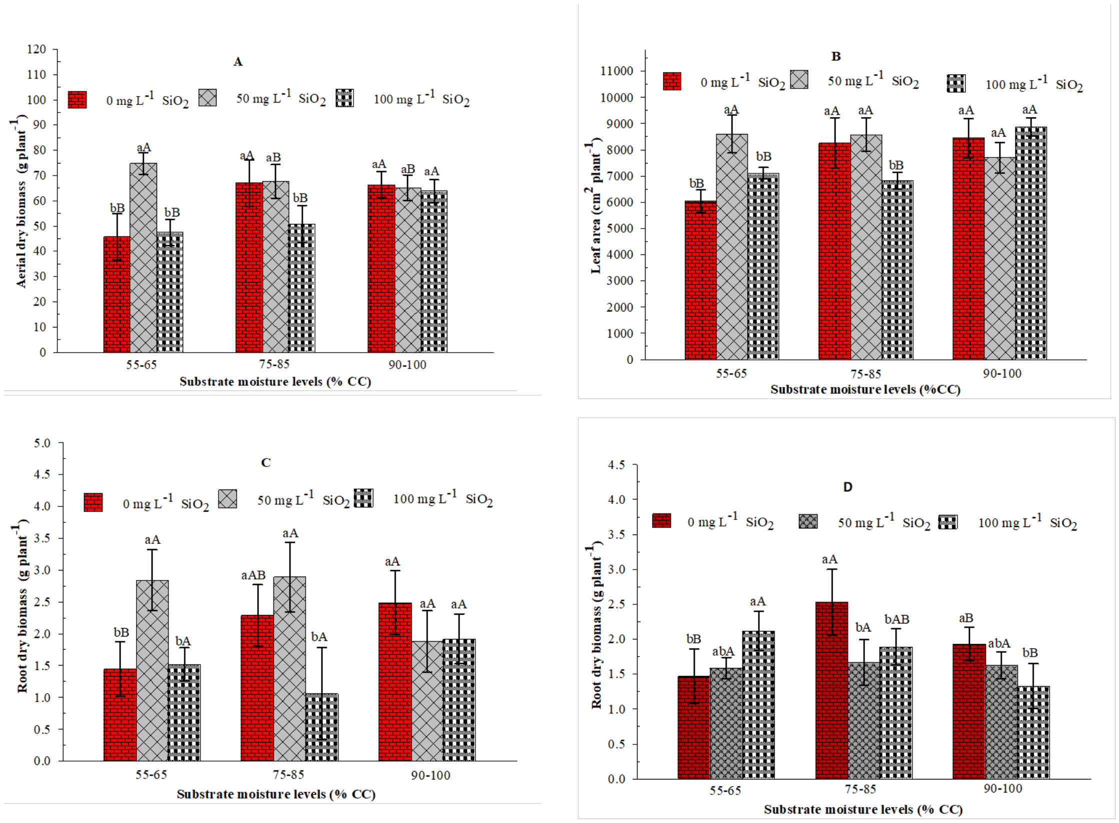

Figure 21. Effect of the interaction between Si dosages and the substrate's moisture levels on the aerial dry biomass production (A), leaf area (B) and root dry biomass (C and D) of 'Braga F1' cucumber hybrid (A, B and C: trial I; D: trial II). Different lowercase letters in the same moisture level indicate differences between SiO2 doses and different uppercase letters for the same SiO2 dose indicate differences between moisture levels, by Tukey's test ($P \leq 0.05$).

The interaction between Si and the moisture levels in the substrate significantly affected the production of dry root biomass (DRB) in both trials (Figures 4C and 4D). Under the highest humidity level, whether Si was applied, there was no effect on the DRB production in the first trial. However, in the second trial, DRB was reduced with 100 mg L^{-1} SiO_2 compared to the treatment without Si. In both tests, the most significant effect of Si occurred at the lowest moisture level in the substrate. The application of Si stimulated the production of radical biomass. At the highest stress, 50 mg L^{-1} SiO_2 increased the root biomass by 48.94% and 46.48% compared to the treatments without Si and 100 mg L^{-1} SiO_2, respectively. In the absence of Si, the higher moisture level generated more DRB than the most stressed moisture level in the first experiment.

In contrast, the intermediate moisture level surpassed the others in the second trial. In both trials, when 50 mg L^{-1} SiO_2 was applied, the production of DRB was similar between the different moisture levels in the substrate. In the first trial, applying 100 mg L^{-1} SiO_2, all moisture levels presented similar root biomass values. However, in the second trial, although the two lowest moisture levels were significantly equal, the lowest moisture produced root biomass 37.3% higher than the highest moisture level.

The effect of Si on plant biomass production can be affected by the silicon source used. A study by Grasic et al. (2021) revealed that the addition of K_2SiO_3 negatively affected the biomass production of the leaf. Ma et al. (2004) observed progressive loss of the green color and severe wilting of the plant leaf at midday in cucumber plants subjected to water stress and Si deficiency. Under the same stress level, the symptoms, as mentioned earlier, were less evident in plants treated with Si. In addition, cucumber plants subjected to water stress and treated with Si accumulated more biomass than plants deficient in Si. Ma et al. (2004) made the same observation as this experiment, mainly in the treatment with higher water stress levels. Likewise, a study by Meng et al. (2021) supports the positive effect of Si on stimulating biomass accumulation in cucumber plants. These findings demonstrate the role of Si in reducing the impacts of drought stress in cucumber plants. According to Ma et al. (2004), under water stress, increased photosynthesis and improved water retention capacity in plants were the main factors responsible for the positive effects of Si on biomass accumulation by plants.

Leaf area

In the first assay (Figure 4B), the leaf area of the crop was significantly affected by the interaction of the Si dosages with the substrate moisture levels. However, in the second assay, this interaction was nonsignificant (Table 6). Under the highest level of humidity, the leaf area of the crop did not show differences in the doses of Si in the first trial. For the intermediate moisture level, the leaf area decreased by 20.5% and 17.5%, respectively, applying 100 mg L^{-1} SiO_2 compared to 50 mg L^{-1} SiO_2 and the treatment without Si. The 50 mg L^{-1} SiO_2 generated greater leaf area under the lowest humidity level, 29.65% and 17.3% more than the treatments without Si and 100 mg L^{-1} SiO_2, respectively. Without Si, the two highest humidity levels presented similar leaf area values. However, they exceeded the lowest humidity level. With the application of 100 mg L^{-1} SiO_2, the highest humidity level produced a leaf area value 23.1% higher than the intermediate humidity and 19.9% higher than the lowest humidity. Under limited water conditions, 50 mg L^{-1} SiO_2 produced similar leaf area values to plants cultivated without water limitations. This result suggests that the Si impact offsets the detrimental effect of water shortage in plants with water restrictions.

Table 20. Silicon dosage and moisture levels on aerial dry biomass (ADB) production and leaf area (AF) of 'Braga F1' hybrid cucumber. Different letters in the same column show significant differences between treatments by Tukey's test ($P \leq 0.05$). % CC: Container capacity.

Treatments	Trial II	
	ADB	LA
	g $plant^{-1}$	cm^2 $plant^{-1}$
SiO_2, mg L^{-1}		
0	52.87 ± 3.2a	6906.48 ± 278.13b
50	57.59 ± 3.2a	7697.49 ± 224.62a
100	54.34 ± 2.8a	7378.56 ± 198.7ab
Humidity, % CC		
55-65	52.59 ± 3.1a	7182.31 ± 248.85a
75-85	58.92 ± 3.7a	7530.90 ± 258.98a
90-100	53.29 ± 3.1a	7269.32 ± 206.02a

Silicon increases plant growth, as can be corroborated mainly by the 50 mg L^{-1} SiO_2. This treatment increased the leaf area by 10.28% compared to the treatment without Si. The isolated effects of moisture levels did not differ regarding the leaf area.

Leaf area can vary depending on the cultivar and the stage of development. Leaf area can be directly related to biomass accumulation and plant performance because it allows better capture of radiant energy. Ortiz-Cereceres et al. (2009) found a positive correlation between leaf area and cucumber yield, observing a production of two more fruits per plant in varieties with a larger leaf area. Ramírez-Vargas (2019) found leaf area values between 433 and 563 cm^2 $plant^{-1}$, much lower than the leaf area (4798 cm^2 $plant^{-1}$) reported by Da Silva et al. (2011) in cucumber plants. The leaf area values obtained for 'Braga F1' at 90 d after transplantation were much higher than those reported by other authors for other cultivars evaluated in earlier stages of development.

Nutrient concentration in different parts of the plant

Fruit. The interaction of the Si dosages with the moisture levels of the substrate slightly influenced the content of N in the fruit in both trials, as well as the contents of P, K, and Mg in the fruits of the first trial (Figure 5). In trial one, under the lowest moisture level and the dose of 50 mg L^{-1} SiO_2, the N concentration was 23.13% higher than the treatment without Si. In contrast, for the two highest moisture levels, the Si dosages did not significantly affect the percentage of N in the fruits. In the second trial, the N concentrations in the fruit for 50 and 100 mg L^{-1} SiO_2 at the lowest moisture level were 13.15 % and 14.52 % greater than the control treatment. At the intermediate moisture level, 100 mg L^{-1} of SiO_2 outperformed the two lowest Si doses, presenting an N concentration of 13.49 % and 9.81 % higher than the treatment of 50 mg L^{-1} SiO_2 and without Si, respectively.

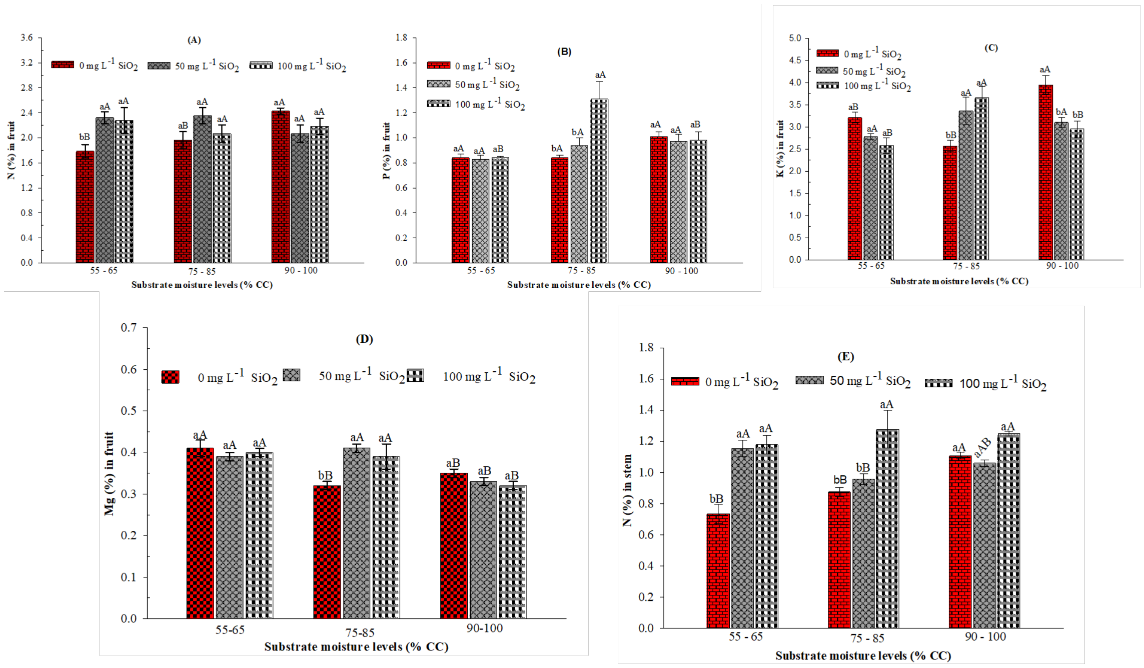

Figure 22. Effect of the interaction between Si dosages and the substrate's moisture levels on the contents of N, P, K and Mg in the fruits (A, B, C, D) and N in the stems (E) of cucumber (trial I). Different lowercase letters in the same moisture level indicate significant differences between SiO2 doses and different uppercase letters for the same SiO2 dose indicate significant differences between moisture levels, by Tukey's test ($P \leq 0.05$).

In contrast, the Si doses did not differ at the highest humidity level. The application of Si favored a greater concentration of P, K, and Mg in the fruits in the first trial, but only at the intermediate moisture level; at the other moisture levels, Si had nonsignificant favorable influence on the content of P, K, and Mg in the fruits. Under the intermediate moisture level, fruits of the plants treated with 100 mg L^{-1} SiO_2 had concentrations of P, K, and Mg that were 35.88%, 29.78%, and 17.95% higher than the fruits of the plants that did not receive Si.

Under the intermediate humidity level, when 50 mg L^{-1} SiO_2 was applied, the P percentage in the fruits was significantly similar to the treatment without Si, and higher concentrations of K and Mg, respectively, 28.61% and 21.95% greater as compared to the fruits from the plants without Si. In the second trial, neither the Si dosages' interaction with the humidity levels nor their isolated effect on the concentration of P in the fruits and stems of the plant, K in the fruits, or Mg in the fruits, leaves, and stems of the plant was significant.

Leaf. In the first assay, the interaction of Si doses with the humidity levels did not significantly affect any of the elements analyzed. In the second assay, the concentration of N, P, and K in leaves have been affected by the interaction of the Si doses with the substrate's humidity levels (Figure 6). In the absence of Si, plant leaves had higher N concentration except at the major humidity level, where N concentration in leaves was similar between the control treatment and the treatment with 50 mg L^{-1} SiO_2. Considering that Si showed a greater effect on the plant under higher stress conditions, it is possible that the lower N concentrations in the leaves of the plants fertilized with Si are due to a greater transfer of N from the leaves to the fruit at lower humidity, which may result in a lower N content in the leaves of the plants fertilized with Si. This explanation is valid only for the interaction of the Si doses with the lowest moisture level and for the interaction of 100 mg L^{-1} SiO_2 with the intermediate moisture level, because the N concentrations in the fruits were similar for the interaction of 50 mg L^{-1} SiO_2 with the intermediate moisture level and both Si doses with the highest moisture level under the respective moisture levels without Si. Although N concentrations in leaves were lower in the interaction of 100 mg L^{-1} SiO_2 with the highest moisture level than in the treatment without Si at that moisture level, no Si transfer from leaves to fruit was evident in fruit. The 50 mg L^{-1} SiO_2 favored a higher concentration of P in the plant leaf at low and intermediate moisture levels while being similar to the 0 and 100 mg L^{-1} SiO_2 under the highest humidity level. Applying 50 mg L^{-1} SiO_2, P concentrations in the leaf were 29.5% and 11.5% higher in comparison to the treatments without Si and 100 mg L^{-1} SiO_2 at the lowest humidity level, and 24.2% and 34.5% higher in comparison to the treatments without Si and 100 mg L^{-1} SiO_2 at the intermediate moisture level. Under the lowest humidity level, the K content in the leaves of plants treated with 50 and 100 mg L^{-1} SiO_2 was 24.4% and 17.4% higher, respectively, than the treatment without Si. The Si treatments did not differ at the other moisture levels.

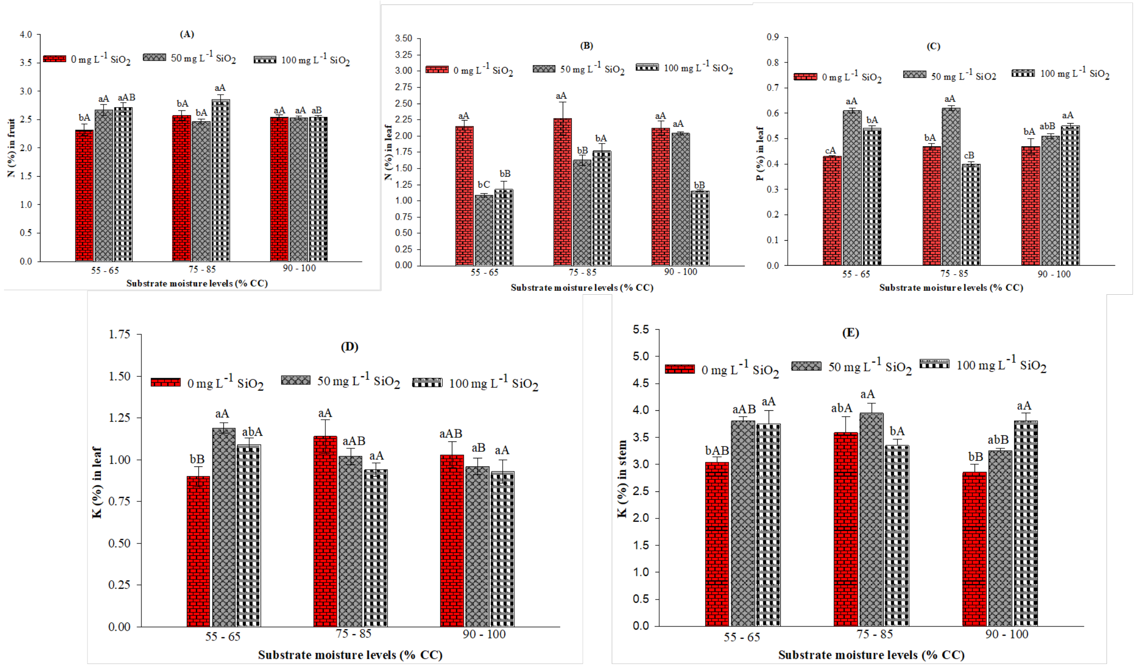

Figure 23. Effect of the interaction between silicon dosages and the substrate's moisture levels on the contents of N in the fruits (A), N, P, and K in the leaves (B, C, D), and K in cucumber stems (E) (trial II). Different lowercase letters in the same moisture level indicate significant differences between SiO2 doses and different uppercase letters for the same SiO2 dose indicate significant differences between moisture levels, by Tukey's test ($P \leq 0.05$).

Stem. In the first trial, the combined effect of the Si dosages with humidity levels substantially influences the concentration of N in the stem (Figure 5). Under the highest moisture level, in the first trial, the Si dosages did not differ from each other; however, at the intermediate moisture level, the concentration of N in the stem was 31.5% higher than the treatment without Si and 25.1% higher than the 50 mg L^{-1} SiO_2. Furthermore, under the lowest moisture level, the N concentration in the stem for the treatment without Si was 36.4% and 37.6% lower than the 50 and 100 mg L^{-1} SiO_2 treatments. In the second trial, the significant effect of the interaction between the Si dosages and the humidity levels influenced the percentage of K in the stem (Figure 6). Applying 100 mg L^{-1} SiO_2 increased the concentration of K in the stem by 24.9% and 18.9%, respectively, under the highest and lowest levels of moisture in the substrate, compared to the plants with no Si application. Also, the application of 50 mg L^{-1} SiO_2 and the lower humidity level generated a K concentration 20.2% higher in the plant stem compared to the treatment without Si. Under the intermediate moisture level, Si-treated plants had significantly similar K concentrations in the plant stem compared to the untreated plants.

Based on the nutrient concentration standards analysis of the upper leaves (third to the fifth leaf) in the early stage of flowering recommended for cucumber cultivation, the concentration of N in the different organs of the plant varied between deficient to low, except in the second trial the fruits presented normal levels of N. The concentrations of P were high in the fruits and ranged from standard to high in the leaves and stems. Regarding K, its concentration was normal in the fruits, deficient in the leaves, and low to normal in the stem. In all organs of the plant, the level of Mg was normal. It is worth mentioning that the analysis of these elements has conducted at the end of the experiment from a sample taken from the total DM produced by the organ. Because of this, the concentrations are subject to significant variations from the recommended standard values. The P and Mg concentrations found in cucumber fruits were quite comparable to those seen in greenhouse cucumber fruits, as by Navarrete (2005). The sequence of concentration of the elements in various plant organs differs by element. The N concentration was higher in the fruit, followed by the leaves, while the stems had the lowest concentration. The fruits had the highest P level, followed by the stems and leaves, which had equal P amounts. In terms of K, the fruits had the highest concentration, followed by the stem and leaves.

Epstein (2009) and Jarosz (2013) reported positive effects of Si application on nutrient uptake and distribution in plants, which was not confirmed by the results of this study, except for some exceptions where the content of P and Mg in leaves was higher than the treatment without Si. Mg concentrations were highest in leaves, then stem, and finally, fruits. The interaction between the two highest doses of Si and the intermediate moisture level presented concentrations of P, K, and Mg in the fruits higher than in the treatment without Si. This investigation revealed a more significant accumulation of K and Mg in the cucumber aerial parts compared to the root part, which agrees with Alsaeedi et al. (2019) and Greger et al. (2018). They also observed a more significant accumulation of K in the cucumber stem compared to the root, indicating a possible involvement of Si in facilitating the movement of these elements toward the aerial part of the plant (Alsaeedi et al., 2019). The examination of the nutrient concentrations in cucumber tissues of this research concurs with Jarosz (2013) in stating that the results of the influence of Si on the absorption and distribution of the elements in plants are frequently conflicting, sometimes revealed as favorable, unfavorable, or simply no impacts of Si.

CONCLUSIONS

The interaction of Si doses with humidity levels in the substrate did not affect fruit production and total soluble solids content. However, the doses of 50 and 100 mg L^{-1} SiO_2 positively influenced cucumber fruit yield, increasing fruit production by 7.89% and 15.56%, respectively, over the control treatment in the second trial.

The decrease in water availability had a detrimental impact on fruit production in both trials and total soluble solids concentration in trial one.

In situations of water stress, particularly in experiment I, application of Si improved aerial dry biomass production, leaf area, and plant rooting. At the lowest moisture level, application of 50 mg L^{-1} SiO_2 showed advantages over 100 mg L^{-1} SiO_2 and no silicon. At 50 mg L^{-1} SiO_2, aerial dry biomass, leaf area, and root dry biomass were 36.5%, 17.3%, and 46.5% higher than at 100 mg L^{-1} SiO_2 and 38.8%, 29.6%, and 48.9% higher than without silicon.

In the second test, silicon’s interaction with the substrate’s humidity and the impacts of the individual factors did not influence the plant's aerial biomass production. However, the dose of 50 mg L^{-1} SiO_2 increased the leaf area by 11.45% compared to the control treatment.

At low and intermediate moisture levels in the substrate, Si enhanced the concentration of N, P, K, and Mg in the fruits, P and K in the leaves, and N and K in the cucumber plants' stems, under the conditions of this study.

Author contribution

Conceptualization: G.F. Methodology: G.F. Validation: R.A-R., J.P-P., M.A.V-P. Formal analysis: G.F. Investigation: G.F. Resources: G.F., R.A-R., J.P-P. Data curation: G.F. Writing-original draft: G.F. Writing-review & editing: G.F., R.A-R. J.P-P., M.A.V-P. Supervision: R.A-R., J.P-P. Project administration: G.F, R.A-R., J.P-P., M.A.V-P. Funding acquisition: R.A-R. All co-authors reviewed the final version and approved the manuscript before submission.

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4. ASSESSMENT OF TWO CALCIUM SILICATE SOURCES ON CUCUMBER UNDER WATER RESTRICTION

Georgy Faroutine[1], Ramón Arteaga-Ramírez[2], Joel Pineda-Pineda[3*] & Mario A. Vázquez-Peña[2]

[1] Institute of Agricultural Engineering and Integral Use of Water, Chapingo Autonomous University, Texcoco, México
[2] Irrigation Department, Chapingo Autonomous University, Texcoco, México
[3] Department of Soils, Chapingo Autonomous University, Texcoco, México
*Correspondence: Joel Pineda-Pineda, Department of Soils, Chapingo Autonomous University, Texcoco, Méx., 56230, México. Tel: +52-556-803-9641 E-mail: pinedapjoel@yahoo.com.mx

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Abstract

Silicon (Si) is beneficial for plants that are under unfavorable conditions. In this study conducted under greenhouse conditions at Chapingo Autonomous University, Si fertilization was tested to examine whether it affected yields, biometrics, physiological parameters, and nutritional attributes of cucumber plants cultivated at different moisture levels in the substrate. Fifteen treatments were tried in a completely randomized design, including three moisture levels (50-60 %, 75-85 %, and 90-100 % of container capacity (CC) and five Si doses (0, 50, 100 mg L^{-1} SiO_2, 2 g L^{-1}, and 3 g L^{-1} Wollastonite). Uniform irrigation was applied until the 18th day after transplantation, and controlled irrigation was applied according to the moisture levels until the end of the experiment. 3 g L^{-1} of wollastonite under 75-85 % CC enhanced cucumber yield by 24.9 % in comparison to untreated plants, while no Si dose affected fruit length, diameter, weight, and total soluble solids. At 90-100 % of CC, 50 mg L^{-1} SiO_2 increased the aerial biomass production (ABP) of the plants by 9.3 %, and at 50-60 % of CC, 100 mg L^{-1} SiO_2 generated 11.8 % more aerial biomass than untreated plants. As Si did not affect root production, mainly at 50-60 % of CC, it improved chlorophyll a, b, and the total content of the leaves. Different parts of the plant saw significant increases in N, P, K, Ca, Mg, and Si concentrations because of Si's interactions

with moisture levels. When the substrate is low in moisture, Si is likely to improve cucumber yields, physiological, and nutritional characteristics of the plant.

Keywords: *Cucumis sativus*, hydric deficit, silicon fertilizer, stressed plant, water stress

1. Introduction

Water is crucial to the morphological, physiological, and biochemical functions of plants. It provides them with the nutrients and hydration needed to show their full potential, making it an essential part of them (Peçanha, da Cunha-Chiamolera, Chourak, Martínez-Rivera, & Urrestarazu, 2021). Hence, ensuring an adequate supply of water is key for ensuring healthy and thriving plants since its absence significantly impacts their water status, their nutrition (Peçanha et al., 2021), and, consequently, their performance (Sharma, Leskovar, & Crosby, 2019).

As an economically and nutritionally valuable commodity, cucumbers (*Cucumis sativus* L.) have a rapidly growing domestic and foreign market and are widely consumed for their rich vitamin content (Orzolek, Kime, Bogash, & Harper, 2017). A small-scale crop, cucumbers are nutritionally high in water, low in calories, high in phenolic compounds and cucurbitacins, and contain antioxidants, anti-inflammatory, hypoglycemic, and cancer-fighting properties (Mukherjee, Nema, Maity, & Sarkar, 2013; Uthpala, Marapana, Lakmini, & Wettimuny, 2020; Ghafoor et al., 2022). Physiological and biochemical processes of the plant can be damaged by unfavorable conditions, such as stress due to hydric deficit (Yuan, Yang, Li, Liu, & Han, 2016), resulting in reduced yields and decreased quality of the fruits (Pal, Adhikary, Shankar, Kumar, & Maitra, 2020). Multiple effects and benefits of root and foliar applications of silicon sources have been investigated and reported in various plant species (Ahmad, Afzal, Ahmad, & Tahir, 2013; Pavlovic et al., 2013; Bityutskii, Pavlovic, Yakkonen, Maksimović, & Nikolic, 2014; Hernández-Apaolaza et al., 2020; Hussain et al., 2021; Martín-Esquinas & Hernández-Apaolaza, 2021). According to Barreto, Schiavon Júnior, Maggio, & Prado (2017), the high concentration of Si in leaf tissue favors yield and tolerance to physicochemical stress. For example, Wenneck, Saath, & Rezende (2022) in an experiment in which they applied to the soil different rates of Si in Cauliflower

(*Brassica oleracea* var. botrytis), grown with different levels of water replenishment, increased dry biomass production and Si content in different plant components, with accumulation between 0.5 % to 2.19 % and 0.29 % to 0.9 % of Si, respectively in the roots and leaves of the plant. Also, according to González-García et al. (2022), silicon can increase the content of bioactive compounds in cucumbers. They found 15.6 % more total soluble solids in treatments with potassium silicate or silicon nanoparticles than in treatments without silicon. The results of Zhu et al. (2016) indicate that 0.3 mM Na_2SiO_3 in nutrient solution increases soluble sugar content (glucose, sucrose, and fructose) in cucumber plants. Also, Hu et al. (2022) corroborated this occurrence with foliar application of 1 mM Na_2SiO_3 in cucumber. In cucumbers, Si regulates the enzymes involved in the acquisition of Fe (Pavlovic et al., 2013). Si-mediated biosynthesis of Fe-chelating compounds in cucumber roots alleviates Fe deficiency and enhances Fe mobilization in roots by increasing apoplastic Fe stores in roots (Pavlovic et al., 2013). Under combined salt and water stress, by adding Si, Zhu, Wei, Li, Qian, & Yu (2004) observed that cucumber plants increased their protein content. Using Si in cucumbers modulates gas exchange, which contributes to drought tolerance (Ma, Li, Gao, & Xin, 2004). Cucumber leaves harbor a high concentration of Si in the cells surrounding the capillary trichome bases (Abe, 2019). In Melon (*Cucumis melo* L.), which is from the same family as cucumber, Nascimento et al. (2020) reported an increase in the absorption of nutrients and their yield due to the application of Si.

In hydroponic systems, De Kreij, Voogt, & Baas (2003) and Kamenidou, Cavins, & Marek (2010) recommend supplementing cucumbers and roses (*Rosa hybrida* L.) with silicon, and according to Ma and Yamaji (2006), the benefits of Si in plants are more evident under stress conditions. In this context, further research on the use of Si as a strategy for mitigating the harmful effects of water scarcity on plants, such as cucumber, is needed. Therefore, in this study, it was investigated whether Si fertilization could reduce the negative impact of water stress on cucumber plant yields, biometrics, physiological as well as nutritional parameters.

2. Method

2.1 Location of the experiment and characterization of the substrate

A greenhouse essay was performed in Texcoco, State of Mexico, at the Chapingo Autonomous University (UACh), located at 19°29' N, 98°53' W. The experiment was conducted in perforated black polyethylene bags filled with 12 L of peat (ProMix®) with respective chemical and moisture retention properties, as shown in tables 1 and 2 and figure 1. The characteristics of substrate water retention were determined according to De Boodt, Verdonck, & Cappaert (1974).

Table 21. Chemical properties of the peat (ProMix®) according to the supplier

Parameter (SME*)	Peat moss (ProMix®)
pH	5.2 – 6.2
EC (dS m^{-1})	1.0 – 1.8
N-NO_3 (mg L^{-1})	70 – 130
P-PO_4 (mg L^{-1})	5 – 40
K (mg L^{-1})	50 – 130
Ca (mg L^{-1})	100 – 180
Mg (mg L^{-1})	20 – 45
S-SO_4 (mg L^{-1})	30 – 100
Fe (mg L^{-1})	0.8 – 2.2
Zn (mg L^{-1})	0.1 – 1.2
Cu (mg L^{-1})	< 0.3
Mn (mg L^{-1})	0.3 – 1.0
B (mg L^{-1})	< 0.6

*SME: saturated media extract

Table 22. Physical and water retention characteristics of the substrate

Bulk density (B_{ap}), g cm^{-3}	0.14
Water holding capacity (WHC), %	79.78
Total pore space (TPS), %	92.71
Aeration capacity (AC), %	12.93
Readily available water (RAW), %	26.61
Buffering capacity water (BCW), %	13.28
Hardly available water (HAW), %	39.89
Total available water (TAW), %	39.89

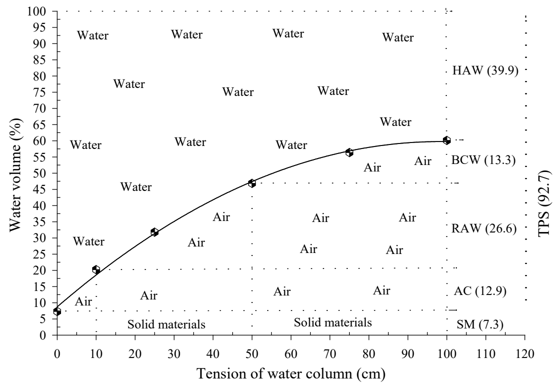

Figure 24. Graphical representation of the water release capacity of the substrate (ProMix®) from 0 to 10 kPa. HAW: Hardly available water; BCW: buffering capacity water; RAW: readily available water; AC: air capacity; SM: solid materials; TPS: total pore space.

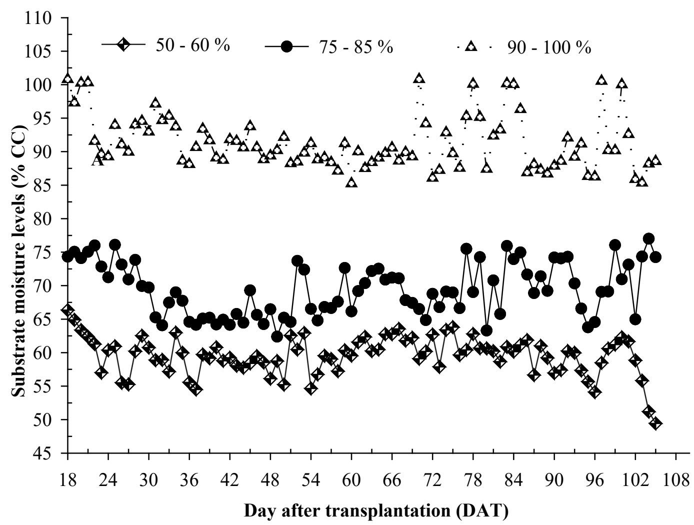

Figure 25. Average daily moisture levels registered in the substrate.

2.2 Treatments, experimental design, and crop management

Seedlings of hybrid cucumbers 'Vitaly' (Syngenta AG, Switzerland) were grown in a seedbed and transplanted 18 days after seeding (DAS) into bags for each treatment. The experiment was established following a factorial arrangement of two factors and according to a completely randomized design (CRD), where each bag with a plant represented an experimental unit. The moisture levels in the substrate (50-60 %; 75-85 %; 90-100 % CC), calculated based on its container capacity (% CC) with the doses of Si (0, 50, 100 mg L^{-1} SiO_2, 2 g L^{-1}, 3 g L^{-1}

Wollastonite) resulted in fifteen treatments that were replicated four times, totaling 60 experimental units (3*5=15*4 = 60).

In terms of the 0, 50, and 100 mg L^{-1} SiO_2 doses, 300 mL of solution were applied to each bag every 8 days from the day of the transplant until day 63, according to the concentration of the treatment, using a concentrate liquid of calcium silicate, branded Barrier®, produced by Cosmocel, Nuevo León, Mexico, with a chemical composition of 10 % Ca, 24 % SiO_2, and 66 % conditioners and diluents. In the treatment with Si formed with Wollastonite, before transplanting, 24 g of product was applied and mixed with the substrate for the 2 g L^{-1} treatment and 36 g for the 3 g L^{-1} treatment. Wollastonite is a very fine granular calcium silicate, apparent as a powder. Table 3 shows the chemical characteristics of the Wollastonite.

The plants were irrigated uniformly until 18 days after transplantation (DAP) and from this date until the end of the experiment, the moisture levels established in the substrate were maintained by applying controlled irrigation according to each moisture treatment (Figure 2). To monitor moisture levels in the growing medium, wireless HOBOnode soil moisture sensors from Onset Computer Corporation (W-SMC, Bourne, Massachusetts, USA) were installed to a depth of 10 cm in the root environment of the plant. The plants were irrigated and nourished through a fertigation system using a nutrient solution prepared according to the recommendations in table 4. As part of cultural practices, tutoring, guiding, and pruning tasks were carried out to keep the plants with a single stem until the end of the cycle (105 days after transplanting). Also, when the plant reached around 3 m in height, the terminal growth bud of the plant was cut. Traps were placed to control the presence of insects and disease vectors that could harm the crop.

Table 23. Chemical composition of the Wollastonite, according to the manufacturer

SiO_2 (%)	48 - 53
CaO (%)	43 - 46
Al_2O_3 (%)	0.15 – 0.30
Fe_2O_3 (%)	0.15 – 0.55
TiO_2 (%)	0.02
S (%)	0.02
P (%)	0.007
LOI* (%)	1 - 4

LOI*: Loss on ignition

Table 24. Chemical composition of the nutrient solution used to irrigate the cucumber plants

Nutrient (mg L^{-1})	Seedling to 1st fruit	1st fruit to the final of the cycle
N	133	240
P	62	62
K	150	150
Ca	130	260
Mg	50	50
S	70	70
Fe	2.50	2.50
Zn	0.09	0.09
Cu	0.10	0.10
Mn	0.62	0.62
B	0.44	0.44
Mo	0.03	0.03

2.3 Biometric and Yield Analysis

2.3.1 Cumulative Yield of Fruits

As the fruits matured, they were gradually harvested and weighed to calculate the cumulative yield of fruits (CYF) per plant by adding the production of each harvest.

2.3.2 Average Length, Diameter, and Weight of Fruits

The length of each fruit and the length of its circumference in the central part were measured using a tape measure graduated in cm. The diameter of the fruit was determined by dividing the length of its circumference by π. Finally, with the data from all the fruits, the average length (ALF) and diameter (ADF) of the fruits were calculated. Also, the CYF was divided by the number of fruits produced per plant to determine the average weight of the fruits (AWF).

2.3.3 Concentration of Total Soluble Solids

A digital sucrose refractometer (HI-96801, Hanna Instruments, Woonsocket, Rhode Island, USA), with a sugar concentration range of 0-85 % °Brix, was used to determine the concentration of total soluble solids (TSS). For this, two fruits were selected in the middle part of each plant and each one was divided in half and squeezed. With the drops of juice produced, the TSS concentration in each fruit was determined and these values were averaged to determine the TSS content in the fruits.

2.3.4 Aerial and Root Dry Biomass

The aerial portion of the plant was cut at ground level at the end of the experiment to quantify its aerial (leaves and stems) biomass production (ABP). The samples were separated into leaves and stems and placed in paper bags to be dried to a constant weight at 70 °C in a forced ventilation oven. Then, they were weighed, and the amount of aerial biomass per plant was determined. Likewise, after the root of each plant was collected and dried under the same conditions as above, its root biomass (RB) was calculated.

2.4 Relative Water Content of Leaves

Leaf sampling was carried out at 103 DAP, collecting one leaf per plant. Subsequently, 3 leaf punches were removed and weighed individually on an analytical balance to determine their fresh weight (FW). Then, in a Petri dish, they were saturated with distilled water and left at room temperature for 19 hours. Then, excess water was removed from the leaf using a paper towel and its turgid weight (TW) was measured. They were then dried in a forced ventilation oven at 65 ˚C for 48 hours and their dry weight (DW) was determined. The relative water content CRA (%) was determined with the following formula:

$$RWC\ (\%) = ((FW - DW) / (TW - DW)) \times 100 \quad (1)$$

2.5 Photosynthetic Pigments of Leaves

At 105 DAP, two leaves were collected at the top of each plant and used to make a composite sample. Subsequently, a subsample of 50 mg of leaf tissue was ground and homogenized in 40 ml of acetone at 80%, filtered, and placed in test tubes. An ultraviolet-visible (UV-Vis) spectrophotometer (Genesys 10-S, Thermo Fisher Scientific, Madison, Wisconsin, USA) was used to measure chlorophyll a, b and total fractions according to Witham, Blaydes, and Devlin (1971) and Lichtenthaler (1987).

2.6 Nutritional Analysis of Fruits, Leaves, Stems and Roots

At the end of the experiment, the dried fruits, leaves, stems, and roots were ground separately and the contents of N, P, K, Ca, Mg and Si in these components of the plants were measured in the Plant Nutrition Laboratory of the Department of Soils at Chapingo Autonomous University. The N in foliar tissues was determined by the Kjeldahl technique and the foliar P by the molybdovanadate colorimetric method, both procedures described by Alcántar and Sandoval (1999). A flame photometer (410, Sherwood Scientific, Cambridge, UK) was used to quantify foliar K and an atomic absorption spectrophotometer (GBC 932 plus, GBC Scientific Equipment, Braeside, Victoria, Australia) to determine foliar Ca and Mg. Also, using the colorimetric method described by Korndörfer, Pereira, and Nolla (2004) Si content was assessed in plant tissues.

2.7 Statistical Analysis

After verifying compliance with the assumptions of normality of variance and homogeneity of residuals, the data of each variable were processed using the statistical program Sisvar version 5.6 (Ferreira, 2014) through analysis of variance (ANOVA) and Tukey tests ($P \leq 0.05$) to compare the means of the treatments. The statistical program SigmaPlot version 11.0 (Systat Software, Inc., San José

California, USA) was used to prepare graphs of results for the variables that presented significant interactions between treatments.

3. Results and Discussion

3.1 Cumulative Fruit yield and Fruit traits

Cumulative fruit yield (CFY) per plant was significantly affected by the interaction of Si with moisture levels in the substrate (Figure 3). Both at the lowest and highest moisture levels in the substrate, the application of Si did not increase fruit production. However, the application of 3 g L^{-1} of wollastonite, under the intermediate moisture level, favored higher fruit production in relation to the other doses of Si and generated a 24.9 % increase in production in relation to untreated plants. Regarding moisture levels, the intermediate moisture level managed to exceed the other levels only when interacting with the 3 g L^{-1} dose of wollastonite. This interaction increased the CFY per plant, respectively, by 26.6 % and 17.9 % in relation to the lower and higher moisture levels in the substrate. Using 3 g L^{-1} of wollastonite for the intermediate moisture level resulted in the highest average fruit production (4.31 kg $plant^{-1}$); however, using 3 g L^{-1} of wollastonite at the lowest moisture level resulted in the least average fruit production (3.16 kg $plant^{-1}$), with a numerical difference of 26.6 % between both treatments. In this study, cucumber fruit production increased with the application of Si as well as Hu et al. (2022) showed an increase in the yield and number of fruits of hybrid cucumber 'Jinyou 315' with foliar application of Si, alone or combined with Se. Likewise, research results by Basirat and Mousavi (2022) agree that Si, applied via foliar to cucumber plants grown under high temperature conditions, improves the total yield of cucumber fruits as well as their quality, with an increase of 36.14 % of the total yield and 40.29 % more marketable fruits. Similarly, root application of 500 mg dm^{-3} and 750 mg dm^{-3} of Si increased the production of cucumber fruits by 8.60 % and 5.89 % respectively, according to Jarosz (2013). Consistent with the results of this study, Alsaeedi et al. (2019) reported a 156 % increase in fruit yield in cucumber plants under an irrigation regime of 85 % ETc and fertilized with 200 mg kg^{-1} of Si nanoparticles. This study, as well as that of other authors, corroborates the positive effects of Si on improving the yield of cucumber fruits under different environmental conditions. These increases may be the result of improvements generated by Si in different components of the plant, such as nutritional aspects.

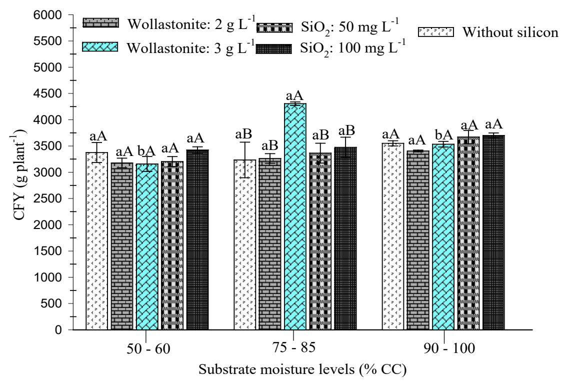

Figure 26. Effect of the interaction between silicon and moisture of the substrate on the average cumulative fruit yield (CFY) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

The interaction of Si with moisture in the substrate does not significantly influence the average length, diameter, weight, and content of total soluble solids in the fruits (Table 5). The length, diameter, weight and content of total soluble solids of the fruits varied between 17.84 to 23.0 cm, 5.0 to 5.67 cm, 243 to 615 g fruit^{-1} and 2.95 to 4.25 %, respectively. According to the technical data sheet of the seed, these data fit within the characteristics of the fruit of the 'Vitaly' cultivar. The ALF has not been affected by the silicon dose or by the moisture levels in the substrate. In the same way, the ADF, AWF and TSS of the fruits were not affected by the doses of Si either. However, a slight decrease in ADF and AWF was observed with the decrease in irrigation. As compared to the highest moisture level in the substrate, the fruits of the two lowest moisture levels had slightly higher TSS concentrations. The length, diameter and weight of cucumber fruit can vary mainly according to the variety. In the present experiment, the average length, diameter, and weight of the fruits of the hybrid 'Vitaly' were similar to those found by López-Elías et al. (2011) in Persian type cucumber. The average weight of the fruits in this study was clearly higher than that of the fruits of the varieties 'Reehan' and

'Khassib' evaluated by Alejo-Santiago et al. (2021). According to the report by Dorais and Thériault (2018), Si does not affect the weight of the cucumber fruit, which agrees with what was observed in this study and with Górecki and Danielski-Busch (2009) who reported increased yield in cucumber fruits due to the greater number of fruits produced per plant, not due to differences in the weight of the fruits. The length, diameter and weight of the fruit are phenotypic variables linked mainly to the genetics of the plant material, not to fertilization or the level of irrigation. This observation agrees with what was reported by Corrêa et al. (2018) and Alejo-Santiago et al. (2021) where the K dose variation has not significantly influenced the length and diameter of cucumber fruits, but they have observed differences between varieties for these variables. The bioactive compounds in cucumber fruits can be augmented by applying Si (González-Garcia et al., 2022). As demonstrated by González-García et al. (2022) when applying potassium silicate and silicon nanoparticles to cucumber plants, the TSS content grew by 15.6 % in comparison to treatments without Si. Increased contents of phenolic compounds, ascorbic acid, flavonoids, titratable acids, antioxidant activities and lipophilic compounds were also reported (González-García et al., 2022). Similarly, the application of 0.3 mM Na_2SiO_3 in nutrient solution increased the content of soluble sugars (glucose, sucrose, and fructose) in cucumber plants (Zhu et al., 2016). Also, Hu et al. (2022) corroborated it with foliar application of 1 mM Na_2SiO_3 in cucumber. However, there is some evidence that Si application did not affect the TSS content of cucumber fruits. For example, in this study there was no increase in the TSS content in the fruits due to the application of Si, coinciding with the results of Abd-Alkarim, Bayoumi, Metwally, and Rhaka (2017), where the TSS content in cucumber fruits, measured at different stages of plant growth, did not differ significantly between the treatments that received Si and those that did not.

Table 25. Individual effects of silicon and moisture in the substrate on average length (ALF), diameter (ADF), weight (AWF), and total soluble solids (TSS) of 'Vitaly' cucumber

Doses of Si	ALF (cm)	ADF (cm)	AWF (g fruit^{-1})	TSS (%)
0	20.04 ± 0.22 a	5.25 ± 0.03 a	324.76 ± 10.33 a	3.62 ± 0.10 a
2 g L^{-1} Wollastonite	20.78 ± 0.27 a	5.29 ± 0.04 a	360.58 ± 16.66 a	3.60 ± 0.07 a
3 g L^{-1} Wollastonite	20.58 ± 0.27 a	5.30 ± 0.06 a	378.83 ± 10.89 a	3.68 ± 0.11 a
50 mg L^{-1} SiO_2	20.25 ± 0.18 a	5.31 ± 0.04 a	362.07 ± 9.70 a	3.56 ± 0.10 a
100 mg L^{-1} SiO_2	20.01 ± 0.34 a	5.33 ± 0.06 a	350.13 ± 27.17 a	3.59 ± 0.10 a
Humidity (% CC)				
50 - 60	19.97 ± 0.19 a	5.19 ± 0.03 b	328.72 ± 7.14 b	3.86 ± 0.05 a
75 - 85	20.53 ± 0.24 a	5.32 ± 0.04 a	364.77 ± 15.94 ab	3.55 ± 0.07 a
90 - 100	20.50 ± 0.17 a	5.37 ± 0.03 a	372.33 ± 12.33 a	3.52 ± 0.06 b

Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

3.2 Aerial and Root Dry Biomass

Figure 4 shows a significant effect of the interaction between Si doses and moisture levels in the substrate on aerial biomass production (ABP) of the plant. ABP of the plant is positively affected by silicon at high and low moisture levels in the growing medium, whereas non-silicon-treated plants, at the intermediate moisture level, produce aerial biomass similar to those treated with silicon. The application of 100 mg L^{-1} SiO_2 generated dry biomass 11.8 % greater than the control treatment at the lowest moisture level. Likewise, at the maximum moisture level, the ABP of the plants fertilized with 50 mg L^{-1} SiO_2 was 9 % more when compared to the treatment that did not receive Si. The ABP at the lowest moisture level was 13.3 % more than the intermediate moisture level and 10.7 % superior in relation to the highest moisture level in the substrate, applied 100 mg L^{-1} SiO_2. While the lowest and intermediate moisture levels in the substrate generated statistically similar aerial biomass values, the intermediate moisture level was 7.7 % more than in relation to the highest moisture level, with the application of 3 g L^{-1} of wollastonite.

Regarding the root production of the plant, there was no significant effect of the interaction of Si with moisture in the substrate on the radical biomass (RB) (table 6). Likewise, the presence or absence of Si did not affect the root production of the plant. However, the reduction of irrigation significantly reduced the amount of root produced by the plant, because the plants grown with the lowest level of humidity produced a root biomass 17.6 % lower compared to the plants treated with the highest level of moisture.

According to Grašič et al. (2021), cucumber plants suffer significant reductions in growth and production due to water deficits. For example, Ma et al. (2004) reported decreased growth in cucumber plants grown without Si and subjected to water deficits. The authors stated that in the plants treated with Si the growth reduction was less evident since they obtained a more substantial accumulation of biomass in these plants than in those deficient in silicon. Also, Meng et al. (2021) supports the positive effect of silicon on increasing biomass accumulation in cucumber seedlings. In the same line, although under different stress conditions, cucumber plants under saline stress treated with Si produced 37 % more fresh mass than plants not treated with Si (Wang et al., 2015). As described by Ma et al. (2004) and noted in this study, 100 mg L^{-1} SiO_2 can also lead to an increased accumulation of aerial dry mass compared to plants grown without it. This is particularly true for plants at the lowest moisture levels. According to Ma et al. (2004), Si positively affects the accumulation of biomass by the plant under water stress because it increases its photosynthetic and water retention capacities. These results support the influence of silicon to reduce the negative impacts of water stress on cucumber crop growth.

Table 26. Individual effects of silicon and moisture in the substrate on root biomass (RB) production of 'Vitaly' cucumber

Doses of Si	RB (g $plant^{-1}$)
0	2.023 ± 0.165 a
2 g L^{-1} Wollastonite	2.472 ± 0.143 a
3 g L^{-1} Wollastonite	2.385 ± 0.077 a
50 mg L^{-1} SiO_2	2.146 ± 0.121 a
100 mg L^{-1} SiO_2	2.370 ± 0.120 a
Humidity (% CC)	
50 - 60	2.077 ± 0.101 b
75 - 85	2.241 ± 0.095 ab
90 - 100	2.520 ± 0.093 a

Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

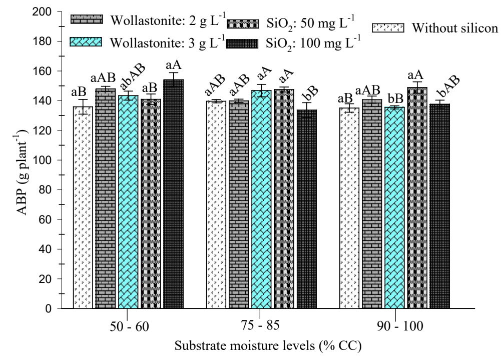

Figure 27. Effect of the interaction between silicon and moisture of the substrate on the aerial biomass production (ABP) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and *upper-case* letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.3 Photosynthetic Pigments and Relative Water Content of Leaves

Chlorophyll a, b and total, and relative water content (RWC) were significantly affected by the interaction between Si and moisture levels of the substrate (Figure 5). At intermediate and high moisture levels, the effects of Si doses did not positively influence the concentrations of chlorophyll a, b and total in the leaves of the plant. For the treatment without Si, the chlorophyll a, b, and total contents were similar to the 2 g L^{-1} wollastonite and 3 g L^{-}1 wollastonite doses and, at the same time, higher than the other Si doses, at the intermediate moisture level. At the highest moisture level, the chlorophyll a, b and total values for the treatment without Si and the 100 mg L^{-1} SiO_2 dose were statistically equal but higher than the other Si doses. Si positively influences chlorophyll a, b, and total content in the leaves of plants mainly under the lowest moisture in the substrate. The 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 doses favored concentration of chlorophyll a, respectively, 15.7% and 18.2% higher than the treatment without Si. Likewise, at the lowest moisture level, the 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 doses generated total chlorophyll contents, respectively 14.7 % and 18.6 % higher than the treatment without Si. Also, under the lowest moisture level, the chlorophyll b content in the leaves of the plants was 19.4 % higher than the control treatment and significantly higher than the other doses of Si, with the application of 100 mg L^{-1} SiO_2. The application of Si led to a significant increase in chlorophyll a, b, and total in the leaves of the plants, especially under the lowest moisture level. The foliar spray of Si in tomato increased the chlorophyll content of the leaf as per Xue, Zhang, Sun, Liao, and Chen (2012). Similarly, a significant increase in chlorophyll content in Zn-deficient sorghum plants was reported by Guedes, Prado, Frazão, Oliveira, and Cazetta (2020) due to foliar applications of Si. Ibrahim and Al-Wasfy (2014) confirmed a significant increase in the combined effect of Si with Se, compared to the individual application of Si, on chlorophyll concentrations in orange trees. Along the same lines, Hu et al. (2022) found that the individual application of 1 mM of Si, via foliar, in cucumber plants barely generated a slight, non-significant increase in the concentration of chlorophyll in the leaves, but its combined effect with 0.025 mM of Se significantly increased the concentrations of chlorophyll a and b, respectively 25.2 % and 29.8 %. Likewise, leaves of melon plants (*Cucumis melo* L.) fertilized with Si had higher chlorophyll content compared to plants not treated with Si (Lu & Cao, 2001). In this study, the plants treated with 100 mg L^{-1} SiO_2 under the lowest moisture level presented the highest chlorophyll a, b and total contents (6.800 g L^{-1}; 3.062 g L^{-1}; 9.864 g L^{-1}, respectively) while the lowest contents of chlorophyll a, b and total (3.070 g L^{-1}; 1.302 g L^{-1}; 4.371 g L^{-1}) were obtained in the treatment resulting from the interaction of 2 g L^{-1} of wollastonite with the highest moisture level. According to Silva et al. (2012), water deficiency significantly reduces the levels of chlorophyll a, b and total in tomato cultivars, while the application of silicon at 0.25, 1.00 and 1.75 μmol in plants with water deficit increases the levels of chlorophyll a, b and total. Chlorophyll a reduction due to water restriction leads to the production of peroxidative enzymes that are associated with chlorophyll a degradation in the thylakoid membrane (Gandul-Rojas, Roca, Mínguez-Mosquera, 2004). The increase in chlorophyll a level due to the application of silicon in cultivars with water deficiencies indicates the synthesis of new pigments and the maintenance of existing chlorophyll a (Silva et al., 2012). Silva et al. (2012) observed a positive interaction between leaf water potential and total chlorophyll. In plants under water deficit, the addition of 1.75 μmol of silicon maintained total chlorophyll levels at same levels as those grown without water deficit (Silva et al., 2012). The relationship between leaf water potential and total chlorophyll explains this result, since adequate amounts of water in leaf tissue maintain chloroplast stability along with other functions such as energy absorption and transport (Silva et al., 2012). Silicon has been shown to modify nitrogen metabolism (Watanabe, Fujiwara, Yoneyama, & Hayashi, 2001) and the latter participates in the formation of chlorophyll (Silva et al., 2012). The decrease in total chlorophyll observed in water-deficient plants in the absence of silicon is the result of a decrease in nitrogen uptake since water is responsible for driving nitrogen and other nutrients through the root system. According to Donegá (2009), silicon improves plant architecture and increases photosynthesis. Its deposition in the cell wall increases the resistance of the tissues and the yield of the plant due to the architecture of the leaves and their capacities to intercept sunlight (Lana, Korndörfer, Zanão Júnior, Silva, & Lana, 2003).

The Si favored higher RWC in the leaves of the plant just under the highest level of moisture in the substrate. Under this scenario, the RWC in the leaves of the plants fertilized with 100 mg L^{-1} SiO_2 increases by 11.9 % in relation to the leaves of the plants not treated with Si. Conversely, the application or omission of Si does not affect the RWC values in the leaves of the plants under the two lowest moisture levels in the substrate. The highest RWC (90.99 %) was observed in plants treated with 100 mg L^{-1} SiO_2 under the highest moisture level, while the lowest RWC (75.25 %) was obtained under the lowest moisture level in the substrate in plants without Si treatment. As observed in this study, as well as in that of Qingfang and Chengcang (2002), silicon positively affects RWC in plants. This statement is corroborated by Ma et al. (2004) by attributing the increased resistance to drought stress seen in cucumber plants fertilized with Si to the ability of the element to increase the water content in the leaves, increase biomass production and reduce the rate of plant transpiration. In cucumber plants under intermediate and severe water stress, Ma et al. (2004), after applying 240 ppm of SiO_2, reported RWC 8 % and 14 % higher than that of deficient plants in silicon. Also, the 120-ppm dose of SiO_2 generated RWC 8 % and 3.4 % higher than those of a plant deficient in silicon (Ma et al., 2004). In a study by Alsaeedi et al. (2019)

the application of Si nanoparticles reduced the negative impacts of water stress in cucumber by improving the water balance in the plant, as also found by Hasanuzzaman et al. (2018) and Jafari, Arvin, and Kalantari (2012) in cucumber and other crops. The effect of silicon on improving the water balance is mainly achieved by favoring better water uptake by the plant (Wang et al., 2015).

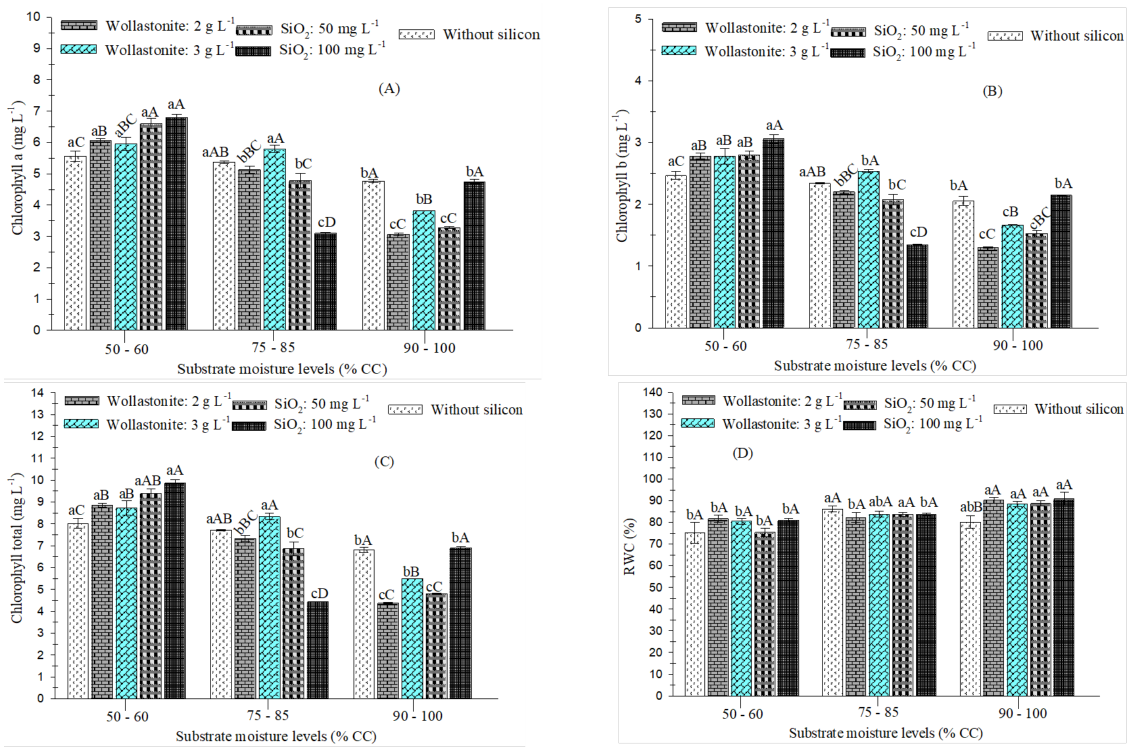

Figure 28. Effect of the interaction between silicon and moisture levels of the substrate on the content of chlorophyll a (A), chlorophyll b (B), total chlorophyll (C) and relative water content (D) in cucumber leaves. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars. RWC: relative water content.

3.4 Concentrations of Nutrients in Different Parts of the Plant

The concentrations of N, P, K, Ca, Mg and Si in the different parts of the plant (fruits, leaves, stem, and roots) were significantly affected by the interaction of Si with the moisture in the substrate, except for the percentages of N in the stem and Ca in the roots. A more significant effect of Si on the concentration of N, P, K, Ca, Mg and Si is observed in different parts of the plant in treatments with the lowest moisture level in the substrate (Figures 6, 7, 8, 9, 10, 11).

3.4.1 Nitrogen (N) concentration

The application of Si significantly affected the N contents in the different parts of the plant (Figure 6), except in the stem (table 7). The fruits presented the highest concentration of N (2.2 % - 2.83 %), followed by the stems (1.94 % - 2.77 %), the leaves (1.49 % - 2.39 %) and the roots (1.81 % - 2.25 %). The treatment with 3 g L^{-1} of wollastonite, under the lowest moisture level, produced the greatest N content in the fruits (2.83 %), with an increase of 15.3 % compared to the treatment without Si. Neither the interaction of Si with the moisture of the substrate nor its individual effects affected the concentration of N in the stem. However, there was more N content in the stem of the plants with the lowest moisture level than at the other moisture levels. The plants grown with the lowest moisture level supplemented with 2 g L^{-1} of wollastonite had the highest level of N (2.4 %) in the leaves, which was 26 % higher than the plants not fertilized with Si. Also, N levels in the roots increased in response to Si application, mainly with the 3 g L^{-1} wollastonite dose. Respectively, under the lowest and intermediate moisture levels in the substrate, 3 g L^{-1} wollastonite produced a 12.9 % and 11.1 % higher N concentration in the roots compared to the treatment without Si. Similarly, the 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 doses, under the lowest moisture level, increased the concentration of N in the roots respectively by 21.3 % and 19.2 % more in relation to the treatment without Si. The application of Si affected favorably the absorption, assimilation, and remobilization of N (Wu et al., 2017; Haddad et al., 2018; Gou et al., 2020, Pavlovic, Kostic, Bosnic, Kirkby, & Nikolic, 2021). It affects N metabolism as well as the C and P stoichiometry in the stem of the plant (Neu, Schaller, & Dudel, 2017; Deus, Prado, Alvarez, Oliveira, & Felisberto, 2020; Pavlovic et al., 2021), and the absorption of nutrients by the roots (Barreto et al., 2017), which enhances the utilization of N in plants (Pavlovic et al., 2021). The greater fixation (Mali & Aery, 2008) and availability of N, increased transcription of the genes involved in its absorption (Haddad et al., 2018), and improved efficiency of its transport are all thought to be contributing factors to the increased absorption of N mediated by Si in different plant species (Sheng, Ma, Pu, & Wang, 2018). Si improves N assimilation (Wu et al., 2017), however various species react differently to silicic fertilization, which varies even within species (Campos et al., 2020; Barreto et al., 2021).

Table 27. Individual effects of silicon and moisture in the substrate on N concentration in the stem of cucumber

Doses of Si	N (%) in stem
0	2.52 ± 0.07 a
2 g L^{-1} Wollastonite	2.36 ± 0.11 ab
3 g L^{-1} Wollastonite	2.20 ± 0.08 b
50 mg L^{-1} SiO_2	2.40 ± 0.06 ab
100 mg L^{-1} SiO_2	2.45 ± 0.07 a
Humidity (% CC)	
50 - 60	2.59 ± 0.05 a
75 - 85	2.34 ± 0.03 b
90 - 100	2.23 ± 0.07 b

Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

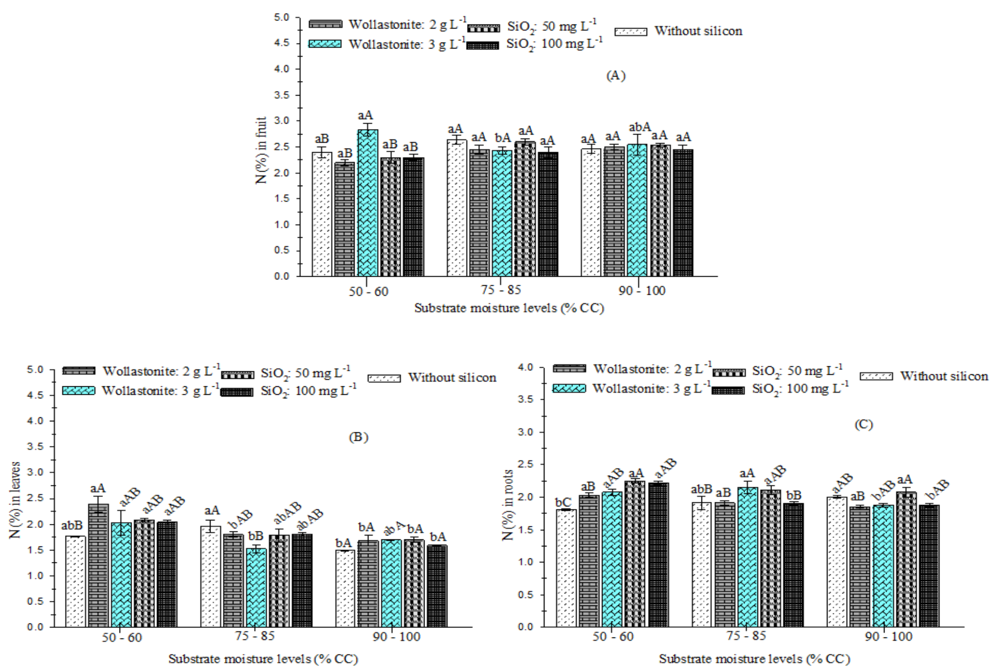

Figure 29. Effect of the interaction of silicon with the moisture of the substrate on the concentration of N in fruits (A), leaves (B), and roots (C) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.2 Phosphorous (P) concentration

Regarding P, its highest concentration was observed in the roots (0.72 % - 1.10 %), followed by the leaves (0.83 % - 1.04 %), the fruits (0.78 % - 0.92 %) and the stems (0.74 % - 0.86 %). The highest concentration of P in the root (1.10 %) is obtained when 50 mg L^{-1} SiO_2 is applied with the lowest moisture level in the substrate (Figure 7). Under this treatment, the P level in the root increased by 10.2 % compared to the treatment without Si. In both the leaves and the fruits, no dose of Si resulted in a favorable effect on the concentration of P in these components of the plant. This is because treatments without Si demonstrated equivalent or higher P levels than the leaves or fruits of plants treated with Si. In the stem, there is a significant increase in P concentrations (0.85 % and 0.86 %) with the 2 g L^{-1} of wollastonite and 50 mg L^{-1} of SiO_2 treatments, respectively, at the lowest moisture level, with higher values of 4.6 % and 5.4 % compared to the treatment without Si. Si has a favorable impact on P nutrition, but its implications are unclear (Pavlovic et al., 2021). Si reduces P deficiency mainly by increasing P uptake by the roots and its substantial utilization in plant tissues (Pavlovic et al., 2021). Kostic, Nikolic, Bosnic, Samardzic, and Nikolic (2017) have demonstrated that Si promotes the expression of genes linked to inorganic P absorption in wheat crops. In an acid soil with low P content, Pavlovic et al. (2021) claim that Si boosted the expression of inorganic P transporter genes, which increased the uptake of inorganic P. Similarly, Kostic et al. (2017) reported that Si promoted the acquisition of inorganic P by the plant root by enhancing carboxylate exudation. In response to Si's application, Soratto, Fernandes, Pilon, and Souza (2019) observed an increase in the concentrations of soluble inorganic P in the leaves, indicating that Si contributes to plant growth under conditions of low P availability. On the other hand, under an excessive supply of P, it has been observed in several plant species decreased P uptake due to Si application, and Ma (2004) attributed this decrease to the formation of physical apoplastic barriers by Si deposition in the plant root.

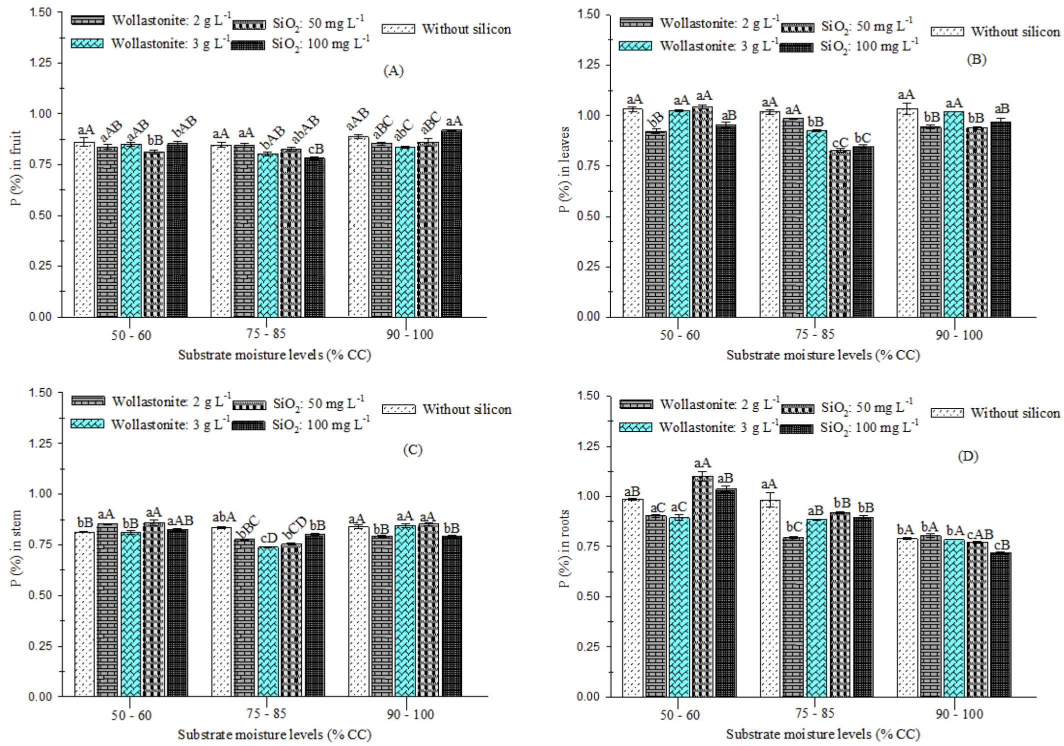

Figure 30. Effect of the interaction of silicon with the moisture of the substrate on the concentration of P in fruits (A), leaves (B), stems (C) and roots (D) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.3 Potassium (K) concentration

The concentration of K was greatest in the stems (2.57 % - 4.21 %), followed by the fruits (2.42 % - 3.35 %), the leaves (1.56 % - 1.97 %) and the roots (0.71 % - 1.57 %). In reference to the concentration of K in the stem, only the interactions of the lower moisture level with doses of 2 g L^{-1} wollastonite and 3 g L^{-1} wollastonite resulted in higher concentrations of K compared to the other doses of Si. These concentrations were greater than the treatment without Si by 23.9 % and 26.6 % respectively (Figure 8). In relation to the concentration of K in the fruits, there was no positive effect of the application of Si on this variable. The fruits of the plants not fertilized with Si presented K concentrations equivalent to those of the plants treated with Si. The two highest concentrations of K (1.90 % and 1.97 %) were observed in the leaves of the plant under the lowest moisture level with the doses 3 g L^{-1} wollastonite and 50 mg L^{-1} SiO_2, being respectively 9 % and 12 % superior to the K level in the leaves of the control treatment. The silica treatments did not favor the concentration of foliar K under the effect of the intermediate moisture level in the substrate. However, with the 50 mg L^{-1} SiO_2 dose, there was an increase in the concentration of K in the leaves of the plants at the highest moisture level, compared to the plants not treated with Si. In the root, the concentration of K (1.19 %) was 39.8 % more than in the treatment without Si, with the application of 50 mg L^{-1} SiO_2 at the lowest moisture level. The highest concentration of K (1.57 %) in the root was obtained with the interaction of 3 g L^{-1} wollastonite with the highest level of moisture in the substrate. This K concentration was 22.5 % higher than in the absence of Si. Under stress situations, such as drought, the concentration of K in plant tissue can be affected by Si (Barreto et al., 2017). Si increases K uptake in K-deficient plants and restores their physiological performance affected by K deficiency (Pavlovic et al., 2021). According to Miao, Han, and Zhang (2010), and Buchelt et al. (2020), the application of Si to soybean and forage crops increased the K content in their leaves. Also, Si modulates antioxidant enzymes, which reduce oxidative stress caused by lack of K, as well as lipid peroxidation of the membrane (Miao et al., 2010; Chen et al., 2016). Under the combined effect of K deficiency and osmotic stress induced by polyethylene glycol (PEG) in Barley (*Hordeum vulgare),* Si does not seem to reduce K deficiency (Hosseini et al., 2017). However, according to the same authors, the likely beneficial effect of Si identified was due to abscisic acid (ABA) homeostasis and increased activity of the cytokinin isopentenyladenine.

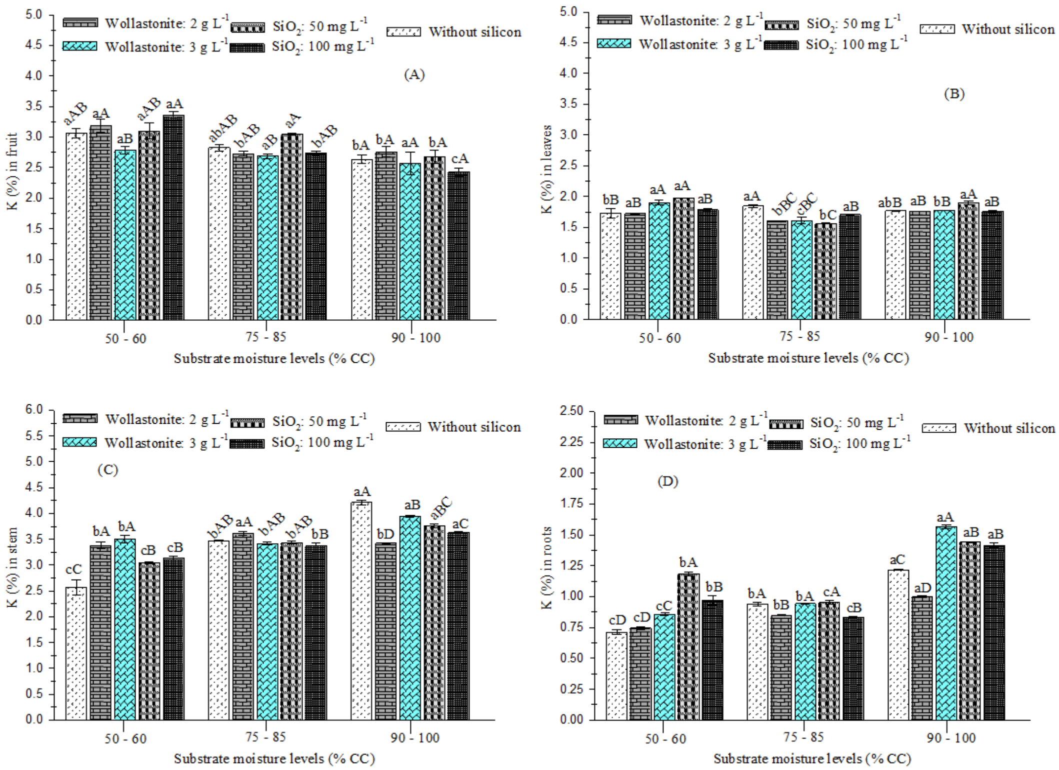

Figure 31. Effect of the interaction of silicon with the moisture of the substrate on the concentration of K in fruits (A), leaves (B), stems (C) and roots (D) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.4 Calcium (Ca) concentration

The leaves presented the highest concentration of Ca (3.27 % - 4.63 %), followed by the stems (1.53 % - 2.11 %), the roots (0.99 % - 1.15 %) and the fruits (0.33% - 0.45%). The interaction of 50 mg L^{-1} SiO_2 with the intermediate moisture level in the substrate favored a higher concentration of Ca (4.63%) in the leaves, 26.9 % greater than in the leaves of the plants not treated with Si (Figure 9). On the other hand, the Ca concentrations in the leaves of the plants that were not treated with Si were statistically equal to or greater than those treated with Si, at the low and high moisture levels. The interactions between the lowest moisture level and the 2 g L^{-1} wollastonite and 3 g L^{-1} wollastonite doses presented significantly greater Ca concentrations in the stem compared to the other Si doses. These concentrations were greater than the treatment without Si by 25 % and 17.6 %, respectively. The interaction between Si and substrate moisture did not affect the percentage of Ca in the root. The individual effect of Si did not affect the concentration of Ca in the root either (table 8). However, there was a higher concentration of Ca in the root of the plants treated with the two lowest moisture levels compared to the highest moisture level. Regarding Ca in fruits, its largest content (0.45 %) has been observed with the application of 50 mg L^{-1} SiO_2 at the intermediate moisture level, with a value 10.4 % more in relation to fruits not fertilized with Si. Various factors such as dose, species, type of stress, and study conditions affect the effects of Si on Ca (Pavlovic et al., 2021). In maize under water stress, Kaya, Tuna, and Higgs (2006) found that Si favors Ca absorption, while studies by Brackhage, Schaller, Bäucker, and Dudel (2013), Cooke and Leishman (2016), and Jang, Kim, Khan, Na, and Lee (2018) stated that Si does not affect or even reduce calcium accumulation. The application of increasing doses of Si to rice (*Oryza sativa* L.) and common reed (*Phragmites australis*) decreased the Ca content accumulated in plant tissues (Brackhage et al., 2013; Jang et al., 2018). Dishon, Zohar, and Sivan (2011), and Fleck et al. (2015) attributed this reduction to the effects of the interaction between Si and Ca in the growth medium or in the apoplast of the plant and decreased Ca uptake due to the biosilicification of the root structures of the plant.

Table 28. Individual effects of silicon and moisture in the substrate on Ca concentration in the roots of cucumber

Doses of Si	Ca (%) in roots
0	1.28 ± 0.14 a
2 g L^{-1} Wollastonite	1.18 ± 0.06 a
3 g L^{-1} Wollastonite	1.14 ± 0.05 a
50 mg L^{-1} SiO_2	1.33 ± 0.05 a
100 mg L^{-1} SiO_2	1.24 ± 0.07 a
Humidity (% CC)	
50 - 60	1.35 ± 0.05 a
75 - 85	1.35 ± 0.04 a
90 - 100	1.00 ± 0.04 b

Different letters in the columns represent significant differences between treatments at a 5% level, by Tukey's test.

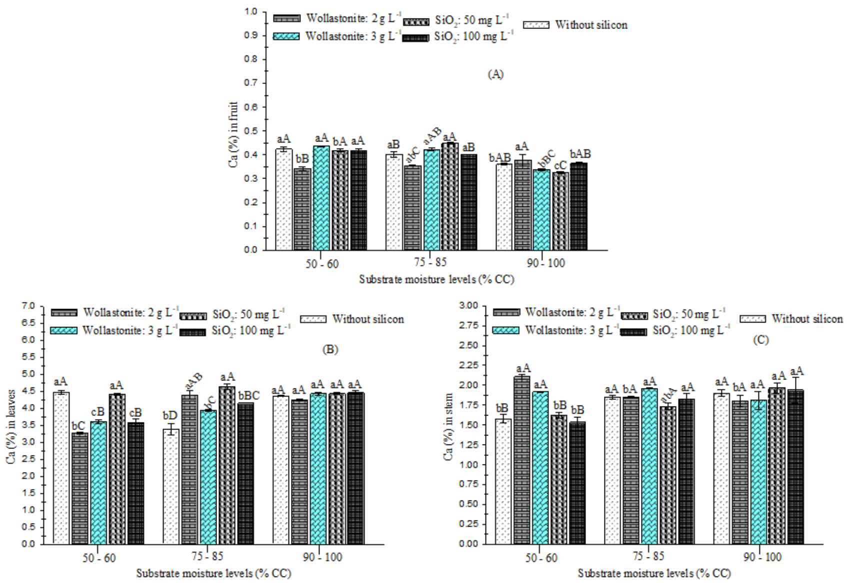

Figure 32. Effect of the interaction of silicon with the moisture of the substrate on the concentration of Ca in fruits (A), leaves (B), stems (C) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.5 Magnesium (Mg) concentration

The Mg concentration was highest in the leaves (0.79 % - 1.41%), followed by the stems (0.71 % - 1.18 %), the roots (0.49 % - 0.83 %) and the fruits (0.36 % - 0.47 %). The Mg levels in the leaf increased with the application of Si. The doses of 2 g L^{-1} of wollastonite and 100 mg L^{-1} of SiO_2 were substantially more successful than the treatment without Si at the lowest moisture level, with respective Mg concentrations of 1.29 % and 1.27 % in the leaves of the plant (Figure 10). Likewise, at the intermediate moisture level, each of the doses of 2 g L^{-1} of wollastonite, 3 g L^{-1} of wollastonite and 50 mg L^{-1} of SiO_2 showed foliar concentrations of Mg (1.34 %, 1.41 % and 1.35 %), greater than the control treatment, respectively. The highest concentration of Mg (1.41 %) in the leaves was produced at the intermediate moisture level with the application of 3 g L^{-1} wollastonite. Likewise, the 3 g L^{-1} wollastonite dose outperforms the other treatments at the biggest humidity level. In the stem, Si increases the concentration of Mg at the highest and lowest moisture levels in the substrate. With the application of 3 g L^{-1} of wollastonite or 50 mg L^{-1} of SiO_2, at the biggest moisture level, or 2 g L^{-1} of wollastonite, at the lowest moisture level, the percentage of Mg in the stem was larger than in the treatment without Si. Si did not significantly affect the concentration of Mg in the roots of the plant at either of the two greatest levels of moisture in the substrate. At the lowest moisture level, root magnesium concentration increases for all Si doses. As compared to the treatment without SiO_2, the application of 100 mg L^{-1} SiO_2 at the lowest moisture level favors a higher Mg concentration in the root by 30.8 %. The highest Mg content (0.47 %) in the fruits, which was 9.6 % higher compared to the plants not treated with Si, was promoted by the interaction of 3 g L^{-1} of wollastonite with the intermediate moisture level. Pavlovic et al. (2021) stated that Si seems to influence Mg in different ways depending on species and environmental conditions. In a hydroponic system with optimal nutrient supply, Si increased Mg uptake and accumulation in the shoots of several plant species (Greger, Landberg, & Vaculík, 2018). Under water stress situations, various Si-fertilized sunflower (*Helianthus annuus*) cultivars accumulated higher Mg contents in their shoots compared to stressed plants not fertilized with Si (Gunes et al., 2008). Buchelt et al. (2020) attributed the effect of Si in cultivated forages with Mg deficiency to a greater efficiency in the use of Mg instead of a greater absorption of the element. Hosseini, Rad, Ali, and Yvin (2019) found no effect of Si supply on the absorption or translocation of Mg in maize plants, but according to the same authors its beneficial effects on chlorophyll levels, sugar metabolism and hormonal balance indirectly contributed to the development of Mg deficient plants. According to Pavlovic et al. (2021), so far, no evidence has been found that Si affects the expression of the Mg transporter.

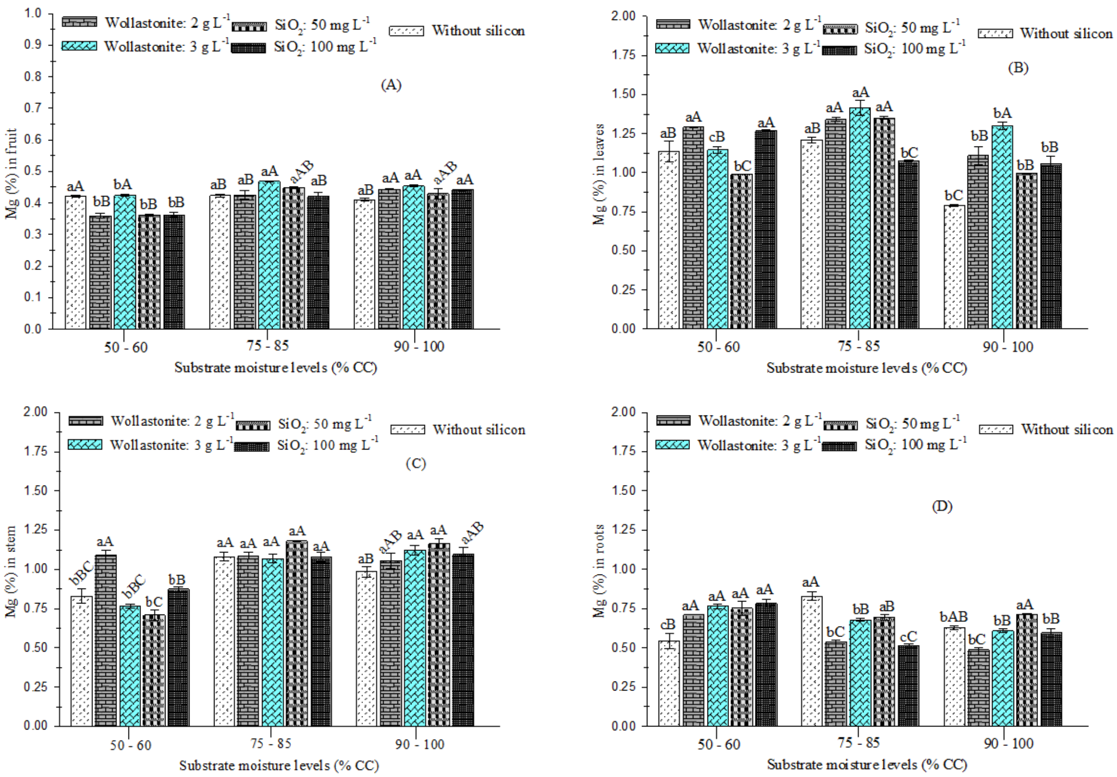

Figure 33. Effect of the interaction of silicon with the moisture of the substrate on the concentration of Mg in fruits (A), leaves (B), stems (C) and roots (D) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

3.4.6 Silicon (Si) concentration

The leaves presented the highest concentration of Si (3.37 % - 5.36 %), followed by the stems (1.04 % - 1.83 %), the fruits (0.30 % - 1.21 %) and the roots (0.52 % - 1.16 %). Regarding the Si concentration in the leaves, only the application of 3 g L^{-1} wollastonite increased the Si content under the effect of intermediate moisture (Figure 11). The doses of Si did not generate an increase in the concentration of Si in the leaves in relation to the treatments without Si at the other moisture levels. In the stem, among the different doses of Si, only 100 mg L^{-1} SiO_2 when interacting with the lowest moisture level favored a more significant Si content. At other moisture levels, there was no difference between the effects of Si doses on the Si concentration in the stem. Under intermediate and higher levels of moisture in the substrate, positive effects of Si on its concentration in the fruit have been observed. With the application of 50 mg L^{-1} SiO_2 and under the highest level of moisture in the substrate, Si content in the fruit has been found to be 22 % superior to the treatment without Si. With the intermediate moisture level in the substrate, the doses of 2 g L^{-1} wollastonite, 50 mg L^{-1} SiO_2 and 100 mg L^{-1} SiO_2 generated Si concentration in the fruit respectively 46.3 %, 42.7 % and 47.2 % more than the treatment without Si, which was not the case for the silicic treatments under the lowest moisture level where Si concentrations in the fruit were lesser than the control treatment. Si does not positively affect the concentration of Si in the roots of the plant at either of the two highest levels of moisture in the substrate. For the concentration of Si in the roots, at the lowest moisture level, there was only an increase in its level in the roots with the dose of 50 mg L^{-1} SiO_2. The application of 50 mg L^{-1} SiO_2 at the lowest moisture level increased the concentration of Si in the root by 53.3 % compared to the treatment without Si. Silicon fertilization can increase the concentration of the element in plant tissues, but very high doses can generate an antagonistic effect (Oliveira, et al., 2019). The contents of Si in plant tissues can vary depending on the applied dose (Oliveira et al., 2019), the genetics and the absorption mechanisms of each plant (Hodson, White, Mead, Broadley, 2005). The distribution of Si in the shoots of the plant is regulated by several factors among which is transpiration (Ma and Yamaji, 2006). In leaves of cucumber plants treated with wollastonite, Dorais and Thériault (2018) reported Si content between 0.48 % and 3.05 %, which were higher than those observed in leaves of plants not supplemented with Si. In the fruits of plants treated with Si, Si concentrations between 0.04 and 0.14 % were observed, while in the fruits of control plants Si was not detected (Dorais and Thériault, 2018). Abd-Alkarim et al. (2017) found Si concentration between 1.30 % to 1.55 % in leaves and between 0.94 % to 1.65 % in cucumber fruits grown with different doses of Si. The leaves of the cucumber plant accumulate more Si than the fruits, which agrees with the results of studies by Górecki and Danielski-Busch (2009), Terraza et al. (2009), Abd-Alkarim et al. (2017), Dorais and Thériault (2018). However, Shalaby et al. (2021) contradict this trend by reporting a higher Si content in the fruits (9.80 % to 10.87 %) of cucumber compared to the leaves (6.01 % to 7.86 %). There is no consistency between authors in the Si concentration data reported in the different parts of the cucumber plant.

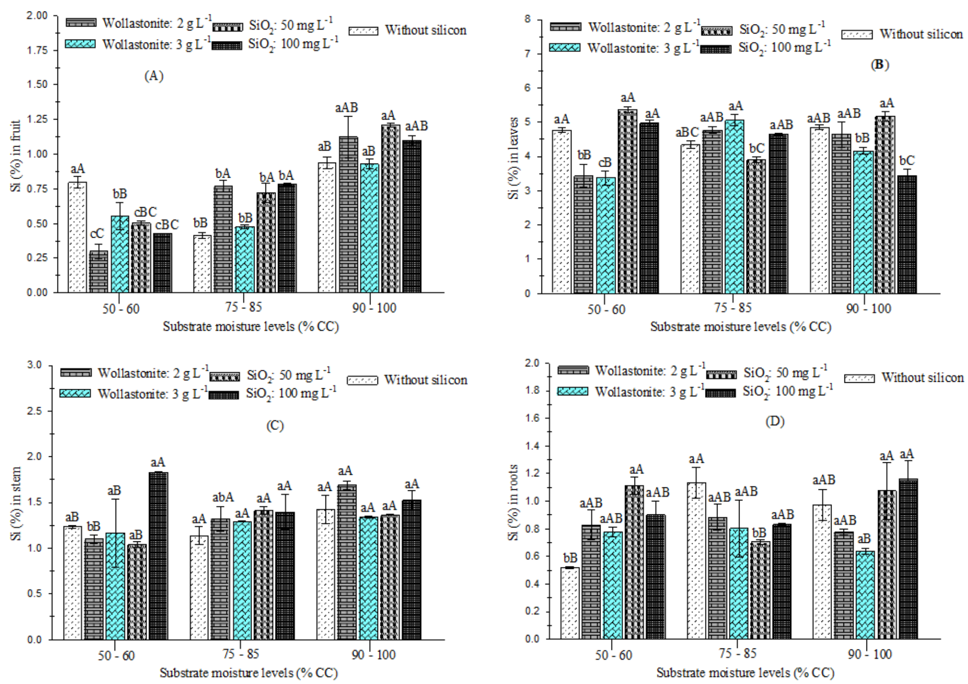

Figure 34. Effect of the interaction of silicon with the moisture of the substrate on the concentration of Si in fruits (A), leaves (B), stems (C) and roots (D) of cucumber. Lower case letters compare the moisture levels with each other for each silicon dose and upper-case letters compare the silicon doses with each other for each moisture level. Standard error of the mean is represented by the error bars.

4. Conclusion

Under the intermediate moisture level in the substrate, 3 g L^{-1} of wollastonite increased fruit production by 24.9 % in comparison to Si-untreated plants.

As moisture levels were reduced, the diameter and average weight of the fruits decreased slightly (3.4 % and 11.7 %, respectively), while soluble solids concentrations increased (8.8 %), and the length of fruits was not affected.

At the lowest moisture level, 100 mg L^{-1} SiO_2 generated 11.8 % more dry biomass than the control. Furthermore, when the plant was fertilized with 50 mg L^{-1} SiO_2, aerial biomass production was 9 % higher than when no Si was applied.

The presence or absence of Si did not affect the root production of the plant.

Si positively influences chlorophyll a, b, and total content in leaves, specifically at the lowest moisture level in the substrate.

When plants were given 100 mg L^{-1} SiO_2, the relative water content in the leaves increased by 11.9 % only when the substrate had the highest moisture level.

The interaction between Si and the moisture in the substrate significantly increased N, P, K, Ca, Mg and Si concentrations in different parts of the plant, with major significant effects under the lowest moisture level in the substrate.

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5. CONCLUSIONES GENERALES

En el segundo ensayo, el Si aumentó la producción de frutos de pepino mientras que en el primer ensayo la reducción del riego disminuyó la producción de frutos y los sólidos solubles totales.

El uso de Si mejoró la producción de biomasa seca aérea, el área foliar y la producción de raíz de las plantas, en el primer ensayo, principalmente en condición de déficit hídrica.

Bajo los niveles de humedad 55-65 % CC y 75-85 % CC en el sustrato, el Si mejoró la concentración de N, P, K y Mg en los frutos, P y K en las hojas, y N y K en los tallos de las plantas de pepino, bajo las condiciones de este estudio, en ambos ensayos.

Bajo el nivel de humedad entre 75-85 % CC y la dosis 3 g L^{-1} de wollastonita, la producción de frutos incrementó en un 24.9 % comparada con plantas no tratadas con Si.

El diámetro y el peso promedio de los frutos disminuyeron con la reducción del riego, mientras que las concentraciones de sólidos solubles aumentaron y no afectó a la longitud de los frutos.

La biomasa seca aérea de las plantas tratadas con Si, en el nivel de humedad entre 50-60 % CC, aumentó en comparación con las plantas del tratamiento control.

El Si influyó positivamente el contenido de clorofila a, b y total en las hojas, específicamente en el rango de humedad entre 50-60 % CC.

El contenido relativo de agua en las hojas de la planta aumentó con la dosis 100 mg L^{-1} de SiO_2 y un nivel de humedad en el sustrato entre 90-100 % CC.

La interacción entre el Si y la humedad en el sustrato aumentó significativamente las concentraciones de N, P, K, Ca, Mg y Si en diferentes partes de la planta, con mayores efectos bajo el rango de humedad entre 50-60 % CC del sustrato.

La aplicación de Si, vía raíz, afectó positivamente los parámetros de productividad y biométricos (producción de frutos, área foliar, biomasa seca aérea y de raíz), fisiológicos (contenidos de clorofila a, b, total y contenido relativo de agua en las hojas) y nutricionales (concentraciones de N, P, K, Ca, Mg y Si en los tejidos foliares) bajo condiciones limitadas de agua, por lo que se le puede considerar como una alternativa viable para reducir los impactos del déficit de riego en el cultivo de pepino en condiciones de invernadero.