# Investigating the role of Si as a biostimulant in hydroponic production systems

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# Investigating the role of Si as a biostimulant in hydroponic production systems.

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# Abstract

The global population is growing, and current food production needs to keep up. This is harder when we are experiencing environmental stresses and land degradation. These challenges led growers to choose greenhouse and soilless cultivation methods, such as hydroponics. However, even these systems are susceptible to stressors that negatively affect the plant. For this reason, biostimulants and performance-enhancing products are being used to improve plant responses under stressful conditions. Silicon is a biostimulant that has the potential to improve the growth, physiology, and yield of several crops. In this study, the aim was to investigate how silicon would behave when supplied to tomato and pea plants, in both stressed and non-stressed conditions. The results showed that silicon had positive effects on both crops, but the effects varied in intensity by crop, concentration, stress level, and application method. Higher concentrations do not necessarily yield better results, and lower concentrations can yield comparable or better results. In tomato plants, the effects of a current market product, Actisil, were also investigated. Actisil tended to form a gel-like layer in the nutrient solution, resulting in inhibition of all studied parameters. This study may provide insight into dose-dependent effects in tomato and pea crops in hydroponic systems.

*Keywords:* Actisil, pea, salinity, silicon, stress, tomato

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# Abbreviations

| Abbreviation | Description |
|---|---|
| Ca | Calcium |
| NaCl | Sodium Chloride |
| BMD | Bone mineral density |
| EC | Electrical conductivity |
| iWUE | Intrinsic water use efficiency |
| ANOVA | Analysis of variance |
| PCA | Principal component analysis |
| FAO | Food and Agriculture Organisation of the United Nations |
| Si | Silica |
| WUE | Water Use Efficiency |
| $CaSiCO_3$ | Calcium silicate |
| $CO_2$ | Carbon dioxide |
| $H_4SiO_4$ | Monosilic acid |
| $SiO_2$ | Mineral silicates |
| KOH | Potassium hydroxide |
| $H_2SO_4$ | Sulfuric acid |
| gs | Stomatal conductance |
| A | Carbon dioxide assimilation |

# 1. Introduction

The global population is increasing rapidly, requiring agricultural production to keep up with current demand. The Food and Agriculture Organisation of the United Nations (FAO) has estimated that production needs to increase by 60 per cent from 2006 levels to meet the demand projected for 2050 (FAO 2016). However, food production is not in line with current needs due to the decline and degradation of agricultural land and the effects of climate change on crops (FAO 2016; Fatemi et al. 2020). Recent global disruptions, such as COVID-19, further underscored the vulnerability of food systems to external shocks, exposing their weaknesses across the agrosystem. This accentuated the impact of food demand on an agrosystem and the need to strengthen it through more sustainable, intensive and resilient food production practices (FAO 2021). In response to this impact, food systems must address two major problems: ongoing land degradation and increasing plant stress (Fatemi et al. 2020; FAO 2025).

Land degradation reduces the amount of fertile land for agricultural production, and although soil restoration strategies are currently underway, they are insufficient to meet future demands without exhausting resources. Therefore, new agricultural practices have emerged as alternatives to soil-based ones, among which are hydroponic systems (Casamayor et al. 2024). Hydroponic systems are a technique for growing plants in a nutrient solution, with or without a soilless substrate for support. This system has many advantages, including year-round crop production, minimal pesticide use, adaptability across diverse locations, and higher water and energy efficiency, all of which contribute to sustainability (Khan 2018; Niu & Masabni 2022; Rajaseger et al. 2023; Casamayor et al. 2024). These systems improve control over growing conditions by creating controlled environments, but remain vulnerable to waterborne diseases, algae growth, and salinity stress, which affect plant yield and quality (Khan 2018). Therefore, optimising hydroponic systems to enhance crop quality and stress tolerance has become the focus, leading to increased interest in the use of biostimulants.

Biostimulants are defined as "(…) an EU fertilizing product the function of which is to stimulate plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: nutrient use efficiency, tolerance to abiotic stress, quality traits or availability of confined nutrients in the soil rhizosphere." *(Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 2019)* Biostimulant products may include humic substances, seaweed extracts, hydrolysed proteins, organic and inorganic compounds, microorganisms (Ertani et al. 2021; Ramawat &

Bhardwaj 2022; İkiz et al. 2024), and any other substances approved under European Union regulations that demonstrate the above-mentioned results. In this thesis, silicon (Si), a beneficial element, is investigated as a biostimulant to improve crop performance and stress tolerance, specifically under salinity stress (Bulgari et al. 2019; Rouphael & Colla 2020; Ertani et al. 2021).

Silicon (Si) is the second-most-abundant element in Earth's crust, after oxygen. It can be found in several forms but is taken up by plants as monosilicic acid ($H_4SiO_4$) and translocated from roots to shoots (Guntzer et al. 2012; Rodrigues & Datnoff 2015; Debona et al. 2017). Despite all this being known, as well as its benefits for plant structure and stress resilience, silicon is still not considered an essential element and is therefore not included in most conventional fertiliser practices today (Ma & Yamaji 2008). Silicon has been shown to enhance plant performance under a range of stress conditions. For example, it preserves photosynthesis, leaf water content, transpiration rate in tomato plants (Shi et al. 2016), and decreases concentrations of $Na^+$ and $Cl^-$ in leaves, stem and roots of tomato seedlings (Li et al. 2015) under salinity stress, and increases water-use efficiency (WUE) in maize under drought stress (Gao et al. 2006). In addition to abiotic stress tolerance, silicon also contributes to plant defence against biotic stress. High-Si diets have been shown to reduce leaf digestibility and increase mandible wear in African armyworms (*Spodoptera exempta*) (Massey & Hartley 2009), while Si supplementation can reduce disease severity in infections such as powdery mildew and root rots (A. Rodrigues et al. 2015; Fortunato et al. 2015). Nevertheless, some regions have adopted silicon fertiliser, particularly in Japan and other Asian countries, where its benefits for rice cultivation have been well documented (Snyder 1996; Ma & Takahashi 2002b; Hu et al. 2023). In recent decades, research interest in silicon has increased (Epstein 2009; Coskun et al. 2019), leading to its inclusion in biostimulant formulations and new fertiliser products. This highlights silicon's potential for use in soilless cultivation systems, where its application has been associated with improved stress tolerance, physiological performance, and crop productivity (Ertani et al. 2021). However, important knowledge gaps remain regarding its role as a biostimulant under hydroponic conditions and specific abiotic stresses.

## 1.1 Objective

Despite increasing interest in silicon (Si) as an element and biostimulant in crop production, the extent to which silicon accumulation in edible tissues is related to dietary exposure, its role in plant physiology and its application in hydroponic systems – particularly under salinity stress - regarding effects on plant growth remains insufficiently characterised. Therefore, future research is required to better understand silicon application strategies in hydroponic nutrient solutions, understand plant uptake and distribution patterns, and evaluate potential food safety implications in edible horticultural crops. This study aims to evaluate the effects of silicon supplementation on pea and tomato plants in a hydroponic system, with particular focus on plant growth physiology, biomass allocation, yield, and stress resistance.

### 1.1.1 Research Questions

1. How does silicon supplementation affect plant growth, physiological performance, and overall plant health in hydroponic cultivation?
2. What is the potential of silicon as a biostimulant for sustainable hydroponic production systems?
3. Does silicon application improve tolerance to salinity stress in a hydroponic system?
4. Do silicon application effects differ on crop and application method?

### 1.1.2 Hypotheses

H1: Silicon supplementation enhances vegetative growth and physiological performance, compared to plants grown without silicon.
H2: Silicon supplementation alters biomass allocation, resulting in increased root, shoot, and/or reproductive organ biomass under hydroponic conditions.
H3: Silicon application improves plant tolerance to salinity stress by mitigating its negative effects on growth, physiology, and biomass accumulation.
H4: Silicon is an effective biostimulant in hydroponic production systems, contributing to improved plant performance without adverse effects on plant development.

# 2. Background

Silicon (Si) was known to be part of soil composition, but its presence in plants was documented in the early 1800s, when Davy (1816) reported that silicon was present in several species in varying amounts. Later studies by Grob (1896) and others observed that the distribution of silicon within plant tissues suggested a protective role against diseases and pests (Ma & Takahashi 2002a; Martin 2013; Rodrigues & Datnoff 2015; Debona et al. 2017). Since then, research interest in this element has increased, focusing on its uptake, allocation and effects on plant stress tolerance, resistance and suppression. Although not classified as an essential element, it can be considered a quasi-essential (Meena et al. 2014) element as there is no evidence of its interference in the plant's life cycle, but it still shows an enhancement in plant performance (Epstein 1999).

## 2.1 Si plant uptake and functions

Silicon is a tetravalent metalloid predominantly present in soils as mineral silicates ($SiO_2$), which are gradually weathered into monosilicic acid ($H_4SiO_4$), a form available for plant uptake (Rodrigues & Datnoff 2015; Debona et al. 2017). The concentration of monosilicic acid in soil ranges from 14 to 20 mg Si/L, depending on soil type, pH, and properties and composition (Broadley et al. 2012; Debona et al. 2017). The extent of silicon uptake varies with plant species and growth stage (Guntzer et al. 2012; Debona et al. 2017). Striegel (1912) noted species-specific differences in their silicon (Si) and calcium (Ca) mineral composition, showing that monocot species (all Graminae plants) accumulated high Si content but low Ca concentrations, whereas dicot species showed the opposite pattern. Based on these results, Ma and Takashi (2002) categorised plant species into three groups based on their silicon content and Si/Ca ratio: Si-accumulators (>1% Si), intermediate accumulators (0.5-1% Si), and Si-excluders (<0.5% Si) (Ma & Takahashi 2002b). Plants absorb monosilicic acid through different mechanisms (Broadley et al. 2012; Rodrigues & Datnoff 2015). Recent research has identified specific Si transporters involved in silica uptake, with their locations varying among plant species (Ma & Yamaji 2008; Guntzer et al. 2012; Rodrigues & Datnoff 2015; Zexer et al. 2025). Si transporters were first identified in rice, where monosilicic acid uptake was observed via two transporters, found in its roots. They are typically located in epidermal, hypodermal, and cortical cells, or in the root's basal regions, often in close proximity to one another (Ma & Yamaji 2008; Broadley et al. 2012). In some species, silicon uptake was observed against the concentration gradient, suggesting energy-dependent active uptake (Guntzer et al. 2012). Foliar Si uptake is also possible, with a transporter expressed in both leaf sheaths and blades, but that can also be found in roots and shoots. After root or leaf uptake, Si is translocated through the xylem, and its distribution is determined by the organ's age and the plant's transpiration rate (Broadley et al. 2012). Most Si is deposited in the apoplast as amorphous silica, accumulated in the epidermal cells, where it contributes to a barrier to water loss, and on both leaf surfaces and within specialised cells, forming structures known as silica cells or phytoliths. The remaining silica is found as polymerised silica after transport as monosilicic acid. Phytoliths are found in locations where transpiration occurs directly, such as the leaf epidermis. In reproductive organs, silicon can accumulate in trichomes, inflorescence bracts, brush hairs, and grain tissues. (Ma & Yamaji 2008; Broadley et al. 2012; Rodrigues & Datnoff 2015)

## 2.2 Si accumulation effects

Silicon (Si) accumulation in plant organs influences a range of physiological and biochemical processes related to plant growth, stress tolerance, disease resistance, and defence (Avestan et al. 2019). Si fertilisation has been shown to stimulate plant growth and yield in direct and indirect ways, such as enhanced seed germination and increased biomass (Ismail et al. 2022). Several papers reported increased growth and biomass compared to untreated controls, while others observed this increase relative to stress conditions (salt, drought, metal toxicity), suggesting that Si benefits depend on plant species and that its positive effects are more pronounced under stress (Broadley et al. 2012; Meena et al. 2014; Avestan et al. 2019; Ismail et al. 2022). Salinity stress from sodium chloride (NaCl) disrupts root osmotic balance, limiting water uptake and leading to plant dehydration (Ahlawat et al. 2024). Many modern cultivars are increasingly tolerant of salinity stress, but productivity can still be negatively affected. Silicon has been shown to mitigate salinity stress by inhibiting $Na^+$ transport to leaves, reducing $Na^+$ accumulation in roots, and improving ionic balance (Guntzer et al. 2012). Its application is associated with improved photosynthetic performance, increased antioxidant activity, and increased chlorophyll content, responses which contribute to improved growth and yield under saline conditions (Hashemi et al. 2010). Similar benefits have been reported for abiotic stresses, such as metal toxicity, and for biotic stresses, including fungal diseases, such as powdery mildew (Guntzer et al. 2012; Ouellette et al. 2017). Silicon improves plant health by regulating the uptake and distribution of toxic ions, strengthening structural barriers through silica deposition in tissues that form a protective outer layer, and enhancing plant defence responses (Guntzer et al. 2012).

## 2.3 Food safety

Although research on silica as a stimulant or on its effects on plants has increased, research addressing human health implications has not kept pace. Current research suggests that silicon levels in food do not pose known health risks, although toxicity thresholds have not yet been defined (Filgueiras 2007; Jugdaohsingh 2007; Martin 2013; Sadowska & Świderski 2020). 26/06/2026 13:09:00Much of the research on the dietary silicon benefits of silica for human health has focused on its role in bone mineral density (BMD) (Martin 2013). Silicon is naturally present in many foods and beverages, such as cereals and beer, resulting in an estimated average daily intake of approximately 20-50 mg Si/day in Western countries and 140-204 mg/day in several Asian countries (Jugdaohsingh 2007). These intake levels are higher than the quantities of silicon applied during production as a fertiliser or biostimulant. Research has also shown that silicon metabolism and absorption may change with age, and that low-silicon diets are associated with reduced bone mineral density (BMD), whereas a balanced silicon intake improves BMD (Jugdaohsingh et al. 2004; Jugdaohsingh 2007). Most dietary silicon is from commonly consumed foods and beverages, including vegetables (0.1-8.73 mg Si/100 g), fruits (0.1–4.77 mg Si/100 g), drinking tap water (0.065-0.61 mg Si/100 g), and grains (0.34-23.36 mg Si/100 g) (Powell et al. 2005; Meena et al. 2014). Therefore, evaluating how silicon accumulates in plant tissues following silicon fertilisation is important for assessing agronomic benefits and potential food safety implications.

## 2.4 Silicon in hydroponic systems

In controlled cultivation systems such as hydroponics, supplementation with biostimulants, such as silicon, has increasingly received attention due to its reported benefits for plant growth, stress tolerance and productivity (Niu & Masabni 2022). However, because silicon is not classified as an essential element, it is not routinely included in standard hydroponic nutrient solutions. As a result, uncertainty remains regarding its plant uptake dynamics in soilless systems, its tissue accumulation in edible tissues, and its implications for human consumption (Niu & Masabni 2022; Rajaseger et al. 2023). Silicon application in hydroponic systems has been studied in crops such as lettuce (Subandi et al. 2021), sugarcane (Ashraf et al. 2010), maize (Vaculík et al. 2009), canola (Hashemi et al. 2010), peas (Ismail et al. 2022; Kumar et al. 2025), and tomato (Romero-Aranda et al. 2006; Baioui et al. 2025). Most studies report greater improvements in plant growth and biomass under salt stress than in non-saline controls. Under control treatments, Si addition shows a slight increase in vegetative growth; however, more pronounced effects were observed on certain crops. For example, tomato plants showed a 42% increase in stem length and a 31% increase in stem width (Baioui et al. 2025), and maize plants showed a 12% increase in wall extensibility (Vaculík et al. 2009). Greater differences were reported in biomass accumulation. Sugarcane showed increases in root dry matter of 40-500% and in shoot dry weight of 24-30% (Ashraf et al. 2010), while tomato plants showed an overall dry weight increase of 71% (Baioui et al. 2025). Aside from biomass, yield was also observed, including a 13.6% increase in peas (Ismail et al. 2022) and a higher number of fruits in Si-treated plants, compared to those exposed to salinity stress without Si supplementation. Although total water content does not appear to be significantly affected, its distribution within plant tissues may be altered. In addition, silicon application has been associated with improvements in physiological parameters. Increases of up to 23% in chlorophyll synthesis and 72% in carotenoid production under non-stress conditions (Baioui et al. 2025), indicating enhanced chlorophyll content (SPAD values) and photosynthetic activity. These studies generally report positive effects on plant growth, biomass, yield, stress resistance, and fruit quality, suggesting that silicon improves crop performance and biofortification under controlled conditions.

# 3. Methods

## 3.1 Experimental design

The experiment on the use of silicon in hydroponic systems was conducted with two crops: peas (*Pisum sativum* L.), due to their sensitivity to salt, and tomatoes (*Solanum lycopersicum* L.), due to their longer production period. The following sections describe the hydroponic systems and experimental design used for each crop, with the aim of evaluating the effects of silicon supplementation on plant performance under hydroponic conditions. This paper was written using AI tools: Grammarly for phrase and language correction, and ChatGPT for facilitating searches on specific topics.

### 3.1.1 Pea (*Pisum sativum* L., var. Norli)

The experiment was conducted over six weeks in a hydroponic system under greenhouse conditions, using a completely randomised design with 12 treatments and five replicates per treatment, resulting in 60 experimental units. Greenhouse conditions were controlled throughout the weeks, during which the plants received a minimum of six hours of natural light, supplemented with artificial lighting to ensure 10 to 12 hours of light for growth. The temperature was maintained between 20 and 22ºC at all times, and humidity was not monitored. The hydroponic system consists of 6 rows of 10 vases, each labelled with 12 different treatments as explained in Table 1 and the vases are randomly placed. Four tubes were attached to air pumps and connected to the vases to continuously supply oxygen to the roots during the experiment, ensuring equal aeration across all vases.

In the first week, the plants were sown in vermiculite and watered as needed. Once the plants had germinated after the initial week, they were transferred to the vases, placed in foam circles so they would float in the nutrient solution added to the vases. The nutrient solution used was a standard Hoagland solution containing equal amounts of Calcinit and Kristalon to achieve a pH of 6 to 6.5 and an electrical conductivity (EC) of 1.5 dS/m. They remained in the nutrient solution without added treatments for a week to allow the plants to adjust to the new growing environment. After their adjustment to the solution, the solution was replaced with a new one, this time a mix of the nutrient solution and the added treatments. Each treatment was performed according to Table 1, with five vases per treatment, each containing only one plant. After this change, the plants were left under the treatments for the following weeks, with top-ups as required, regular pH and EC checks, and adjustments as needed, until it was possible to conduct a first harvest or the plants withered. Harvest time was set on the same day for each plant and treatment and was determined by the last plant to enter this growth stage, as indicated by a full, mature pod.

*Table 1 – Experimental treatments applied to pea plants (Pisum sativum L.) and corresponding label and code used throughout the study.*

| Treatment | Explanation |
|---|---|
| Control | Nutrient solution |
| A | 150 mM of NaCl + Nutrient solution |
| B | 200 mM of NaCl + Nutrient solution |
| C | 1mM of $CaSiO_3$ + Nutrient solution |
| D | 2,5mM of $CaSiO_3$ + Nutrient solution |
| E | 3mM of $CaSiO_3$ + Nutrient solution |
| F | 1mM of $CaSiO_3$ + 150mM of NaCl + Nutrient solution |
| G | 1mM of $CaSiO_3$ + 200mM NaCl + Nutrient solution |
| H | 2,5mM of $CaSiO_3$ + 150mM NaCl + Nutrient solution |
| I | 2,5mM of $CaSiO_3$+ 200mM NaCl + Nutrient solution |
| J | 3mM of $CaSiO_3$+ 150mM NaCl + Nutrient solution |
| K | 3mM of $CaSiO_3$+ 200mM NaCl + Nutrient solution |

### 3.1.2 Tomato (*Solanum lycopersicum* L., var. Hildaris F1)

The experiment was conducted over six weeks in a manner similar to the previous experiment, with regard to the hydroponic system, sample size, and greenhouse conditions. In this experiment, fewer treatments with salt (NaCl) and $CaSiO_3$ were done; instead, they were replaced with the addition of a current market product – YaraVita Actisil - that contains silicon in a concentrated form. The treatments and amounts were done as indicated in Table 2. Each treatment was mixed individually in 10 L buckets of nutrient solution, with five replicates per treatment. We aimed for a constant pH between 6 and 6.5 and an EC of 1.5 dS/m or 9 dS/m for plants under salt stress. The Actisil treatment was performed according to the product's labelled instructions. All plants were left under the treatments for the coming weeks, with regular pH and EC checks and adjustments as needed, using potassium hydroxide (KOH) as the base and sulfuric acid ($H_2SO_4$) as the acid.

*Table 2 – Experimental treatments applied to tomato plants (Solanum lycopersicum L.) and corresponding label and quantities for a 10 L hydroponic mix used throughout the study.*

| Treatment | Explanation |
|---|---|
| Control | Nutrient solution |
| A | 350 mM of NaCl + Nutrient solution |
| B | 0,1g of $CaSiO_3$ with leaf application + Nutrient solution |
| C | 0,1g of $CaSiO_3$ with root application + Nutrient solution |
| D | 1 g of $CaSiO_3$ with leaf application + Nutrient solution |
| E | 1 g of $CaSiO_3$ with root application + Nutrient solution |
| F | Actisil + Nutrient solution |

| | |
|---|---|
| G | 0,1g of $CaSiO_3$ + 350 mM of NaCl with leaf application + Nutrient solution |
| H | 0,1g of $CaSiO_3$ + 350 mM of NaCl with root application + Nutrient solution |
| I | 1 g of $CaSiO_3$ + 350 mM of NaCl with leaf application + Nutrient solution |
| J | 1 g of $CaSiO_3$ + 350 mM of NaCl with root application + Nutrient solution |
| K | Actisil + 350 mM of NaCl + Nutrient solution |

## 3.2 Measurements

### 3.2.1 Growth and morphological traits

Plant height and stem thickness data were recorded during the experiments. Height was measured once per week with a standard ruler from the stem base to the highest apical meristem, given in centimetres (cm). Stem thickness was measured at the base of the stem in millimetres with a digital caliper. All measurements were done on all plants.

### 3.2.2 Leaf chlorophyll content

Chlorophyll content was measured with a chlorophyll meter (Apogee Instruments MC-100 chlorophyll concentration meter, Utah, USA), three times a week, during both experiments on the youngest mature leaf. The data was recorded using chlorophyll index (SPAD) values.

### 3.2.3 Gas exchange parameters

Gas exchange on the leaf was measured every two weeks during the experiments using a LI-COR infrared gas analyser (LI-COR PRO), resulting in a total of two measurements. We recorded stomatal conductance and $CO_2$ assimilation rate. Each measurement took 15 minutes per plant. Using these two parameters, we calculated their ratio to obtain the intrinsic water use efficiency (iWUE).

### 3.2.4 Biomass

For biomass measurements, the dry and fresh weights of roots, shoots, and pods were measured using a balance with 0.01 g precision. The roots and shoots of every plant were separated at the base of the stem and weighed for their fresh weight. After weighing the fresh weight, the different pea plant parts were placed in labelled bags, with the corresponding treatment and plant part, for oven-drying. Pea stems and roots were weighed and dried in constructed aluminium foil bags, and tomato shoots and roots were separated into paper bags and aluminium foil bags, respectively. Oven-drying was performed at 60 °C for pea plants and at 90 °C for tomato plants until the roots, shoots, and pods reached a constant mass. From the dry weight of the roots and shoots, a root/shoot ratio was calculated by dividing the root dry weight by the shoot dry weight.

### 3.2.5 Yield components

Once pea plants reached the harvest stage, the number of mature pods per plant was counted, more closely reflecting growers' actual first harvest in a production context. To show the overall harvest, the total number of pods, mature and non-mature, was counted. Tomato yield components included the number of fruits and flowers produced by each plant. These measures represent each plant’s yield and are recorded as numbers without explicit units.

## 3.3 Data analysis

All data were analysed using MiniTab and R software. Using Minitab’s data analysis tools, analyses of variance (ANOVAs), pairwise comparisons, and correlation were performed on the collected data to evaluate the effects of the treatments. One-way ANOVA was performed in all variables apart from photosynthesis, where a mixed effects model was performed on variables of carbon dioxide ($CO_2$) assimilation and stomatal conductance (gs) recorded in two separate weeks. The mixed effects model assumed plant as a random factor and week and treatment as fixed factors. All analyses were conducted at a statistical significance level of $p \leq 0.05$, assuming normality and homogeneity of variance, to test for significant differences between treatments. Treatments that showed a significant difference underwent a Tukey post hoc test to identify pairwise differences. Pairwise comparisons were performed on the treatments that showed significant differences on post hoc tests. Correlation analysis was performed on parameters obtained directly from experimental results in both crops.

# 4. Results

The responses to silicon supplementation were evaluated in both pea and tomato plants; however, because of differences in measurement parameters and treatments used, the results are presented separately.

## 4.1 Pea (*Pisum sativum* L., var. Norli)

### 4.1.1 Plant growth

*Height*

Plant height in pea (*Pisum sativum*) was measured over a four-week time period. Over this period, plant height increased across all treatments (Figure 1). Under control conditions, plants reached a mean height of 43 ± 7.1 cm by week four. Salinity stress reduced growth, specifically when 200 mM salt was added, with plants reaching 39 ± 2.7 cm. In contrast, Si-supplied plants under non-stress conditions increased overall height, reaching a maximum of 46.2 ± 5.2 cm for plants treated with 2.5 mM of silica. Under stress conditions, silica partially mitigated reductions of plant height. Si-treated plants stressed with 150 mM NaCl showed values comparable to or slightly higher than those in NaCl-only treatments, while greater variability was observed at higher stress levels.

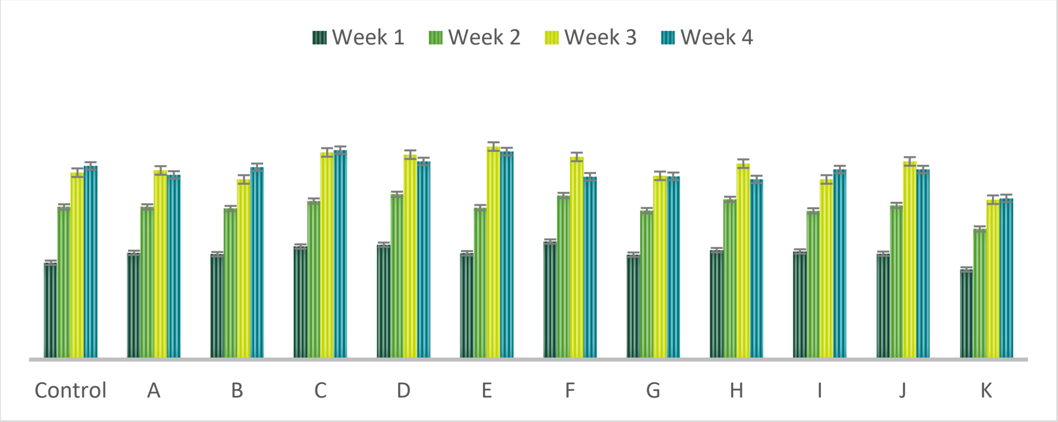


*Figure 1 - Effect of silicon supplementation on pea plant height over four weeks under control and salinity stress conditions. Values represent mean ± standard error (n = 5). Treatments: A) 150 mM of NaCl, B) 200 mM of NaCl, C) 1 mM of $CaSiO_3$, D) 2.5 mM of $CaSiO_3$, E) 3 mM of $CaSiO_3$, F) 1 mM of CaSiO3 + 150 mM of NaCl, G) 1 mM of $CaSiO_3$ + 200 mM NaCl, H) 2.5 mM of $CaSiO_3$ + 150 mM NaCl, I) 2.5 mM of $CaSiO_3$ + 200mM NaCl, J) 3 mM of $CaSiO_3$ + 150 mM NaCl, and K) 3 mM of $CaSiO_3$ + 200mM NaCl.*

However, these differences weren’t statistically significant ($p > 0.05$) until the 3rd week. Both weeks 3 ($p = 0,033$) and 4 ($p = 0,048$) showed significant differences, observed in certain treatments in subsequent post hoc comparisons. Post hoc ANOVA tests indicated that the K treatment differed significantly from treatment D ($p = 0.049$), and treatment B differed significantly from both treatment A and the Control, with treatment B consistently having the lowest mean. The difference between treatments K and D was consistent with pairwise comparisons using a t-test, which also indicated a significant difference ($p = 0.002$), with a mean difference of 10,62 ± 3,79, where treatment K showed a higher mean. However, in pairwise comparisons between treatment B and control, and between treatment A and B, there was no significant difference in either case. Correlation tests confirmed the increase in plant height over time ($r = 0{,}770$ to $0{,}908$), making the results more reliable.

*Stem Thickness*

Stem thickness was measured twice during the four-week period, once in the second week and again in the fourth week (Appendix Table 4). Most treatments showed an overall increase in stem thickness; however, the increase did not differ significantly between the two measurement points ($p > 0{,}05$). Pairwise comparisons between treatments showed a significant difference between treatments K and D ($p = 0.027$), with a mean difference of 0.660, indicating that treatment K had a higher mean.

### 4.1.2 Physiological parameters

Physiological parameters included chlorophyll content, an indicator of photosynthetic capacity; gas exchange measurements ($CO_2$ assimilation and stomatal conductance), direct indicators of photosynthetic capacity; and intrinsic water use efficiency (iWUE), obtained indirectly from the gas exchange parameters.

*Chlorophyll*

Chlorophyll measurements were taken weekly over a four-week period. The result values are the mean of three measurements taken per plant during each week (Figure 2). Under control conditions, the plants maintained a relatively stable chlorophyll content throughout the experiment, with mean values of 26.15 ± 5.02 SPAD units in the beginning and 26.3 ± 6.62 SPAD units by week 4.

Under stress conditions, chlorophyll content decreased over time, with differences of 11.88 and 11.13 units for treatments A and B, respectively. A similar pattern was observed in silica-treated plants, although the magnitude of reduction varied between silicon concentrations, with differences of 10.88, 7.63, and 5.45 units for treatments C, D, and E, respectively. No consistent increase in chlorophyll content was observed in plants treated with silicon under stress conditions.

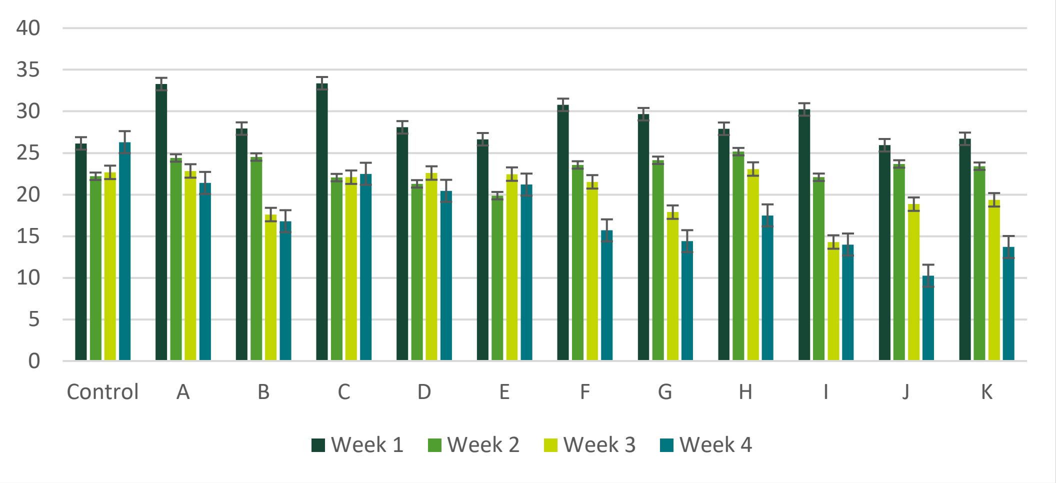


*Figure 2 - Chlorophyll content response to all treatments over time, represented by means ± standard error (n=5) per week. Treatment codes as indicated in Table 1.*

Significant differences were found in week 3 ($p = 0.036$) and week 4 ($p = 0.027$). Post hoc analysis showed significant differences primarily among treatments with plants exposed to high salinity. During the 3rd week, treatment B differed significantly from both Control ($p = 0.001$) and treatment A ($p = 0.008$). However, in week 4, significant differences were only observed between treatment B and the Control ($p = 0.009$). Subsequent pairwise comparisons showed a similar result.

Pearson correlation analysis revealed a moderate positive correlation between chlorophyll measurements over time ($r = 0.277$ to $0.582$), indicating moderate consistency in chlorophyll responses throughout the experimental period.

### *Photosynthesis*

Gas exchange parameters, including $CO_2$ assimilation (A) and stomatal conductance (gs), were analysed using a mixed-effects model, with week and treatment as fixed factors and plant as the random factor.

For $CO_2$ assimilation (A), significant differences were observed among treatments, weeks, and the treatment x week interaction across the experimental period. The biggest differences were observed in treatments with combined silicon and salt, exposed to the highest NaCl concentration (200 mM), particularly in treatments I and K, which received 2,5 mM and 3 mM silicon supplementation, respectively. Pairwise comparisons showed similar results across both measurement periods, with the exception of some treatment comparisons that were not statistically significant, including the treatment F versus K in the first period ($p = 0.063$) and the treatment C-I comparison in the second period ($p = 0.064$).

Analysis of stomatal conductance (gs) results also revealed significant differences between weeks and treatments. However, no significant treatment x week interaction was observed, indicating that treatment responses remained relatively consistent over time. The greatest differences in gs were observed in treatments with combined high salinity and silicon supplementation (treatments I and K), particularly relative to lower salinity levels (150 mM NaCl). However, pairwise comparisons showed only small differences between treatment means, which remained below 1 unit across both measurement periods.

Intrinsic water use efficiency (iWUE) was calculated from the ratio between $CO_2$ assimilation rate (A) and stomatal conductance (gs) across both measurement periods (Figure 3). Under control conditions, iWUE values remained relatively stable throughout the experiment, showing a small decrease between the two measurement periods, from 32.18 to 25.40 units. Under salinity stress, iWUE varied with NaCl concentration, with treatment B (200 mM NaCl) showing an increase from 35.84 ± 4.55 to 61.89 ± 29.67 between measurement periods. This increase was accompanied by a reduction in gs from 0.45 to 0,.9 mol $H_2O$ $m^{-2}$ $s^{-1}$, while A decreased proportionally less, from 16.13 to 11.76 µmol $CO_2$ $m^{-2}$ $s^{-1}$.

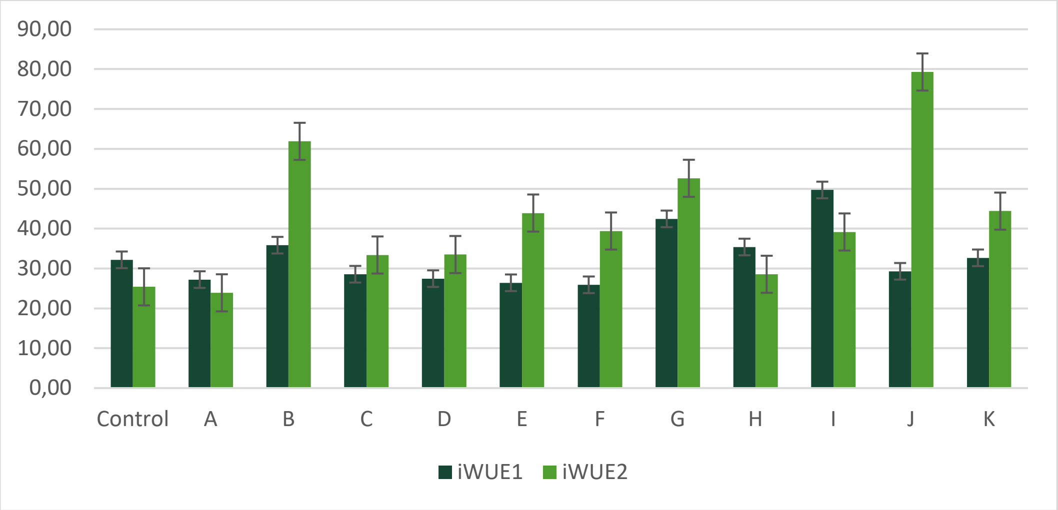


*Figure 3 - Treatment effects on the intrinsic water use efficiency of photosynthesis parameters of pea plants, represented by the means ± standard error (n=5). Treatment codes as indicated in Table 1.*

Under non-stress conditions, iWUE values generally increased proportionally with increasing silicon supplementation, with treatment J (3 mM Si) showing the highest increase from 35.84 ± 1.23 to 81.22 ± 1.23 between measurements. Combined silicon and salinity also showed elevated iWUE values, particularly treatments J and K, which showed the highest values during the second measurement period. These increases were accompanied by a simultaneous decrease in both A and gs values. Mixed-effects analysis indicated no statistically significant effects of treatment ($p = 0.062$), week ($p = 0.054$), or treatment x week interaction ($p = 0.151$) on iWUE.

Correlation analysis of photosynthetic parameters A and gs showed that, over time, a strong correlation was present between them. This could indicate a progression of treatment effects over time and a possible direct association between stomatal conductance and photosynthetic activity. In contrast, lower correlations were observed between A measurements over time and gs measurements over time, indicating that stomatal regulation may have played an important role in photosynthetic performance.

### 4.1.3 Biomass

Biomass accumulation was evaluated using measurements of stem and root fresh and dry weights, as well as the respective root/shoot ratio. Although the treatments differed in several biomass parameters, most differences were not statistically significant ($p > 0.05$).

Under salinity stress, stem and root biomass generally decreased with increasing NaCl concentration, except for stem and root dry weight, which decreased from a mean of 9.07 g to 8.72 g and from 5.38 g to 5.02 g, respectively. The same trend was observed when calcium silicate was added to the treatments, with the highest mean fresh stem weight in treatment F (36.67 ± 13.29 g) and the lowest in treatment I (14.68 ± 9.34 g) (Figure 4).

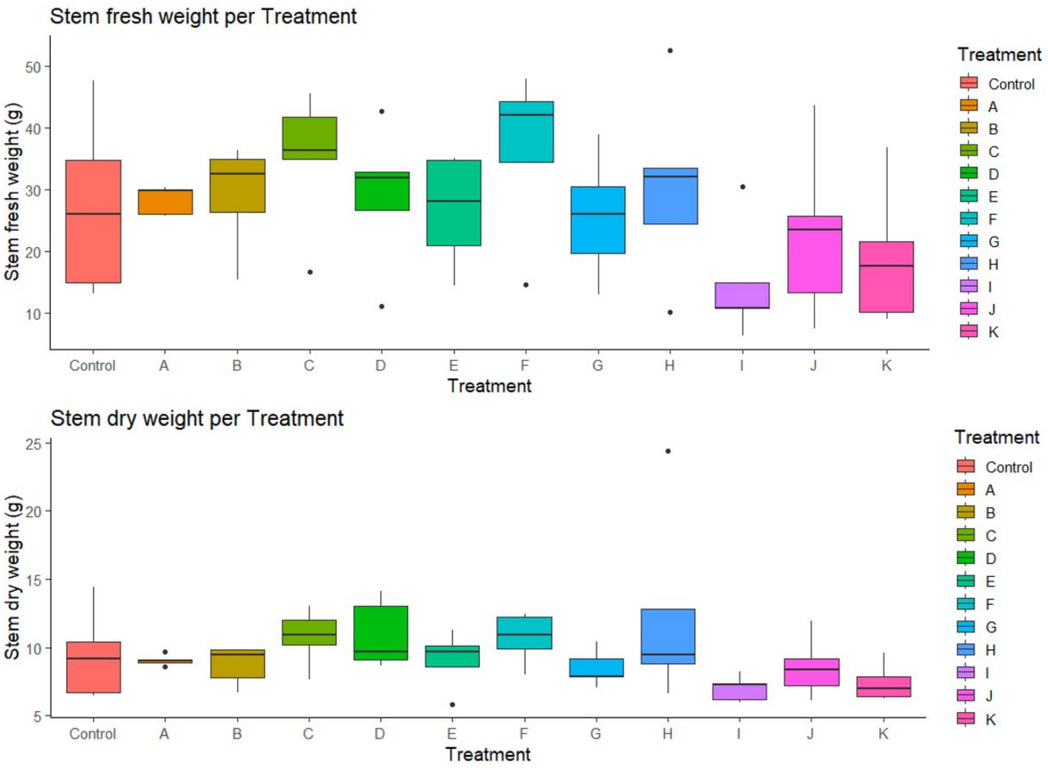


*Figure 4 - Stem biomass responses to the different treatments at the end of the experimental period. The upper panel shows stem fresh weight, and the lower panel shows stem dry weight per treatment. Treatment codes as indicated in Table 1.*

Root fresh and dry weights, as well as stem dry weight, followed a similar pattern under high-NaCl conditions. Silicon supplementation under non-stress conditions showed different effects on biomass accumulation. Treatment C (1 mM Si) showed the highest mean fresh stem biomass (35.02 ± 11.1 g) and root biomass (16.33 ± 5 g), while treatment D showed the highest mean stem dry weight (10.92 ± 2.24 g), and treatment E the highest mean root dry weight (5.27 ± 0.43 g). The responses are shown in Figure 5 below.

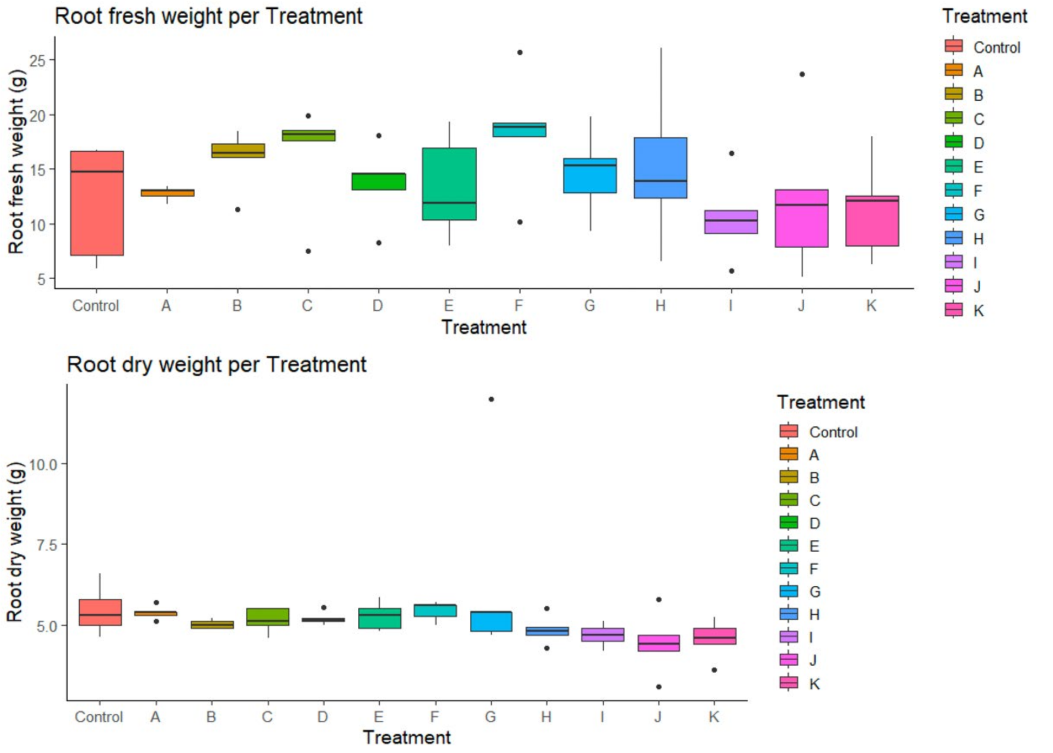


*Figure 5 - Root biomass responses to the different treatments at the end of the experimental period. The upper panel shows root fresh weight, and the lower panel shows root dry weight per treatment. Treatment codes as indicated in Table 1.*

Tissue water was estimated from the difference between fresh and dry biomass. Water loss remained relatively high throughout the experiment, ranging from 52.25–70.84% in stems and 52.85–70.42% in roots, across all treatments. (Figure 6). Although overall biomass accumulation was reduced under salinity stress, tissue water content remained similar to that of the control plants. Combined NaCl and silicon treatments showed reduced biomass accumulation, with lower water content observed at high NaCl concentrations. No consistent trend was observed across all silicon concentrations.

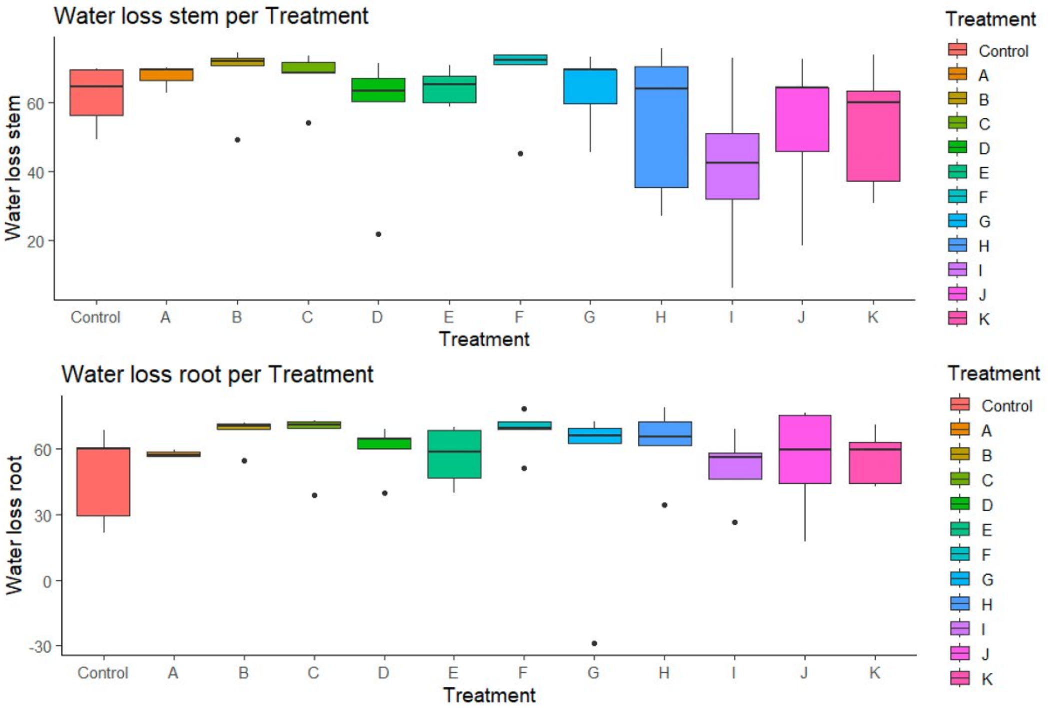


*Figure 6 – Water tissue content responses to the different treatments at the end of the experimental period. The upper panel shows water loss from the stem, and the lower panel shows water loss from the roots. Treatment codes as indicated in Table 1.*

Despite these biomass trends, differences in accumulation and water content among treatments were generally small. However, statistically significant differences were detected in the root/shoot ratio between salinity-treated and combined silicon-salinity treatments, and in a single comparison of pod dry weight, as indicated by one-way ANOVA.

The root-shoot ratio of salinity-only-treated plants remained similar to that of the control under both salinity levels (0.58-0.59), whereas combined Si and NaCl treatments showed greater variation (0.51-0.81). The highest root-shoot ratio was observed in treatment G (0.81 ± 0.57), and the lowest in treatment F (0.51 ± 0.08). Post hoc analysis showed significant differences between salinity-only treatments and combined silicon-salinity treatments. These differences were primarily detected between salinity treatments and the control, between salinity-only treatments, and between all combined treatments and treatment G (Figure 7).

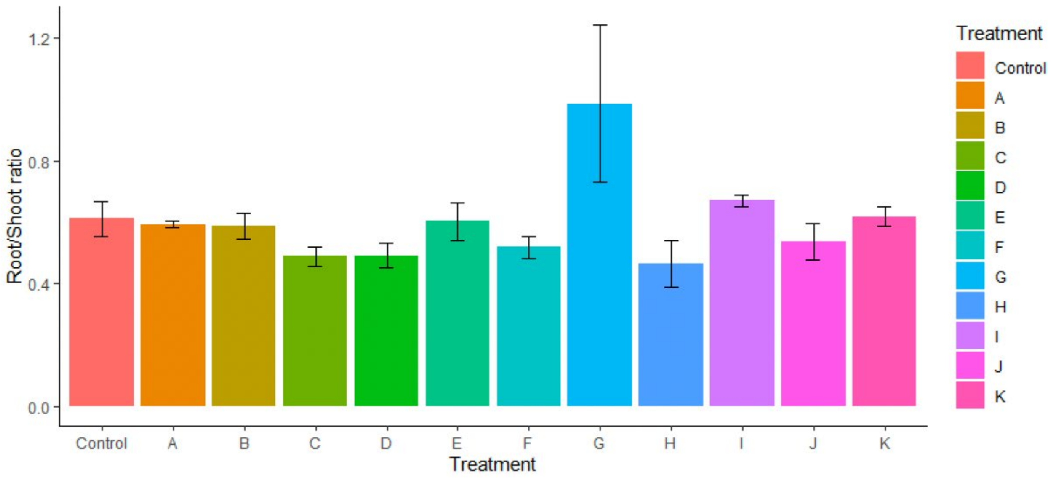


*Figure 7 - Root-shoot ratios calculated with the subtraction of fresh and dry weight of the roots and shoots of pea plants. Treatment codes as indicated in Table 1.*

Pairwise comparisons further confirmed that not all treatments in the post hoc analysis were significantly different. In these comparisons, only the comparison between treatment G and F ($p = 0.035$) showed a significant difference. In the post hoc analysis of pod dry weight, pairwise comparisons showed that treatment I versus F ($p = 0.001$) was the only significant difference.

Correlation analysis of biomass parameters showed strong positive relationships between stem and root fresh weight, and a weak relationship between root dry weight and other biomass parameters. The strongest correlation was observed between stem and root fresh weight ($r = 0.916$), indicating a coordinated whole-plant growth across treatments. The weakest correlation was observed between root and stem dry weight ($r = 0.148$), indicating greater variability in root structural responses across treatments.

### 4.1.4 Yield

Yield performance was evaluated by measuring pod number per plant and fresh and dry biomass of harvested organs to assess the effects of salinity stress and silicon supplementation on crop productivity and marketable yield.

Plants under salinity stress generally showed reduced pod biomass and tissue water content (Appendix Figures 16 and 17). This trend was also observed in treatments combining silicon and NaCl, with lower values recorded under the higher NaCl concentration (200 mM). Pod number followed a similar pattern, except for salinity-only treatments and treatments J and K, where pod number per plant increased with increasing NaCl concentration.

Silicon supplementation had variable effects on pod number, biomass, and tissue water content, depending on the concentration applied (Appendix Figure 15). Treatment F, which received the lowest silicon concentration (1 mM), consistently showed the highest values for pod number (18.40 ± 7.30), pod fresh weight (39.78 ± 12.79 g), and pod dry weight (9.30 ± 1.74 g). Despite these trends, no yield parameters showed statistically significant differences between treatments ($p > 0.05$).

Correlation analysis of pea yield parameters showed a strong relationship between the total number of pods and pod fresh weight ($r = 0.742$), indicating that plants with more pods accumulated greater pod fresh biomass. In contrast, the correlation between total pod number and pod dry weight was weaker ($r = 0.333$), indicating greater variability in pod structural biomass among treatments.

## 4.2 Tomato (*Solanum lycopersicum* L., var. Hildaris F1)

### 4.2.1 Plant growth

*Height*

Plant height in tomato (*Solanum lycopersicum)* was measured over a six-week time period. Throughout this experimental period, plant height increased across all treatments (Figure 8).

Under control conditions, plants reached a mean height of 112.4 ± 6.3 cm by week 6. Salinity stress reduced plant growth, with plants reaching 108.1 ± 7.58 cm in the NaCl-only treatment (Appendix Figure 18). Silicon supplementation generally increased or maintained growth, with values relatively similar to those of the control plants (Appendix Figure 19).

The biggest height was observed in those treated with 0.1 mM calcium silicate, reaching 116.1 ± 7.63 cm when applied as a foliar spray and 117.7 ± 3.53 cm when supplied through the hydroponic solution. The difference in height between silicon concentrations was relatively small; however, the method of application influenced plant growth (Appendix Figure 20), with higher values obtained via foliar application rather than through the hydroponic solution.

The biggest reduction in plant height was observed in plants treated with the commercial silicon product Actisil (Appendix Figure 21). Plants receiving the product reached lower mean heights under both control (89.8 ± 50,7 cm) and salinity stress (78.8 ± 17,8 cm) conditions.

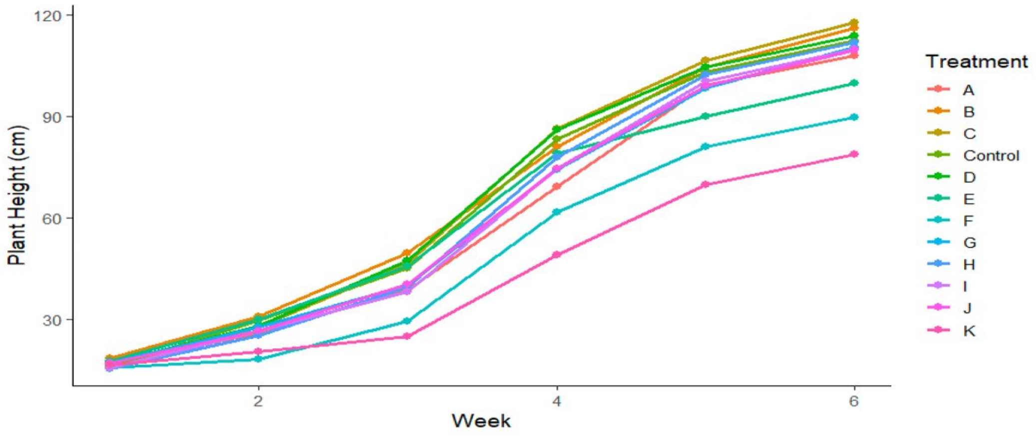


*Figure 8 - Effect of silicon supplementation on tomato plant height over six weeks under control and salinity stress conditions, represented by the mean over time. A) 350 mM of NaCl, B) 0,1g of $CaSiO_3$ with leaf application, C) 0,1g of $CaSiO_3$ with root application, D) 1g of $CaSiO_3$ with leaf application, E) 1g of $CaSiO_3$ with root application, F) Actisil, G) 0,1g of $CaSiO_3$ + 350 mM of NaCl with leaf application, H) 0,1g of $CaSiO_3$ + 350 mM of NaCl with root application, I) 1g of $CaSiO_3$ + 350 mM of NaCl with leaf application, J) 1g of $CaSiO_3$ + 350 mM of NaCl with root application, and K) Actisil + 350 mM of NaCl.*

Differences between treatments were found to be significant from the second week onwards and remained significant until week six, suggesting that treatment effects became more pronounced as plants grew. Post hoc ANOVA showed that the most significant differences occurred between silicon-treated and Actisil-treated plants, whereas NaCl-only treatment (treatment A) and the control were significant only during weeks 3 and 4. Pairwise comparison tests further showed that most differences were found when treatments F and K were involved.

Correlation tests showed strong positive relationships between weekly measurements (r = 0.708-0.980), indicating a consistent growth pattern and supporting the reliability of the results. Lower correlations were observed between early and late measurements, which suggests increasing treatment-related effects over time.

### *Stem Thickness*

Stem thickness was measured over the same six-week period as plant height. Throughout the experimental period, stem thickness increased in all treatments but remained below the control values in most cases (Appendix Figure 22).

Salinity stress reduced stem thickness across all NaCl-treated treatments, with the lowest mean value of 6.12 ± 0.30 observed in treatment K. Plants receiving silicon supplementation under non-stress and stress conditions showed greater stem thickness (Appendix Figure 23). The silicon solution generally showed higher values, reaching 9.46 ± 0.87 in treatment E, as well as plants under high silicon concentration (1 mM), whereas Actisil-supplemented treatments consistently showed the lower values throughout the experimental period. The application method showed differences until week six, in which both treatments showed similar values. During this period, the root application showed a steady increase (Appendix Figure 24).

Similar to the plant height results, significant differences were observed from week 2 onwards. The most significant differences involved treatments F and K, which had lower mean stem thickness than the remaining treatments. Pairwise comparison tests further confirmed that treatments F and K differed significantly from several silicon-only and silicon-salt-combined treatments.

Correlation analysis showed a strong positive relationship among weekly measurements ($r = 0.597$-$0.925$), with stronger correlations between adjacent weeks and weaker correlations between measurements further apart in time.

### 4.2.2 Physiological parameters

Physiological parameters included chlorophyll content, an indicator of photosynthetic capacity; gas exchange measurements ($CO_2$ assimilation and stomatal conductance), direct indicators of photosynthetic capacity; and intrinsic water use efficiency (iWUE), obtained indirectly from the gas exchange parameters.

*Chlorophyll*

Chlorophyll measurements were taken once a week during the six-week experimental period on all plants, in triplicate. The results in this section are from the analysis of the means of these values.

Treatments under stress conditions, silicon supplementation, and their combination generally showed higher chlorophyll levels than the control throughout the experiment, whereas treatments I, J and K maintained similar values. The highest mean value, 29.9 SPAD units, was shared by treatments B and F at week six (Appendix Figure 25). Under salinity stress, values decreased compared to the control treatments, and were higher when in the presence of silicon, regardless of the application method (Appendix Figure 26). The application methods showed higher chlorophyll when silicon was supplied via the hydroponic solution; however, this effect was not observed under stress conditions.

Significant differences were found in all weeks, generally between the control treatments and the silicon or silicon-salinity combined treatments. Actisil-treated plants consistently showed significant differences from other treatments throughout the experimental period. The differences became increasingly evident in the later weeks, as the plants began to show effects of the treatment. Pairwise comparisons between treatments showed that the lowest mean was observed in treatments with Actisil, compared with treatments with silicon supplementation. NaCl-only treatments differed significantly from the control treatment in most weeks, but not from other treatments.

Correlation analysis showed moderate-to-strong positive relationships across all weeks, with the strongest between consecutive weeks (r = 0.719-0.851) and the weakest between earlier and later weeks (r = 0.426-0.720). This indicates a stable chlorophyll development throughout the experiment and increasing treatment-related variation over time.

### *Photosynthesis*

Photosynthesis measurements were taken every two weeks, for a total of three measurements during the experimental period. The measurements included direct gas exchange parameters, $CO_2$ assimilation (A) and stomatal conductance (gs), and an indirect parameter, intrinsic water use (iWUE). The treatments showed variable results across all parameters, with most values below those of the control treatment for direct parameters and above for indirect.

For $CO_2$ assimilation, NaCl stress reduced values, while silicon supplementation increased and decreased depending on application and concentration. The real effect was observed across application methods (Figure 9), with plants given Si via foliar spray showing higher values, reaching 10.046 ± 2.73 in the silicon control treatment at the lowest concentration (0.1 mM). Plants treated with Actisil showed lower values under both stress and non-stress conditions, with no significant effect on parameter A.

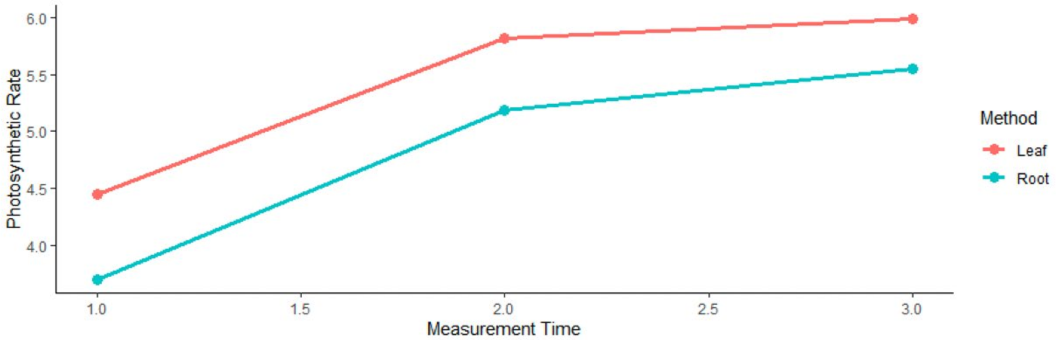


*Figure 9 - Leaf and root silicon application methods effects on the photosynthetic rate of $CO_2$ assimilation (A), represented by means in the three measurements.*

For stomatal conductance, most treatments showed lower values than the control (0.426 ± 0.18), except for treatment F, which had a mean of 0.434 ± 0.48 (Figure 10). Salinity stress and the silicon supplementation method affected the changes in gs. A decrease in gs was observed in plants under stress conditions and in plants supplied with silicon via a hydroponic solution, compared with foliar spray. In Actisil-treated plants, NaCl stress induced a clear decrease to 0.072 ± 0.054, from the treatment F's highest gs mean value. Actisil-treated plants under added stress exhibited substantial initial variation, resulting in the death of one plant. Therefore, the means of this treatment in the initial weeks for gs reflect the imbalance the plants suffered. This imbalance later decreases, and the plants show consistent treatment effects.

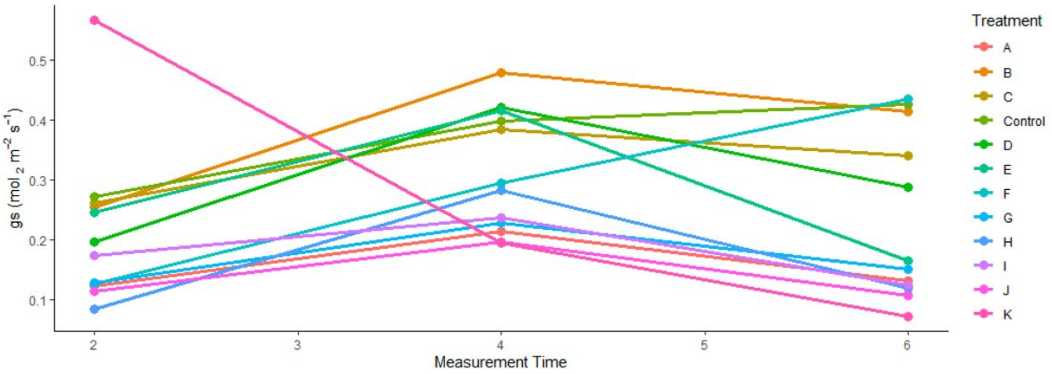


*Figure 10 - Treatment effects on stomatal conductance (gs) represented by means over time. Treatment codes as indicated in Table 2.*

Intrinsic water use efficiency (iWUE) is an indirect calculation based on the ratio between A and gs to understand how efficient the carbon assimilation was during photosynthesis. The iWUE values observed in tomato plants varied among treatments and measurement weeks (Appendix Figure 27). Salinity stress generally increased iWUE relative to the 18.16 iWUE value of control plants, with control NaCl plants reaching 51.41. Silicon supplementation showed variable responses depending on the concentration and application method. In most cases, silicon supplied via a hydroponic solution resulted in lower iWUE values than when applied as a foliar spray. The highest iWUE value was consistently observed in treatment K, reaching 66.58 in the last measurement week. Higher levels can indicate a stress response through stomatal closure, restricting water loss via transpiration.

Statistical analysis was conducted on A, gs, and iWUE parameters using a mixed-effects model that included treatment and week as fixed factors and plant as a random factor. Necessary post hoc comparisons using Tukey's test were conducted for parameters that showed significant differences for treatment, week, and treatment x week interaction. Statistical differences were found for all fixed factors, namely treatment and week. However, stomatal conductance values in further comparisons did not reveal where these differences lay.

For A, Tukey's comparison tests showed that treatment B had a higher mean than the other 4 treatments (10.05 for the 3rd measurement): treatments E (4.73), H (3.81), J (4.21), and K (4.27). Pairwise comparisons confirmed these differences and showed that the biggest difference between treatments was 6.23 between treatment B and treatment H.

iWUE showed the biggest differences between treatments and weeks. These differences are mostly between treatment K and most other treatments, with an additional comparison between the control treatment and treatment G (p = 0.019). In all comparisons, treatment K shows the biggest mean (66,6) compared to the other treatments.

Correlation analysis between $CO_2$ assimilation (A) and stomatal conductance (gs) showed variable relationships over time. During the first measurement (week 1), A and gs showed little correlation (-0.043), which may reflect plant stability and limited association between stomatal conductance and photosynthetic activity. Stronger correlations were observed over time between both photosynthetic measurements and between A measurements over time. This increase in correlation could indicate a progression of treatment effects throughout the experimental period, and consistent photosynthetic performance. In contrast, gs measurements showed weaker correlations between weeks, indicating greater variability in stomatal behaviour under stress and silicon treatments.

Overall, stress, silicon supplementation, and application method affected photosynthesis parameters, with particular emphasis on effects in Actisil-treated plants.

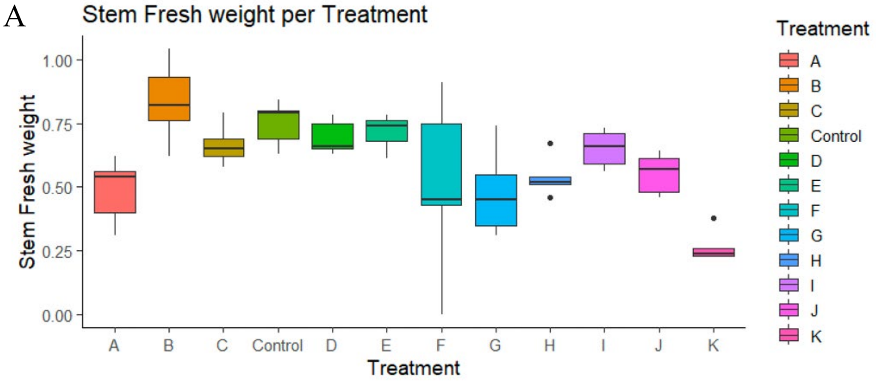
### 4.2.3 Biomass

Biomass accumulation was evaluated using measurements of stem and root fresh and dry weights, the root/shoot ratio, and water loss.

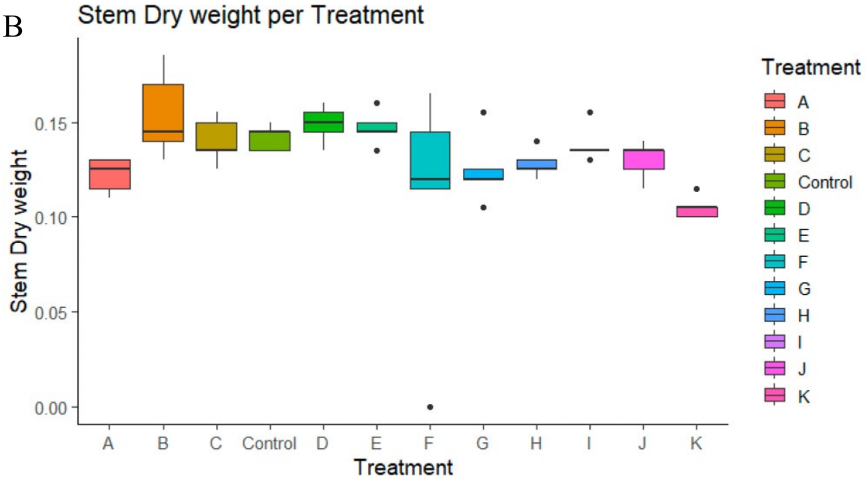
Salinity stress affected all treatments, resulting in reduced growth in both stems and roots, as seen in Figure 11, where treatment A shows lower biomass than the other treatments. Silicon supplementation generally recovered some plant mass under stress conditions. As evidence that the biplots of both root and shoots recovered to values close to those of silicon-only treatments. However, its effect depended on silicon concentration and application method. A lower silicon concentration (0.1 mM) showed higher values under non-stress conditions and when applied via foliar spray, and lower values when under stress, with an increase when applied via hydroponic solution. A higher silicon concentration (1 mM) had the opposite effect in both stress and non-stress conditions. This effect is well represented by fluctuations in biplot positions for treatments G to J, in which the plants are under stress. However, in the root dry weight results, most values showed similar variation, consistent with the observed similar root size between treatments, but not measured.

Plants treated with Actisil showed lower values under both stress and non-stress conditions than most treatments. When under stress, these values decreased further, except for the root dry weight of treatment K, which increased compared to treatment F.

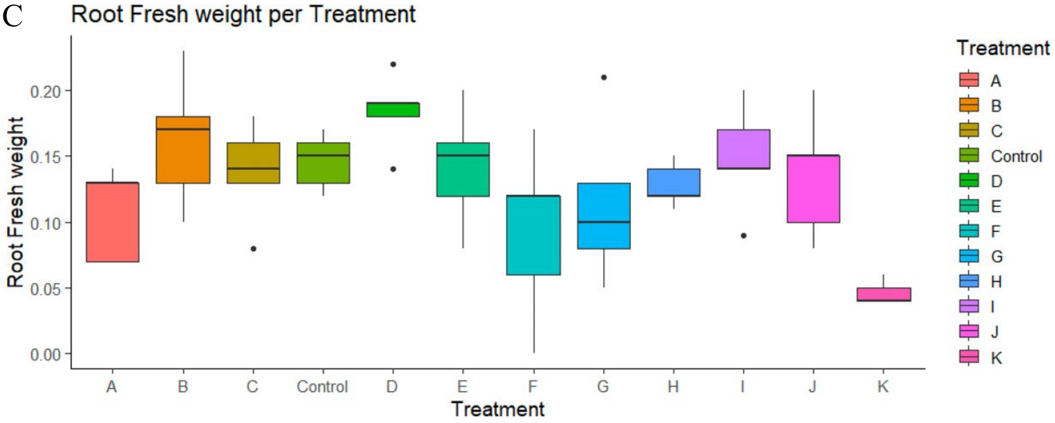
A


Stem Fresh weight per Treatment

B


Stem Dry weight per Treatment

C


Root Fresh weight per Treatment

D

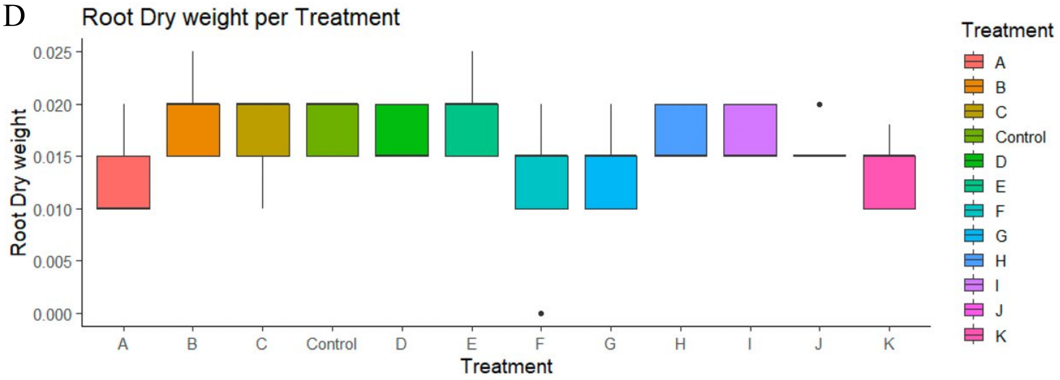

Root Dry weight per Treatment

*Figure 11 – Biplots of treatment effects on all biomass parameters of tomato plants. A) Stem fresh weight, B) Stem dry weight, C) Root fresh weight, D) Root dry weight. Treatment codes as indicated in Table 2.*

The water loss of tomato plants remained generally high, at 90-93% in stems and 91-98% in roots, except for treatments with Actisil, where water loss was 73-92% in stems and 76-89% in roots. These treatments consistently showed an increase in the control treatment with the product, and in the product treatment with added NaCl stress (Appendix Table 5).

Root/shoot ratios ranged from 0.09 to 0.24 across all treatments, indicating proportionally higher shoot biomass relative to root biomass (Table 3). Lower ratios can indicate a predominance of shoot growth and biomass accumulation in tomato plants, whereas higher ratios can indicate an adaptive biomass allocation strategy under salinity stress and silicon supplementation. This variation among treatments shows that salinity and silicon treatments may have influenced above- and below-ground tissues.

*Table 3 – Means of root/shoot ratios per treatment.*

| Treatment | Root/Shoot ratio | Treatment | Root/Shoot ratio |
|---|---|---|---|
| Control | 0.15 | F | 0.11 |
| A | 0.09 | G | 0.11 |
| B | 0.14 | H | 0.18 |
| C | 0.14 | I | 0.15 |
| D | 0.12 | J | 0.15 |
| E | 0.16 | K | 0.24 |

Significant differences were found in all measurements except root dry weight. For all comparisons, differences were assessed in silicon-treated and stressed plants, which were mostly compared with Actisl-treated plants. These differences are consistent with findings that silicon concentration and application method may have influenced plant mass allocation and stress responses in tomato plants. Salinity-only treatments differed significantly from the control treatment, with lower mean biomass in salinity-only-treated plants, indicating that salinity influenced biomass allocation. Pairwise comparisons confirmed the ANOVA results and showed that most treatments differed from Actisil-treated plants, regardless of the measurement type.

Correlation analysis showed a strong positive relationship between stem and root biomass measurements. The strongest correlation was observed between stem fresh weight and stem dry weight (r = 0.922), and stem dry weight and root fresh weight (r = 0.869), indicating that increases in fresh biomass were associated with greater structural biomass allocation that was coordinated between above-ground and below-ground tissues. In contrast, a moderate correlation was observed between root dry and fresh weight, indicating variability in root tissue water content across treatments.

### 4.2.4 Yield

Yield performance was assessed by measuring the number of fruit and flowers per plant. These parameters were used to evaluate the effects of both salinity stress and silicon supplementation on crop productivity and performance (Figure 12).
The number of flowers in the silicon-only treatment was similar to that in the untreated control, but decreased under salinity stress. Silicon's application method had no clear effect on the number of flowers, since most treatments showed similar amounts of flowers. However, plants treated with silicon via foliar spraying under stress conditions showed greater variation among plants within the same treatment. The only clear and significant difference was observed in Actisil-treated plants, in which the number of flowers was much higher than in the control under both stress (15.20 ± 3.83) and non-stress (29.60 ± 24.32) conditions.

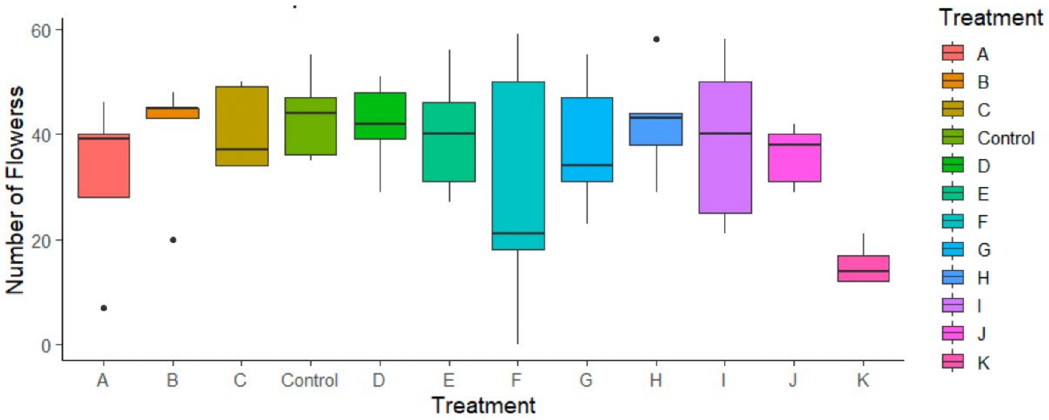


*Figure 12 – Treatment effects on the number of flowers in tomato plants. Treatment codes as indicated in Table 2.*

The number of fruits was clearly affected by silicon concentration and application method (Figure 13). Salinity stress did not seem to affect fruit production, with values similar to those of the control treatment. In contrast, silicon-salinity combined treatments generally produced more fruit than other treatments, reaching a mean of 13.60 ± 8.62 fruits, particularly at higher silicon concentrations. These numbers also varied depending on the application method. When silicon was applied via foliar spray, the number of fruits increased in control treatments and in silicon-salinity combined treatments in plants with lower silicon concentration. In contrast, higher silicon concentration under non-saline stress resulted in decreased fruit production. Actisil-treated plants showed the fewest fruits, with some plants not producing any.

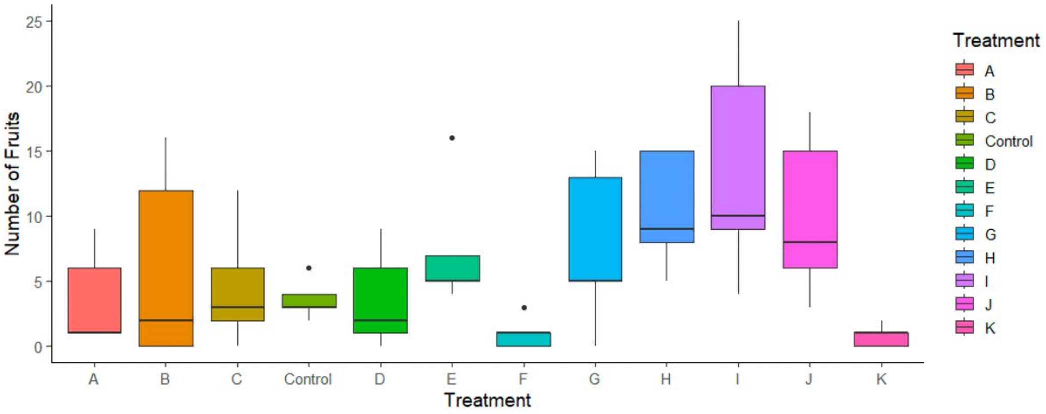


*Figure 13 – Treatment effects in the number of fruits of tomato plants. Treatment codes as indicated in Table 2.*

Significant differences were only found between treatments for the number of fruits. These differences were mainly observed between Actisil-treated plants and the treatment I and silicon control treatments, which had higher means. Pairwise comparisons indicated that 4 groups differed significantly. The comparisons were between treatment F and treatment I ($p = 0.032$), between treatment F and treatment E ($p = 0.048$), between treatment K and treatment I ($p = 0.030$), and between treatment K and treatment E ($p = 0.042$).

A weak positive correlation was found between the number of flowers and fruit ($r = 0.352$), indicating that increased flowering did not necessarily result in more fruit. Overall, fruit production appeared more sensitive to salinity stress than flower production, while silicon supplementation partially mitigated these effects, depending on concentration and application method.

# 5. Discussion

This study aimed to evaluate the effects of silicon supplementation on the growth, physiology, biomass allocation, and yield responses of pea (*Pisum sativum*) and tomato (*Solanum lycopersicum*) plants grown hydroponically, with and without salinity stress. Tomato plants showed greater responses to silicon supplementation in growth and physiological parameters, with and without stress, whereas pea plants were not affected. While many parameters in pea plants showed only small or non-significant differences among treatments, several trends suggest that silicon supplementation partially mitigated the stress present and altered biomass allocation under hydroponic cultivation. Overall, silicon supplementation influenced plant responses based on crop species, application method, silicon concentration, and salinity levels.

## 5.1 Interpretation of results

In this section, an overview of the main results and their interpretation is provided, based on responses to different variables.

### 5.1.1 Salinity stress effects on plant performance

Salinity stress negatively affected plant growth and performance in both crops, with the magnitude varying by crop and salt concentration. Pea and tomato plants showed signs of salt stress through both physical and biological responses.

Pea plants mostly showed stress symptoms during the third week, including necrosis and early senescence. Most of the symptoms were only perceptible in the data, which showed decreases in all plant parameters, except root/shoot ratio, which remained similar to the control. It should be noted that only some parameters: plant height, chlorophyll and photosynthesis showed statistically significant changes.

Tomato plants showed clear physical symptoms of salt stress, with severity varying with treatment. Plants under stress showed leaf curling, leaf tip burn, necrosis, and slight discolouration. These physical symptoms were particularly visible in plants treated with Actisil, which seemed to suffer not only from salt stress later on but also from possible root asphyxiation at the beginning of the experiment.

The symptoms in the tomato experiment became evident before reductions in growth parameters were visible, suggesting that visual assessment of growth progression may provide an early indication of stress. The visible symptoms were accompanied by decreases in plant height, stem diameter, photosynthetic rate, yield, and biomass parameters, along with an increase in chlorophyll content. The reductions observed in growth and physiological traits of both pea and tomato crops are consistent with most studies on salt stress. However, variation in chlorophyll content has been reported to increase with species and salt level (Popova et al. 2023).

Salt stress occurs when there is an imbalance of ions between the nutrient solution and the roots, a condition known as osmotic stress. Under osmotic stress, the concentration of $Na^+$ ions in the solution limits water uptake by the plant. The continuous uptake of Na+ ions transported within the plant and accumulated in several parts can cause ion toxicity if the plant does not limit it (Liu et al. 2024). These cause the plant to redirect its efforts toward mitigating stress symptoms. In pea plants, we repeatedly observed an increase in EC in plants given NaCl until the third week, after which they began to show rapid and pronounced signs of stress. In contrast, tomato plants showed early stress, possibly due to salt accumulation in their tissues, as the EC decreased when plants began to stress. Rao et al. (2006) in the third chapter of the book, *Physiology and Molecular Biology of Stress Tolerance in Plants*, discusses salt stress, describing its symptoms, mechanisms, and mitigation processes. Its explanation is consistent with the findings of this experimental study.

Chlorophyll content is an indicator of stress; reduced chlorophyll content is associated with lower net photosynthesis rate and water use efficiency. These reductions are associated with reduced Rubisco activity in the photosystem due to $CO_2$ limitation caused by stomatal closure. In pea plants, both parameters decreased, suggesting a sudden impact of stomatal closure on the plant, leading to reduced photosynthetic activity and, consequently, severe stress responses. In contrast, tomato plants showed an increase in chlorophyll rather than the expected decrease. However, this increase has also been observed in another study, in which some crops exhibit salt-tolerant traits that help them respond to stress symptoms (Popova et al. 2023).

Similar results were reported in several studies for the same parameters in comparable and variable salt concentrations. The studies showed biomass reductions, a response to limited water uptake due to osmotic stress and, reduced carbon assimilation (Habibi & Sediqui 2021; Ismail et al. 2022; Roşca et al. 2023). Although this trend was observed for both crops in this study, the root-to-shoot ratios remained similar to those in the control treatment despite the overall reduction in growth. This suggests that growth inhibition occurred uniformly across the plant, without creating a disproportionate effect. The stress symptoms were seen in both crops, but their severity varied, suggesting species-specific response to salinity stress, with differences in ion regulation and osmotic adjustment capacity.

### 5.1.2 Silicon supplementation effects

Silicon supplementation generally improved several growth, physiological, and yield parameters, although responses varied by crop, concentration, and treatment.

Physical evidence of silicon supplementation-based changes emerged over time, with more pronounced visual effects on tomato plants than on pea plants.

These changes were due to height differences, where tomato plants with silicon grew taller than control plants, and to increased stem thickness and rigidity, as evidenced by the string needing to be loosened more often than in control plants. Silicon is taken up by the roots or introduced through the leaves when applied as a foliar spray and transported within the plant to settle in several locations (epidermal cells, trichomes, inflorescence bracts, brush hairs, grain tissues, etc.). In those locations, silicon is deposited, forming a gel layer that provides protective properties, such as limiting water loss. As this layer reinforces the cells, it can also promote cell elongation and strengthen the shoot, thereby improving plant erectness and, consequently, increasing plant height and stem thickness.

Similar studies have reported similar results, in which stem elongation and Si accumulation in leaves, shoots, and other reproductive organs were observed (Ma & Yamaji 2006). Although we cannot be sure this was true in this study, other experiments have reported that increased plant growth is associated with changes in plant hormones, such as auxins and gibberellins, which play important roles in cell division and elongation (Baioui et al. 2025). This influence on plant hormones is often associated with improvements in secondary metabolism, as well as in nutrient accumulation and uptake (Reboredo et al. 2013; Cuong et al. 2017).

Physiological parameters of pea and tomato plants showed different responses to silicon supplementation. Pea plants showed decreases in gs and chlorophyll, increases in iWUE, and A values similar to the control treatment. The decrease in gs can indicate stomatal closure, reducing the transpiration rate and water loss from the plant. As it is coupled with similar A values across treatments, with a higher value at the highest silicon concentration, which may have improved carbon assimilation and increased water use efficiency, silicon supplementation improved photosynthetic efficiency. Similar results have been observed with other crops, such as maize (Vaculík et al. 2009), cucumbers (Gonzalo et al. 2013), tomatoes (Li et al. 2015), and peas (Kumar et al. 2025).

Tomato crops showed greater variation in responses between treatments, indicating dose- and application-method dependence. In low-concentration silicon treatments (0.1 mM), A increased with foliar application and was maintained with root application; gs decreased in both application methods, and iWUE increased. This combination shows that this $CaSiO_3$ concentration improved water use and photosynthetic efficiency, with the best results observed with foliar spraying. At higher concentrations (1 mM), stomatal conductance decreased significantly, with a more modest decrease in A and a larger increase in iWUE. In this case, silicon induced a greater need to conserve water and limit transpiration rates, which did not improve photosynthetic efficiency or performance; it only limited stomatal opening. However, chlorophyll content increased with both concentration and application method, suggesting improved physiological functioning.

Studies reported that plants with similar results showed an improved secondary metabolism, nutrient availability and uptake, and altered ion concentrations (Li et al. 2015). They observed that, independent of dose and application method, silicon does, in fact, improve plant performance in both crops when compared to plants without added silicon. These results confirm our earlier assumptions that silicon had a positive effect on overall plant growth and physiology.

Under stress conditions, plants adjust their physiological functioning to 'compensate' for the introduction of toxic ions, organisms or pests. Salt stress leads to increased salt accumulation in the plant, which was mitigated in the presence of silicon. Silicon has the potential to regulate how much $Na^+$ the plants take up and how it is used in the plant system. It is hypothesised that silicon can interact with ions in NaCl, thereby limiting their availability in solution for plant assimilation (Romero-Aranda et al. 2006). Another effect is that when salt accumulates in the plant's tissues, reactive oxidative species (ROS) increase their activity. In some studies, ROS levels decreased in the presence of silicon in the plant (Debona et al. 2017; Song et al. 2026). As it was not explored, the accumulation of silicon and how it interacted in the plant, we can only speculate that the decrease of chlorophyll, photosynthetic rate and iWUE in both crops to similar values to the control treatment, with the exception of gs values, which had a positive effect on tomato and pea plants' response to salinity stress. This improvement was possible due to the water-loss-prevention mechanisms that silicon promotes through its accumulation in epidermal cells.

Several studies confirm these findings and suggest that the benefits of silicon were more pronounced under stress (Rea et al. 2022). The pea study showed clearer differences in the impact of silicon supplementation under stress, whereas in the tomato experiment, the effects were evident in silicon-only treatments as well. In the tomato study, we can see the benefits of both silicon-only and combined silicon and salt stress treatments, indicating that silicon improves salt tolerance and mitigates its negative effects on growth, physiology, and biomass allocation, as we theorised.

Root/shoot ratios were particularly interesting because both crops, regardless of treatment, maintained values similar to the control treatment. This indicates that plant biomass, despite fluctuations, benefited all plants, which may explain the use of hydroponic systems that provided sufficient water availability. This availability allowed for greater root growth in both crops, which aids nutrient and water uptake, potentially leading to higher photosynthetic activity and biomass accumulation under these treatments (Coskun et al. 2019; Roşca et al. 2023).

An interesting observation in the yield results was that the number of fruits increased unexpectedly under stress conditions. Salt-only-treated tomato plants showed a reduction in the number of fruits, whereas combined silicon and salt treatments showed an increase. This improvement may be another indication of silicon effects, which, along with the maintenance of photosynthetic activity and vegetative growth, may have enabled greater allocation of nutrients to reproductive development. However, as the weight, size and carbohydrate allocation were not measured in tomatoes, this may not necessarily be true.

Silicon's influence on the plant is evident in this study and in other studies that support these results, where its intensity has been seen to depend on crop, concentration, method of application, and production method, as we suspected. Its influence occurs under both stress and non-stress conditions, with Si supplementation showing clearer effects under stress, where concentration-dependent responses suggest that an adequate silicon supply is necessary. These observations support the view that silicon, as a biostimulant, functions primarily in a protective role, enhancing plant tolerance to environmental stress rather than directly stimulating plant growth under optimal conditions.

### 5.1.3 Actisil usage effects on tomato plants

Actisil is a current market product from the brand Yara that contains silicon in the form of orthosilicic acid ($H_4SiO_4$), which plants take up through their roots via irrigation, fertigation or the leaves via foliar spray (*Actisil* 2018). The product came with instructions for its appropriate use based on crop and application method.

As $H_4SiO_4$ is unstable, it was stabilised to maintain its form in the packaging. For tomato crops specifically, the information on their usage in a hydroponic system was unclear and not directly indicated for several species. As such, those indications, along with no specific regard for EC and pH levels, may not have provided the most appropriate information for adding Actisil to the hydroponic solution.

The hydroponic solution with added Actisil was maintained under the same conditions as the other treatments throughout the experimental period. During the first week, a gel-like layer began to form in the solution and attach to the plant roots, negatively affecting the plants (Figure 6). This was accompanied by variation in EC and pH levels in opposite directions. To overcome this, the solution was adjusted several times, sometimes on the same day. The availability of $H_4SiO_4$ in solution was theorised to improve growth and physiological parameters.

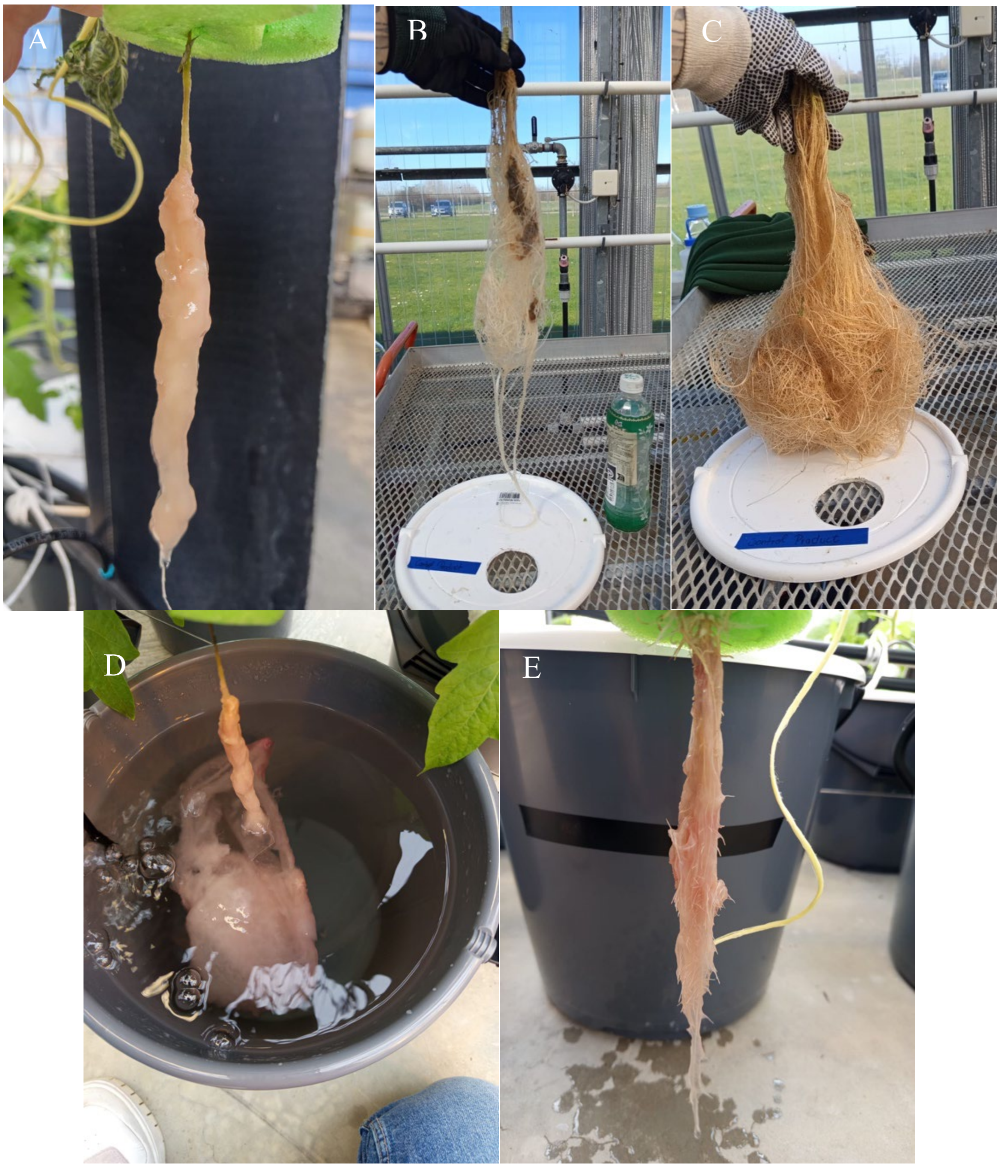


*Figure 14 – Actisil-treated plants with a gel-like layer attached to the roots, found in the solution in the early weeks, and the root at the end of the experiment for both Actisil control treatments (blue) and stressed treatments (black). A) Young tomato plant treated with Actisil with a gel-like layer attached to the root, B) tomato root at the end of the experimental period heavily affected by Actisil during the experiment, C) tomato plant that didn't form the gel-like layer after the first two weeks, D) root and solution with the gel-like layer, and E) tomato root less affected by the Actisil treatment after continuous solution adjustments.*

With the gel layer attached to the roots, the available surface area for water and nutrient uptake decreased, leading to an insufficient nutritional balance in the plant. This imbalance caused the growth of the plants to stop and severe stress symptoms to settle, almost causing senescence. This may have been the reason for the overall reduction in growth, physiological, and biomass allocation. The product itself destabilised the solution and possibly polymerised or otherwise associated with the ions in the nutrient solution, reducing their availability. The reduced availability of silicon, a biostimulant used to enhance plant performance and meet the crop's nutritional needs, created a new stress condition for the plant. As salt was also added to the solution to create the required salinity stress, the plant was under severe stress and responded accordingly.

Recent studies that included similar Actisil products showed an overall positive effect on growth and yield parameters. The effect is clearer in studies using substrates and *in vitro* conditions rather than in this hydroponics study (Debicz et al. 2016; Krupa-Małkiewicz & Calomme 2021; Wadas & Kondraciuk 2025). A study conducted to assess the influence of Actisil on the growth, flowering, and chemical composition of three flower species showed that different concentrations did not increase growth compared to the control treatment. However, the number of foliar spray applications had a positive influence, with more sprays resulting in better plant growth (Debicz et al. 2016). A similar study done with petunias, using different concentrations of Actisil, showed a similar trend during the growth and flowering stages (Krupa-Małkiewicz & Calomme 2021). These results contrast what was seen during the experimental period of this study. Therefore, it can be speculated that the problem lay in the preparation of the solution and the application method, which may not have been the most appropriate, causing the solution to lose stability and leading to the polymerisation of silicon. Monosilic acid has an added effect in solutions with low pH and high EC, dissociating especially when in contact with other nutrients, thereby becoming unavailable to plants (Datnoff et al. 2001; Ma & Yamaji 2006; Rodrigues & Datnoff 2015; Debona et al. 2017).

The tomato trial demonstrated that although stabilised orthosilic acid provides readily available Si, it remains sensitive to the chemistry of the hydroponic solution that may compromise silicon availability over time. The product instructions did not specify whether Actisil could be added directly to the nutrient solution. However, it did indicate the water-product ratios for its supplementation via irrigation or fertigation systems. In contrast, calcium silicate provided a more stable and slow-release source of silicon that avoided polymerisation and root-surface deposition. The resulting limitation in silicon availability due to polymerisation may partially explain the large reduction in growth parameters and the limited mitigation of salt stress.

### 5.1.4 Differences between crops

Takahashi et al. (1976-1981) studied the ability of several species to accumulate Si under identical growth conditions (Ma & Takahashi 2002b). He separated several species into three categories: Si-accumulator, intermediate, and non-accumulator, based on the Si/Ca ratio and the Si content of the top of the plants (Epstein 1999; Ma & Takahashi 2002b). Most plants, mainly dicots, are non-accumulators and cannot accumulate high levels of Si in their shoots. Tomatoes and peas are both dicots categorised as low-level Si accumulators (Mitani & Ma 2005; Ma & Yamaji 2006; 2008; Meena et al. 2014). Belonging to this category may partially explain the modest effects of silicon supplementation observed in this study, compared with those in high accumulators such as rice. Even though high concentrations of silicon are not accumulated or taken up by both crops, the concentrations present in the plants are beneficial for enhancing plant performance. This suggests that even a modest silicon uptake can confer physiological and growth benefits under both stressed and non-stressed conditions, supporting the use of silicon as a biostimulant for low-accumulator crops (Ma 2003; Ma & Yamaji 2006). Despite this, differences in root uptake efficiency, transport, growth habit, or sensitivity to stress were seen between crops, resulting in different responses to supplementation.

Based on both data and physical indicators, tomatoes appeared to exhibit more pronounced visual and physiological responses to salinity stress than pea plants, although both trials showed positive results. However, the intensity varied between experiments and treatments. Tomato plants showed enhanced performance with silicon supplementation and a robust stress response, allowing them to continue their functions in a manner similar to control plants. Pea plants did not show much change with silicon supplementation, but showed results when salt stress was imposed on the crop, suggesting that silicon's potential may lie solely in protecting the plant rather than improving performance. Therefore, silicon, as a biostimulant in hydroponic systems, offers benefits to crops that can vary in intensity depending on the crop. In no way did silicon in the form of $CaSiO_3$ provide negative effects on the plant's development. The exception lay in the use of Actisil, a more readily available form of silicon.

The trials conducted in this study cannot be compared directly due to differences in the administered concentrations. However, the calcium silicate dosage of 1 mM was common to both experiments and thus comparable. In this treatment, height, yield, and biomass generally increased, whereas some physiological parameters showed weaker responses. The results showed that tomato plants seemed to benefit more from silicon supplementation, which improved growth and physiological parameters, whereas pea plants' response was generally weaker and less consistent. It also indicated that lower concentrations can achieve results similar to or better than those of higher concentrations. Tomato plants appeared more salt-sensitive than pea plants, which may explain the pronounced stress symptoms observed in tomato plants. Overall, under the conditions tested in this study, silicon supplementation appeared to provide more consistent benefits to tomato plants than pea plants over time.

### 5.1.5 Influence of silicon application methods on plant performance

Two silicon application methods were tested in the tomato experiment: foliar application via spraying and root application via addition of Si to the nutrient solution. From the experimental results, we can tell that foliar application improved physiological responses, and in the literature, both Si uptake and physiological responses also improved compared with root application (Rezende et al. 2009; dos Santos Sarah et al. 2021; Lozano-González et al. 2021; Desher et al. 2023). This improvement showed overall increases in growth, physiological and yield parameters. Some studies have reported that foliar spraying with silicon can improve yields (dos Santos Sarah et al. 2021; Hu et al. 2023), consistent with the experimental results. For this reason, foliar application could be seen as a ‘first option’ (Desher et al. 2023) when the choice is based on the grower’s projection for economic profits.

In this study, foliar and root silicon supplementation showed differences between results and concentration. For growth and photosynthesis measurements, root application performed better, but biomass and yield parameters were improved via foliar application. An improvement in the plant's performance seen with root supplementation may be due to the constant availability of silicon for uptake from the hydroponic solution. In contrast, foliar application periodically provides silicon to the plant in a form it can more readily accumulate, specifically in the leaves, which may be why plant yield is higher. All this was true for the lowest silicon concentration given to tomato plants. However, a higher silicon concentration proved the opposite. Yield and biomass were higher when Si was supplied via a hydroponic solution, whereas growth and physiological parameters decreased across application methods. This suggests dose dependence in both methods and crops, with tomato plants possibly more sensitive to higher doses than other crops. Since pea plants didn’t experience such fluctuations when given silicon through the solution, it can be said that tomato plants perform better in lower concentrations.

When plants are under abiotic or biotic stress, both methods have been reported to be beneficial, positively influencing plant responses. The present study supports that idea. When tomato plants were subjected to salt stress, both methods improved all studied parameters, with better results from foliar spraying. A study conducted on potassium (K) deficiency concluded that Si root uptake by bean plants was more effective in mitigating K deficiency than leaf sprays, even when both showed positive results (dos Santos Sarah et al. 2021). Another study investigated the influence of both methods on rice plants' response to brown spot development (Rezende et al. 2009). It concluded that foliar application was the method of choice, since it responded better in the presence of the disease by attacking it directly through direct spray in the area, without the need for nutrient translocation (Guével et al. 2007). This allowed the gel layer in the leaves to form earlier and more quickly, thereby limiting the disease's effects on the plant (Rezende et al. 2009). Therefore, depending on the application method used, plants under stress and non-stress conditions benefited from its use, leaving the choice up to the grower's production priorities.

## 5.2 Implications for hydroponic cultivation and silicon application

Hydroponic systems are an important cultivation strategy for sustainable practices and for meeting the growing need for increased production (İkiz et al. 2024). This system offers several advantages, including minimal pesticide use, increased yield, water conservation, and continuous production (Khan 2018; Rajaseger et al. 2023; İkiz et al. 2024). Despite these advantages, it is still susceptible to environmental stresses, such as salt stress. Salinity is a common challenge in greenhouse hydroponic systems due to water sources that may not always be up to par and the recirculation of nutrient solutions. Therefore, there is a need to provide biostimulants or other performance-enhancing formulations. Silicon is an element reported to improve stress response in plants. As demonstrated in this study's experiments, Si mitigated salt stress by improving physiological and growth parameters. This improvement allowed the plant to continue functioning under conditions close to those of non-stressed plants.

Silicon's ability to alleviate salt stress in plants grown in hydroponic systems suggests its potential to enhance resilience in hydroponic systems, particularly when they are at risk of stress. From a commercial perspective, silicon supplementation is an additional management tool for growers to improve crop resilience without requiring modifications to current hydroponic cultivation methods. Silicon, as demonstrated by this study, can be incorporated into the nutrient solution without causing pH or EC imbalances, unless it is a stabilised formula. Although Actisil has been reported to work when applied as a foliar spray, this may entail additional costs for growers, whereas providing silicon through the root allows continuous, direct supplementation of silicon to the plant within existing systems, which may provide more long-term benefits. However, growers want to improve plant yields to increase profits from crop production, and foliar silicon supplementation tends to yield more positive results than root supplementation (dos Santos Sarah et al. 2021; Hu et al. 2023).

In short, this study confirmed our initial hypothesis that silicon could serve as a biostimulant in hydroponic systems. Silicon can provide benefits, provided the crop receives the optimal concentration of the corresponding formulation, regardless of the application method, which is up to the grower.

## 5.3 Study limitations

During both experiments, there were challenges with the trials and treatment plans that were not always possible to address. Silicon and salt concentrations were chosen based on previous literature. Although the salinity concentrations were effective, their effects on pea plants were not observed until close to the end of the experiment.

Silicon concentrations could have been chosen differently. Unfortunately, limited information was available in the literature on the use of calcium silicate. Therefore, we tried to keep the concentrations consistent with those used in comparable studies. However, lower concentrations could have been tested in the first trial to avoid heavy precipitation of the silicon compound when added to the nutritional solution. These factors contributed to variability in plant responses and may have accounted for the inconsistent effects of silicon supplementation observed during the study.

In the second study, lower silicon concentrations were tested in the trial to improve the experimental setup and obtain more significant results. When using Actisil, product research and understanding of the labelled instructions were lacking and should have been more thoroughly checked. As the product instructions for its use in hydroponic systems were unclear, it was interesting to see what happened when it was not handled correctly. To reduce concentration inconsistencies between trials, an experiment on the solubility of $CaSiO_3$ from this source should have been conducted to inform its use in both experimental trials.

Despite these limitations, the present study clearly showed salinity and silicon effects in both trials, providing valuable insight into the challenges associated with silicon application in hydroponic systems.

## 5.4 Future Perspectives

Research on silicon as a biostimulant and stress-mitigating agent has demonstrated several benefits across a wide range of crops. However, important knowledge gaps remain regarding its use in agricultural systems. For a better understanding, future research should prioritise comparisons of silicon sources and concentrations across different cultivation conditions (soil, hydroponics, and vertical farming). Such studies would improve understanding of silicon availability, optimal concentration, uptake efficiency and effectiveness under stress and non-stress conditions. The variability observed among silicon sources ($CaSiO_3$ and $H_4SiO_4$) and concentrations in the present study highlights the need for comparisons between silicon formulations across crops.

A second focus should be on specifying silicon applications based on crop and growth stage. As reported in several studies, silicon concentration and formulation affect crop development differently (Savvas & Ntatsi 2015; Coskun et al. 2019). As such, it is important to identify application rates that maximise plant performance. A third research direction should be on silicon accumulation in plants and its levels. Such studies can serve as a basis for a better understanding of whether silicon accumulation in edible plant tissues has implications for dietary exposure and food quality. Future research should investigate the stability of market products in hydroponic nutrient solutions under varying pH and EC conditions. This research would enable better management in hydroponic systems when using stabilised silicon formulations.

An important consideration is the long-term effects of silicon supplementation in continuous, large-scale production. Such studies should take into account silicon application strategies, nutrient management practices, and an economic assessment of production costs under commercial growing conditions. Future studies should also evaluate the economic benefits of production, including improvements in fruit quality, yield and overall production efficiency. Advancing knowledge in these areas will contribute to the development of more silicon-based products and support their practical implementation in sustainable crop production systems.

# 6. Conclusion

The conclusions of this study are presented in bullet points as follows:

⇒ Salinity stress negatively affected plant performance and growth in both crops, with visible symptoms in tomato plants.

⇒ Silicon supplementation mitigated the effects of stress on both crops, enhancing growth and plant performance compared to stressed control plants.

⇒ Silicon effects varied with silicon source, concentration, application method, salinity stress severity, and crop choice.

⇒ Root silicon supplementation generally produces stronger responses than foliar application, which can provide greater benefits in hydroponic cultivation systems.

⇒ The choice of application method used should be based on the grower’s production objectives.

⇒ Actisil requires careful management and proper application methods to yield positive results without reducing plant performance.

⇒ Silicon shows potential as a hydroponic biostimulant to improve plant resilience and productivity under stressed and non-stressed conditions.

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# Popular science summary

As climate change and intensive agricultural practices continue to affect the soil, plants become more stressed, and farmers face growing challenges. One challenge is soil salinity, which makes it harder for the plants to take up water and nutrients, reducing growth and productivity. In view of this problem, farmers have begun to adopt hydroponic systems, which allow for greater control over growing conditions and can reduce several stress factors. However, salt stress remains a significant concern for crop production.

Silicon is the second most abundant element in the Earth's crust after oxygen. Although it is not considered essential, research has shown that it can provide several benefits to plants, including improved plant growth and salt tolerance. To investigate whether silicon could help plants tolerate salt stress, tomato and pea plants were grown under greenhouse conditions in a hydroponics system and exposed to different levels of silicon and salt. Silicon was supplied to pea plants through the roots, while tomato plants received it either through the roots or the leaves. Plant growth, physiological responses and yield traits were then measured.

As expected, salt negatively affected plant growth and overall plant performance in both crops. In many cases, the addition of silicon helped the plants perform better under saline conditions and, in tomato treatments, also promoted growth in the absence of salt. While responses varied across crops, application methods, and silicon and salt doses. The overall results indicate that silicon can act as a biostimulant, helping plants grow and cope with environmental challenges. In tomato plants, foliar spraying often produced better results than root application, particularly for yield-related traits. Surprisingly, the commercial silicon product Actisil led to poorer plant performance than expected, sometimes worse than salt stress treatments. This result highlights the importance of evaluating different silicon formulations before their widespread use in crop production.

These findings suggest that silicon can be a useful tool for farmers to improve crop performance in stressful environments. As soil salinisation becomes an increasing threat to agricultural production worldwide, silicon-based strategies could help growers maintain productivity while reducing reliance on more resource-intensive approaches. While additional studies are needed to understand the mechanisms underlying this effect, this study adds to the evidence that silicon can enhance plant resilience to environmental stress.

# Appendix A

*Table 4 - Stem measurements of pea plants of two different weeks based on treatment and the difference between the two weeks.*

| Treatment | Week 2 | Week 4 | Difference |
|---|---|---|---|
| Control | 2.9 | 2.96 | 0.06 |
| A | 2.9 | 3.2 | 0.3 |
| B | 3.38 | 3.02 | -0.36 |
| C | 3.36 | 3.5 | 0.14 |
| D | 3.38 | 3.58 | 0.2 |
| E | 3.1 | 3.42 | 0.32 |
| F | 3.3 | 3.38 | 0.08 |
| G | 3.04 | 3.3 | 0.26 |
| H | 3 | 3.14 | 0.14 |
| I | 3.08 | 2.96 | -0.12 |
| J | 2.98 | 3.16 | 0.18 |
| K | 3.02 | 2.92 | -0.1 |

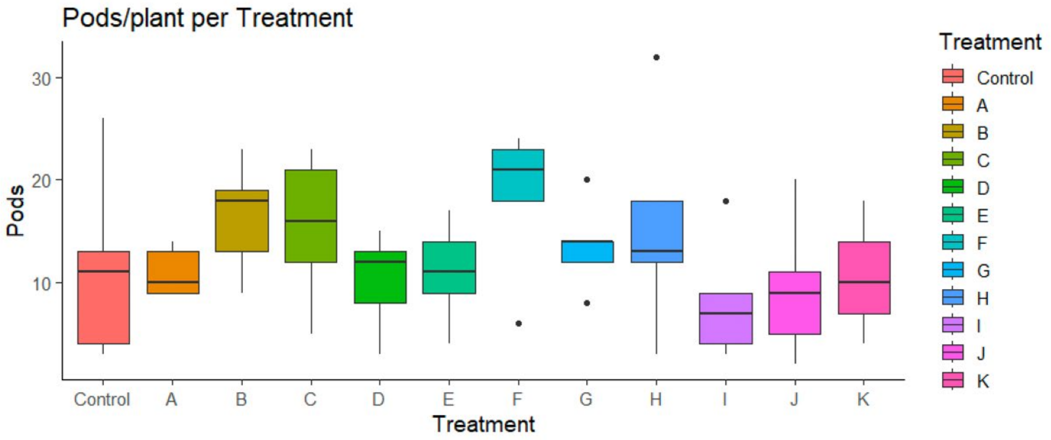

*Figure 15 – Treatment effect on the number of pods per plant of pea plants. Treatment codes as indicated in Table 1.*

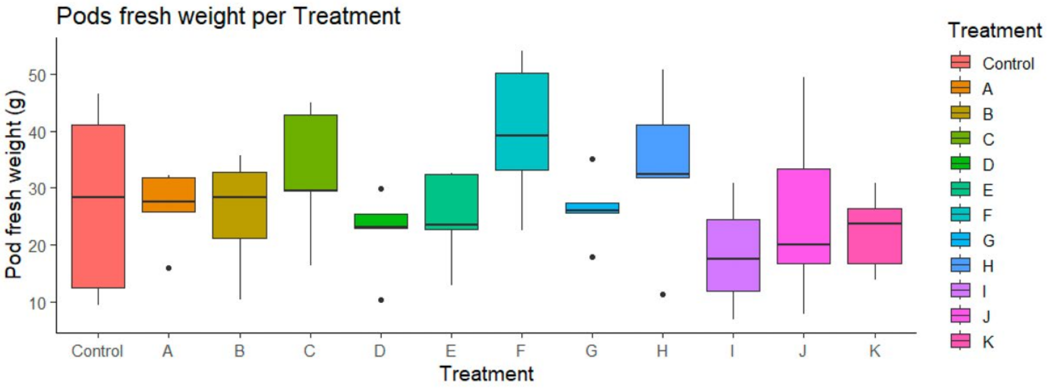

*Figure 16 - Treatment effect on the pod fresh weight of pea plants. Treatment codes as indicated in Table 1.*

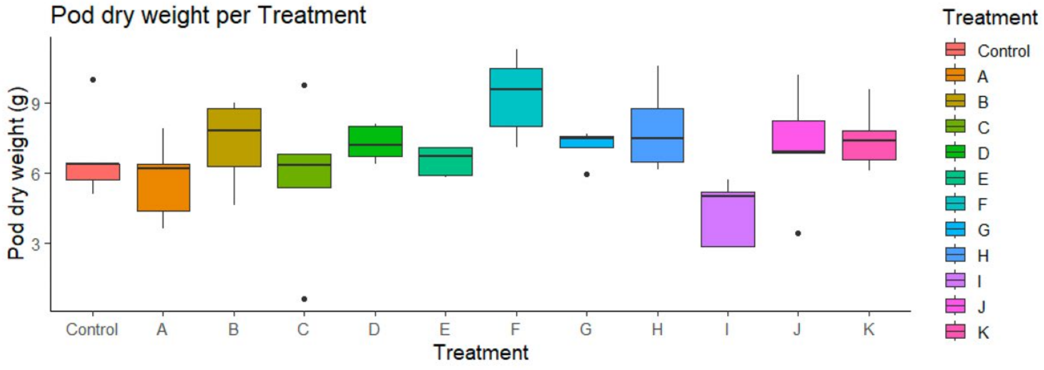

*Figure 17 - Treatment effects on the number of pods per plant of pea plants. Treatment codes as indicated in Table 1.*

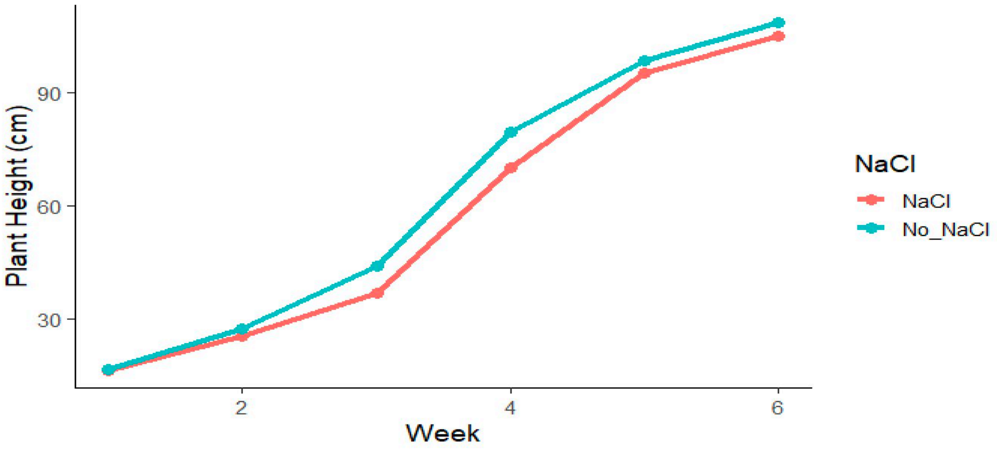

*Figure 18 - Salt treatment effects on the plant height of tomato plants, represented by the means over time. Treatment codes as indicated in Table 2.*

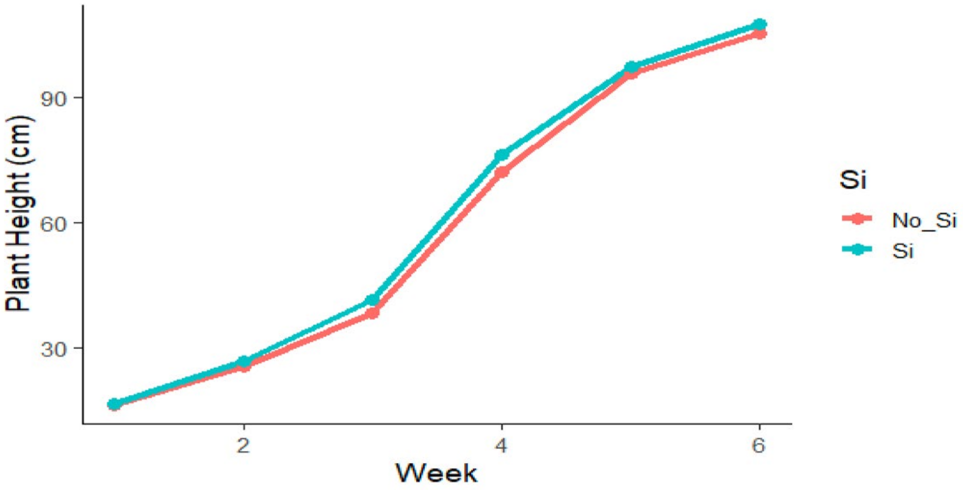

*Figure 19 - Silicon treatment effects on the plant height of tomato plants, represented by the means over time. Treatment codes as indicated in Table 2.*

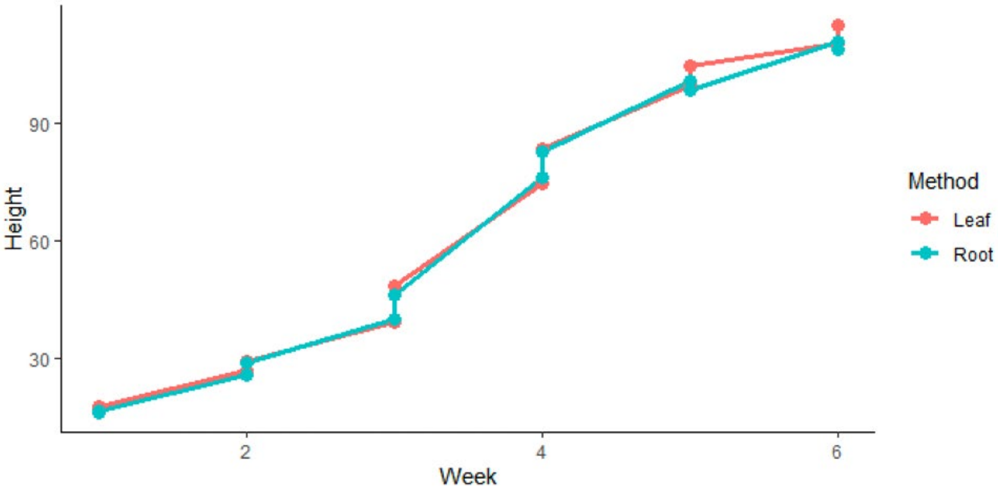

*Figure 20 – Leaf and root application of $CaSiO_3$ effects on the plant height of tomato plants, represented by the means over time. Treatment codes as indicated in Table 2.*

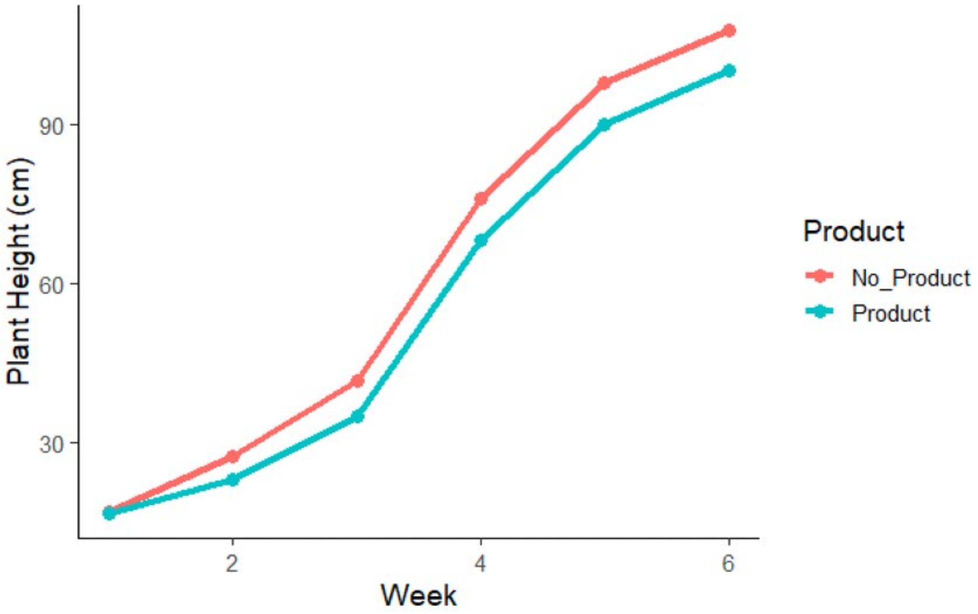

*Figure 21 - Effects of the use of the commercial product Actisil on plant height, represented by the mean over time. Product: Actisil-treated plants and No_Product: control plants without Actisil treatment.*

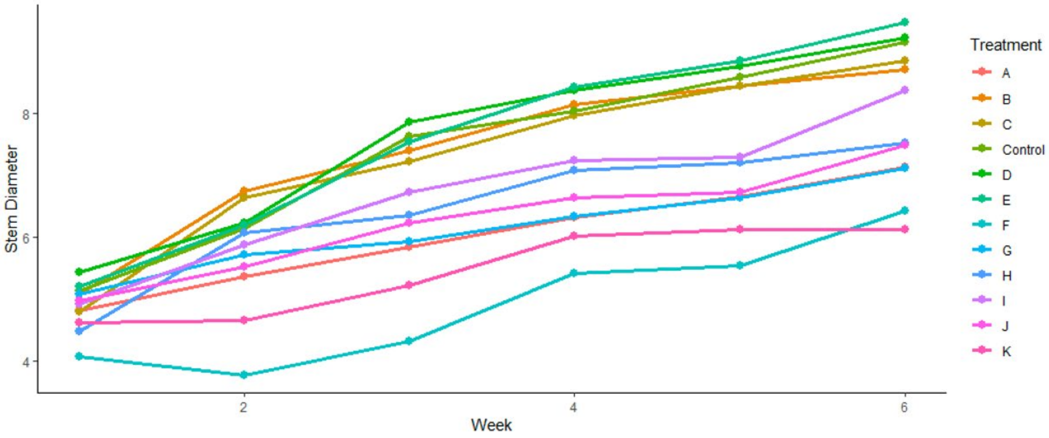

*Figure 22 - Treatment effects on stem diameter (mm) of tomato plants, represented by the means over time. Treatment codes as indicated in Table 2.*

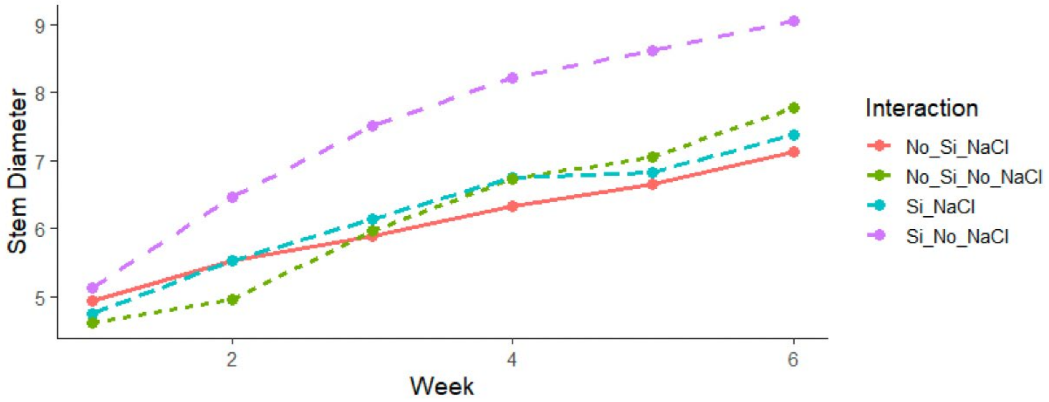

*Figure 23 –Treatment salt-silicon interaction effects on stem diameter (mm) of tomato plants, represented by the means. No_Si_NaCl: control treatment, No_Si_NaCl: salt control treatment effects, Si_No_NaCl: silicon treatment effects, and Si_NaCl: combined salt and silicon treatment effects.*

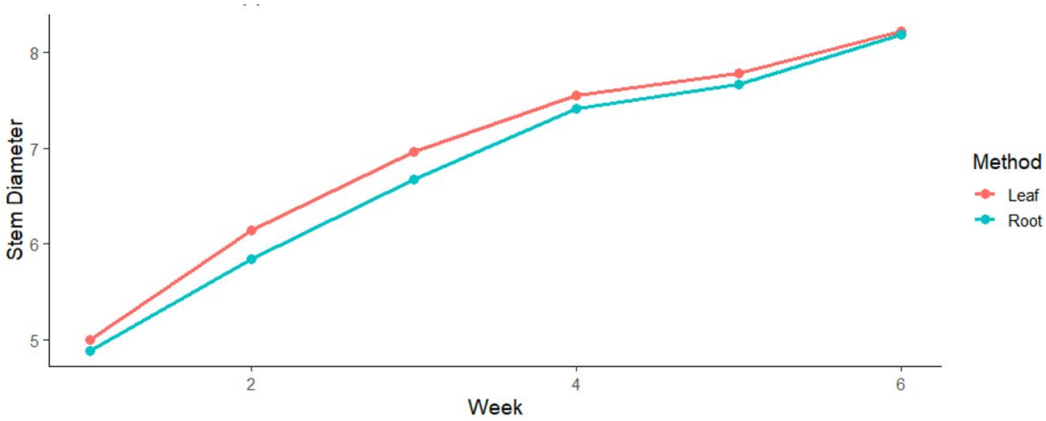

*Figure 24 - Effects of leaf and root application methods on stem thickness of tomato plants represented by the means over time.*

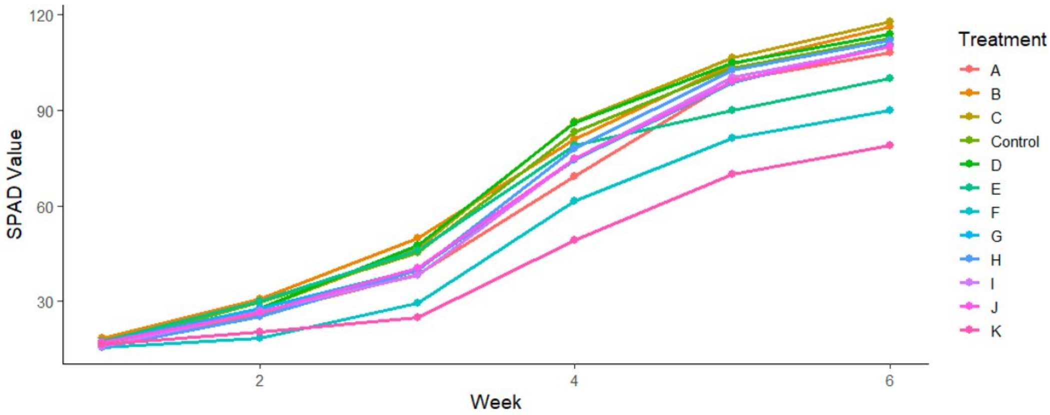

*Figure 25 - Treatment effects on chlorophyll content of tomato plants, represented by the means over time. Treatment codes as indicated in Table 2.*

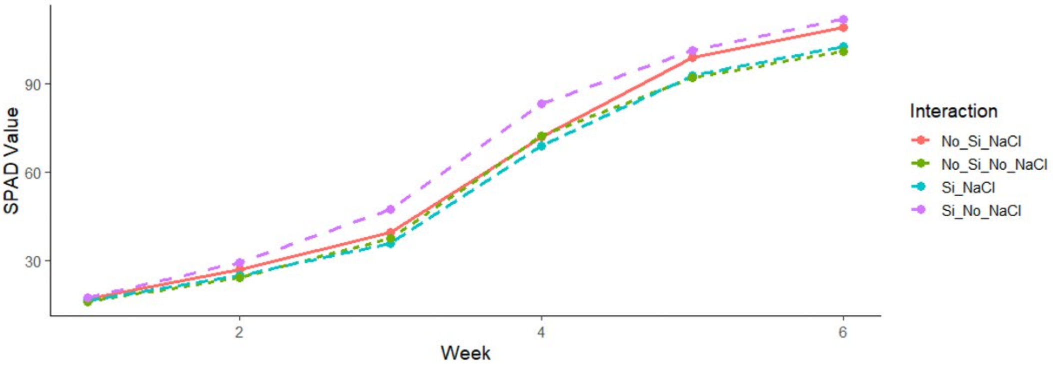

*Figure 26 - Treatment salt-silicon interaction effects on chlorophyll content of tomato plants, represented by the means over time. No_Si_NaCl: control treatment, No_Si_NaCl: salt control treatment effects, Si_No_NaCl: silicon treatment effects, and Si_NaCl: combined salt and silicon treatment effects.*

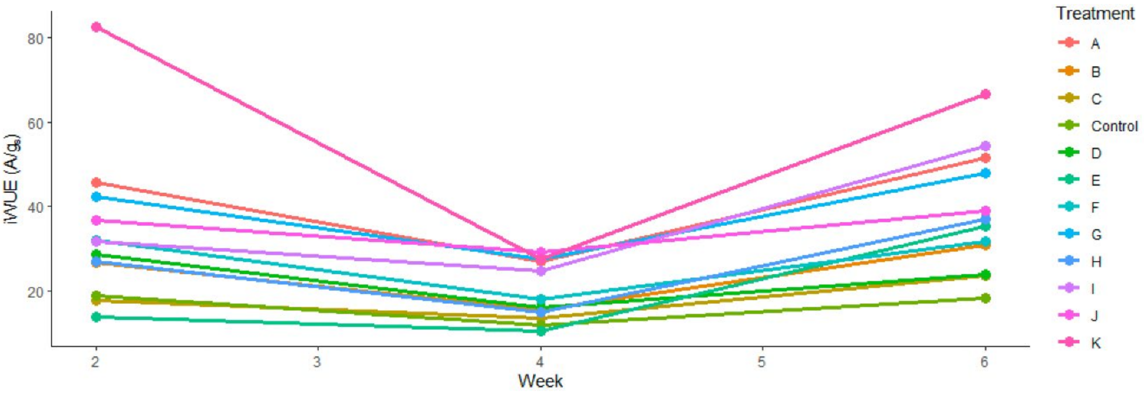

*Figure 27 - Treatment effects on intrinsic water use efficiency of tomato plants, represented by the means over time. Treatment codes as indicated in Table 2.*

*Table 5 - Water loss of stem and root per treatment of tomato plants, calculated by subtracting the respective fresh and dry weight.*

| Treatment | Stem water loss | Root water loss |
|---|---|---|
| Control | 92,11 | 94,04 |
| A | 91,80 | 97,63 |
| B | 91,59 | 94,13 |
| C | 91,34 | 94,95 |
| D | 90,04 | 96,02 |
| E | 90,85 | 91,52 |
| F | 73,35 | 76,93 |
| G | 91,14 | 97,06 |
| H | 91,57 | 94,02 |
| I | 91,36 | 94,76 |
| J | 91,43 | 94,98 |
| K | 91,61 | 88,83 |

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