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Management of Crop Water Stress in the Tropics and Subtropics (490g)

Influence of air humidity and salt stress on plant growth and nutrient uptake of hydroponically grown quinoa and eggplant

Bachelor's thesis

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FAO	Food and Agricultural Organisation of the United Nations
NUR	nutrient uptake rate
RH	relative air humidity
UN	United Nations

Abstract

Climate change, the growing population and multidimensional land degradation are putting pressure on the already fragile ecosystems of today's world and are threatening the goal of ensuring global food security. Rising temperatures accelerate the already widespread salinisation of soils and water scarcity. Since salinity and drought induced stress are one of the key factors reducing crop yield, it is important to study the mechanisms of salinity and air humidity tolerance and establish cultivation methods for a sustainable intensification of agriculture.

Eggplant and quinoa are both plant species of great importance, due to their high nutritional values and other beneficial properties that make them promising crops for ensuring food security. Therefore, the impact of salinity and air humidity on plant growth and nutrient uptake on those crops were studied in this experiment, to evaluate their suitability for saline growth and to investigate effects of controlled growing environments on salinity induced stress.

24 plants of each species were grown hydroponically in a controlled farming system. To study the effect of salinity 12 plants of each species were treated with 40mM NaCl two days after being transplanted into the hydroponic system set ups and compared to a control group growing under non-saline conditions. To study the effects of air humidity, two different air humidity levels were created in the growth chamber, in which the experiment took place. A group of 6 plants treated with 40mM NaCl and a group of 6 plants without salt treatment for both plant species were cultivated in each humidity level.

Salinity had a significant inhibitory effect on plant growth for eggplants, while quinoa plant growth was enhanced under saline conditions. While the different air humidity levels didn't show a significant effect for either plant species, quinoa plants benefited from high humidity levels and eggplants didn't show an effect to changing air humidity levels under non-saline conditions. Under saline conditions high air humidity levels further inhibited eggplant growth. Nutrient Uptake Rates were only slightly affected by salinity, as well as air humidity levels. Ultimately it was shown that eggplants experienced the biggest plant growth under non-saline and low air humidity conditions, opposingly to quinoa plants, which experienced the biggest plant growth under saline and high air humidity conditions.

Zusammenfassung

Der Klimawandel, die wachsende Bevölkerung und die multidimensionale Bodendegradation setzen die ohnehin schon anfälligen Ökosysteme der heutigen Welt unter Druck und bedrohen das Ziel weltweite Ernährungssicherheit zu gewährleisten. Steigende Temperaturen beschleunigen die bereits weit verbreitete Versalzung der Böden und die Wasserknappheit. Da salz- und trockenheitsbedingter Stress einer der Hauptfaktoren für die Verringerung der Ernteerträge ist, ist es wichtig, die Mechanismen der Salz- und Luftfeuchtigkeitstoleranz zu untersuchen und Anbaumethoden für eine nachhaltige Intensivierung der Landwirtschaft zu entwickeln.

Auberginen und Quinoa sind beides Pflanzenarten, die aufgrund ihres hohen Nährwerts und anderer vorteilhafter Eigenschaften vielversprechend für die Gewährleistung der Ernährungssicherheit sind. Daher wurden in diesem Versuch die Auswirkungen des Salzgehalts und der Luftfeuchtigkeit auf das Pflanzenwachstum und die Nährstoffaufnahme dieser Pflanzen untersucht, um ihre Eignung für den Anbau unter salzhaltigen Bedingungen zu bewerten und die Auswirkungen einer kontrollierten Wachstumsumgebung auf den salzbedingten Stress zu untersuchen.

Von jeder Art wurden 24 Pflanzen in einem kontrollierten Anbausystem hydroponisch angebaut. Um die Auswirkungen des Salzgehalts zu untersuchen, wurden 12 Pflanzen jeder Art zwei Tage nach dem Einpflanzen in das Hydrokultursystem mit 40 mM NaCl behandelt und mit einer Kontrollgruppe verglichen, die unter nicht salzhaltigen Bedingungen wuchs. Um die Auswirkungen der Luftfeuchtigkeit zu untersuchen, wurden in der Wachstumskammer, in der der Versuch stattfand, zwei verschiedene Luftfeuchtigkeitsstufen geschaffen. Je Spezies wurde eine Gruppe von 6 Pflanzen, die mit 40 mM NaCl behandelt wurden, und eine Gruppe von 6 Pflanzen, die nicht mit Salz behandelt wurden, unter den jeweiligen Luftfeuchtigkeitsniveaus angebaut.

Die Behandlung mit Salz hatte eine signifikant hemmende Wirkung auf das Pflanzenwachstum von Auberginen, während das Pflanzenwachstum von Quinoa-Pflanzen unter salzhaltigen Bedingungen gesteigert wurde. Während die unterschiedlichen Luftfeuchtigkeitsniveaus für keine der beiden Pflanzenarten eine signifikante Auswirkung auf das Wachstum aufzeigten, profitierten Quinoa-Pflanzen von hohen Luftfeuchtigkeitsniveaus, während Auberginen unter nicht-salzigen Bedingungen keine Wirkung auf wechselnde Luftfeuchtigkeitsniveaus zeigten. Unter salzhaltigen Bedingungen hemmte eine hohe Luftfeuchtigkeit das Wachstum der

Auberginen zusätzlich. Die Nährstoffaufnahmeraten wurden nur geringfügig durch den Salzgehalt und die Luftfeuchtigkeit beeinflusst. Letztlich zeigte sich, dass Auberginen unter nicht-salzhaltigen Bedingungen und bei niedriger Luftfeuchtigkeit das größte Pflanzenwachstum aufwiesen, im Gegensatz zu Quinoa-Pflanzen, die unter salzhaltigen Bedingungen und hoher Luftfeuchtigkeit das größte Pflanzenwachstum aufwiesen.

1. Introduction

Providing nutritious and environmentally sustainable food for the growing population facing climate change is amongst society's greatest challenges. Despite years of progress, global hunger has been increasing again over the last decade (Molotoks et al., 2021), highlighting the urgency of finding effective strategies for tackling the intertwined challenges of today's world. As the population is growing, the demand for food, water and many other essential resources intensifies, which is adding pressure on the already fragile ecosystems. According to the United Nations (UN) the world's population will reach 9.7 billion individuals by 2050, the majority of growth happening in developing countries (UN, 2022). In order to feed the growing population, food production has to increase by 70% to achieve the second sustainable development goal (SDG) of 'zero hunger' (FAO, 2009), but as of right now the world is moving further away from achieving food security and fighting malnutrition on a global scale (FAO, 2022).

Soils play a fundamental role in ensuring food and water security, as well as in providing climate regulation, but while the need to increase productivity in agricultural food production is growing, arable land is degrading. The pressure of population growth, economic development and climate change are further challenging the productivity of soils and contribute to the decline of their resources and ecosystem services, which are crucial to ensuring global food security as 99% of food is produced on land (Montanarella et al., 2016). Land degradation is a multidimensional problem influenced by various factors, with the five major pathways being aridity, land erosion by water, salinisation, soil organic carbon loss and vegetation decline (Prăvălie et al., 2021). Especially the salinization of soils, which refers to the accumulation of soluble salts in the root zone (Hopmans et al., 2021), has an adverse impact on agricultural productivity, due to its severe effects on soil fertility and plant growth. It is estimated that until 2050, 50% of all arable land will be affected by salinity, with semi-arid and arid regions being most prone to this degradation pathway due to low rainfall and high evapotranspiration (Butcher, 2016). Simultaneously freshwater resources are becoming increasingly scarce as the demand is rising due to population growth and the corresponding need to intensify food production (Hopmans et al., 2021). Through rising temperatures, climate change presents another factor further contributing to water scarcity, with the availability of surface and groundwater declining as evaporation rates are increasing. These effects are further contributing to the degradation of arable land. Beyond that, achieving effective irrigation becomes increasingly challenging, with poor irrigation management in semi-arid and arid areas already limiting productivity in food production (Hopmans et al., 2021).

To meet these multidimensional challenges, alternatives to conventional farming must be explored to achieve a sustainable intensification of agricultural production. Hydroponics are considered to be a suitable alternative to traditional soil-based agriculture (Kannan et al., 2022). This soil-less farming method offers several advantages that address the discussed limitations agricultural productivity is facing. Since hydroponics are operating in controlled indoor farming environments, which are adjustable to the needs of specific crops, environmental impacts such as soil degradation and adverse climatic conditions are being circumvented. This results in higher productivity and crop yield (Kannan et al., 2022). Additionally, hydroponics can reduce the water requirements by 70-80% to produce the same amount of crop as in conventional farming, which represents a great opportunity in dealing with the existing water scarcity (Kannan et al., 2022). Another benefit is the option to use wastewater as a nutrient source in hydroponic systems (Cifuentes-Torres et al., 2021). This results not just in an effective way to utilize wastewater, which is otherwise often used for irrigation without being treated, but can also provide additional income, since farmers could simultaneously produce food and purified water (Cifuentes-Torres et al., 2021). This cultivation technique could be particularly important for semi-arid and arid regions with limited access to water and poor soils. Further research needs to be done to make controlled faming systems more lucrative and accessible. Moreover, it is important to explore the suitability of different plant species for hydroponic growth and wastewater treatment, since currently predominantly lettuce, herbs and vegetables are being cultivated in those systems. With the challenges our world is facing it is important to integrate the growth of staple foods as well, to limit malnutrition and ensure global food security.

1.1 Aim of this study

The main aim of the experiment was to determine the effect of relative air humidity (RH) and salinity on plant growth and nutrient uptake of hydroponically grown quinoa and eggplant.

The main objectives of the experiment were

1. To study the suitability of quinoa and eggplant in saline conditions
2. To understand the effect of air humidity on growth of quinoa and eggplant
3. To study the interactions between air humidity and salinity under controlled conditions

From the objectives above the following hypotheses were formulated:

1. Quinoa is more suitable to grow under saline conditions due to its salinity resistance compared to eggplant.
2. Different plant species respond differently to changes in air humidity.

1.2 State of the art

1.2.1 Quinoa

Quinoa *(Chenopodium quinoa WILLD)* is an annual pseudocereal crop that belongs to the family of Amaranthaceae and has been cultivated in the Andean region for more than 7000 years (Jacobsen, 2003). Almost 159 thousand tons quinoa were produced globally in 2022, with the main production happening in Peru, Bolivia and Ecuador (FAOSTAT). Due to its high nutritional value, huge genetic variability and resistance to adverse abiotic factors the importance of this crop in the challenge of ensuring food security around the world is rising (Bazile et al, 2016). The nutritional characteristics of quinoa stand out due to the high contents and quality of protein, lipids, fibre, vitamins, minerals and its excellent balance of essential amino acids (Vilcancundo et al., 2017). The huge genetic variability results in cultivars being adapted to a large range of environmental conditions from cold, highland climate to subtropical conditions. Furthermore, quinoa plants are tolerant to several extreme growing conditions including drought, frost and salinity, resulting in wide adaptability and the chance for considerately contributing to food security in the face of soil depletion due to human activity and climate change (Jacobsen, 2003). The early maturity of the crop due to its short development time of 150 days is another advantage when facing water scarcity and extreme climate conditions (Jacobsen, 2003). In addition, quinoa belongs to the group of facultative halophytes, which means it has the ability to grow under saline conditions, thereby increasing the importance of the crop in the face of advancing soil salinisation worldwide. The Food and Agriculture Organization (FAO) declared 2013 to be the international year of quinoa to promote the research and production of this crop, which lead to a significant increase in countries cultivating quinoa (Alandia et al., 2020). These properties make quinoa a promising research objective for this experiment.

1.2.2 Eggplant

Eggplant *(Solanum melongena L.)* is a perennial vegetable crop that belongs to the family of Solanaceae and is being cultivated in many tropical and temperate parts of the world, especially in South and South-East Asia (Sharma et al., 2020). In 2022 59,3 million tons eggplant were produced globally, with the main producers being China and India (FAOSTAT). Eggplant is the fifth most economically important crop within the Solanaceae family and is considered as one of the 35 foods with the most considerable relevance in achieving global food security (Fowler, 2003). Furthermore, eggplant is ranked amongst the top ten vegetables providing healthy food due to its unique amount of various nutrients, minerals and phenolic acids (Quammruzzaman et al., 2020). Eggplants have a large amount of morphological diversity, suggesting a high genetic variation, though the current lack of research leaves many biotic and abiotic tolerances unknown (Chapman, 2020). Although eggplant is the third most widely grown solanaceous vegetable after potatoes and tomatoes, research about this crop is far behind research of other Solanaceae crops (Wei et al., 2020). Eggplant belongs to the group of glycophytes, which opposite to halophytes describes plants sensitive towards salinity. Nevertheless, this trait could be enhanced by genetic engineering (Brenes et al., 2020). It is of high importance to include this crop in various research because eggplant is an important crop but there exists only limited knowledge about traits that could be beneficial for future agriculture.

1.2.3 Hydroponic farming

Hydroponics is a method of cultivating plants in soil-less conditions with their roots immersed in nutrient solution. The term ‘hydroponics’ was introduced by Professor William Gericke in 1930 and derives its name from the Greek words ‘hydro’ (water) and ‘ponics’ (labour) (Jan et al., 2020). There are two large classification groups for hydroponic systems: open and closed systems. In open systems the nutrient solution flows through the system only once and is not recirculated or recycled. Most hydroponics are operating in closed systems, where the nutrient solution is flowing through the system in a circuit (Cifuentes-Torres et al., 2021).

Hydroponic farming offers numerous benefits over conventional soil-based agriculture. Challenging factors like soil degradation due to aridity, salinity and nutrient loss have no influence in hydroponic farming and the multiple pressures of climate change which decrease yield and productivity are avoided as well. Another major advantage in facing water scarcity around the world is the reduced requirement of water in hydroponic farming, since compared to traditional farming 70-80% less water is required to produce the same yield (Kannan et al., 2022). Furthermore, soil-borne infections can be avoided and there is no need for pesticides, which eliminates the resulting toxicity for both food consumption and the environment. The growing environment in hydroponics can be controlled and set to the optimal conditions for individual crops, which results in the chance for higher productivity and a bigger yield (Kannan et al., 2022).

Although hydroponics could help to face numerous challenges resulting from climate change, there are some disadvantages using this method as well. The higher initial cost is often a huge burden for farmers, which makes this alternative farming method less attainable. The need for constant supply of light and energy adds operational costs and complexity, which further limits the accessibility, especially in rural areas. Additionally, a high level of technical knowledge is required to manage hydroponics effectively. The monitoring and maintenance of pH, electrical conductivity and nutrient concentration is of high importance, especially for limiting the likelihood of contamination and water borne diseases. Pathogens can spread rapidly through the nutrient solution, which bears a high risk of all plants getting infected when cultivated in a closed system, since the solution is constantly circulating through the system. Poor oxygen supply can limit plant growth as well (Kannan et al., 2022).

1.2.4 Salinity

Salinity refers to the accumulation of soluble salts such as Sodium (Na^+), Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) cations, as well as Chloride (Cl^-) and Sulfate (SO_4^{2-}) anions in the soil solum (Butcher et al., 2016), with sodium chloride (NaCl) being the most soluble and abundant salt (Munns & Tester 2008). Soils are classified as saline when their electrical conductivity exceeds 4 dS/m, which is equivalent to approximately 40 mM NaCl. Soil salinity represents a significant abiotic limitation for agricultural production, particularly in arid and semi-arid regions, due to their low rainfall and high evapotranspiration (Singh, 2022). Approximately 1 billion hectares of land, spanning over 100 countries, are currently affected by salinity and it is anticipated that the salinization of soils will increase significantly in the future (Tian et al., 2020).

There are two main causes for the development of soil salinity, the first being primary salinity and the second being secondary salinity (Butcher et al., 2016). Primary or dryland salinity occurs naturally through the accumulation of soluble salts, originating either from saline parent material or capillary rise from saline groundwater. Secondary or irrigation salinity on the other hand is caused anthropogenically, mainly because of the use of poor irrigation water (Butcher et al., 2016). In both cases the accumulation of salts results from poor drainage or inadequate leaching. Globally, 30% of irrigated land is affected by secondary salinity (Hopmans et al., 2021), in semi-arid and arid regions, which constitute 46% of the world's total area, approximately 50% of irrigated land is degraded to varying degrees due to salinity (Okur & Örçen, 2020). Plants display a biphasic response to salinity, initially experiencing osmotic stress, followed by the consequences of ion toxicity (Butcher et al., 2016). Osmotic and drought stress arise mainly from salt accumulation in the root zone, restricting water uptake and thus inhibiting plant growth or causing the plant to wilt. The second phase is ion specific and occurs when salt concentrations within the plant reach toxic levels. In this phase the toxicity primarily accelerates the senescence of older leaves, which is limiting the photosynthetic capacity of the plant as soon as the rate of old leaf death exceeds the production of new leaves. This results in reduced carbon fixation in the plant, therefore further limiting plant growth (Munns & Tester 2008). Additionally, high ion concentrations within the plant affects nutrient uptake as well. Especially the impact of Na^+ and Cl^- toxicity is affecting plants significantly. Na^+ has the most detrimental impact on plant growth and development by inducing Ca^{2+} and Potassium (K^+) deficiencies. This occurs because Na^+ displaces Ca^{2+} on cell walls and membranes, leading to protein denaturation and destabilization of the plant. Furthermore, Na^+ is replacing K^+ in biochemical reactions, thus disrupting several physiological processes. While Cl^- is an essential micronutrient involved in enzyme regulation and photosynthesis, excessive concentrations are interfering with Nitrate (NO_3^{2-}) uptake, leading to chlorophyll degradation, thus restricting photosynthetic activity as well. However, the extend in which salinity limits crop production and yield is highly variable, since the impact depends on various factors, such as soil texture and moisture content, nutrient concentrations in the soil, plant species and cultivar, as well as growth stage (Butcher et al., 2016).

1.2.5 Vapour pressure deficit

Vapour pressure deficit (VPD) is defined as the difference between the saturation vapour pressure (e_s) and the actual vapour pressure (e_a) at a given temperature and is expressed in kPa (Amitrano et al., 2019). Expressed mathematically, $VPD = e_s - e_a$ (Grossiord et al., 2020). Vapour pressure describes the amount of water in its gaseous form in the air. When the vapour pressure is saturated, the relative air humidity (RH) is at 100%, meaning the air has reached its maximum capacity for holding water vapour in the air. VPD is dependent on RH and temperature, the higher the temperature, the more water vapour can be hold in the air (Grossiord et al., 2020). For plants, VPD is sensed as the difference between the vapour pressure inside the leaf and the vapour pressure of the atmosphere, often described as the leaf-to-air vapour pressure deficit (VPD_L) (Grossiord et al., 2020). Plant physiology as well as plant growth are impacted by VPD, since it is a key driver for transpiration, regulated by stomatal movements. A high VPD (2-6 kPa) is increasing transpiration, thus increasing water loss. The plants respond with closing their stomata, which is not only reducing transpiration but carbon fixation as well, which leads to a decrease in photosynthetic activity, ultimately reducing plant growth and productivity. A low VPD (0.2-2 kPa) on the other hand promotes stomatal opening, increasing photosynthetic carbon gain. Because of the high-water vapour saturation in low VPD environments, transpiration rates decline despite open stomata. However, plant responses to VPD and other environmental conditions vary depending on species or cultivar, meaning that a low VPD environment doesn’t necessarily result in enhanced plant growth or productivity (Amitrano et al., 2019).

2. Material and Methods

2.1 Plant varieties and cultivation

For the experiment two different vegetable species with different salinity resistances were selected for comparison. The chosen species are Eggplant *(solanum melongena L.)* cv. Jaylo (Rijk Zwaan Welver GmbH, Welver, Germany) and Quinoa *(Chenopodium quinoa WILLD)* cv. Titicaca (Quinoa Quality ApS, Regstrup, Denmark).

The seeds were placed on wet filter paper inside a plastic container, until they germinated. After radicle emergence the seedlings were planted in growing trays holding sand as substrate. Three weeks later the plants were transplanted into the hydroponic system setup, where they were cultivated for 33 days and then harvested.

2.2 Experimental setup

The experiment took place in the Phytotechnikum and was conducted in a growth chamber (fig) built by the team working on marginal water and hydroponics of the Hans-Ruthenberg-Institute (490). The growth chamber contained eight hydroponic systems, four for each plant species. Each system accommodated six plants, resulting in a total of 48 plants, 24 individuals per species.

2.2.1 Growing conditions and treatments

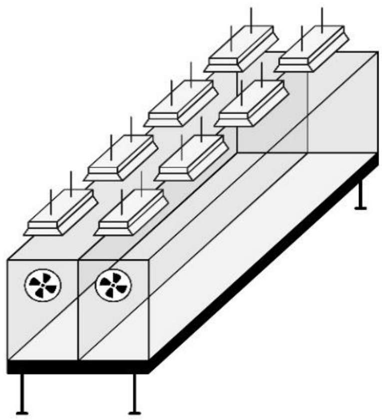

Figure 1: Schematic visualisation of the growth chamber

The growth chamber (Fig. 1) measures 6m in length, 1.5m in width, with a height of 1m and is divided lengthwise by a plexiglass pane to make maintaining two different environmental conditions possible. The chamber was equipped with artificial light to provide plant active radiation and a steam humidifier (RM 2, Condair, Norderstedt, Germany), as well as a dehumidifier (DC-10, Seibu Giken DST AB, Spanga, Sweden) each running 14 hours a day from 9:30 am to 11:30 pm. The humidifiers created different environmental conditions (Tab.1) on each side of the plexiglass pane, on the left side the plexiglass pane the dehumidifier obtained a relative air humidity of approximately 40%, while on the right side the steam humidifier created a relative air humidity of approximately 80%.

The temperature and air humidity were measured in a 10-minute interval by dataloggers (Tinitag Plus 2, Gemini Data Loggers, Chichester, United Kingdom), that were hung up inside the chambers.

Table 1: Environmental conditions inside the chamber

	Average temperature [°C]	Average RH [%]	Average VPD [kPa]
High VPD	25.19	43.01	2.74
Low VPD	25.44	80.20	0.40

The pH and the electrical conductivity were measured daily with a pH-meter (WTW pH/Cond 3320 SET 2, Xylem Analytics Sales GmbH & Co. KG, Weilheim, Germany), the pH of the nutrient solution was maintained between 4,0 - 5,7 using a 3M hydrogen chloride (HCl) solution.

Four hydroponic systems, two for each species, were placed on each side of the pane. Two days after transplanting, NaCl was added into the nutrient solution of one system per species and relative air humidity level until a concentration of 40 mM was reached, the remaining systems were functioning as a control and subjected to 0 mmol NaCl (Fig. 2).

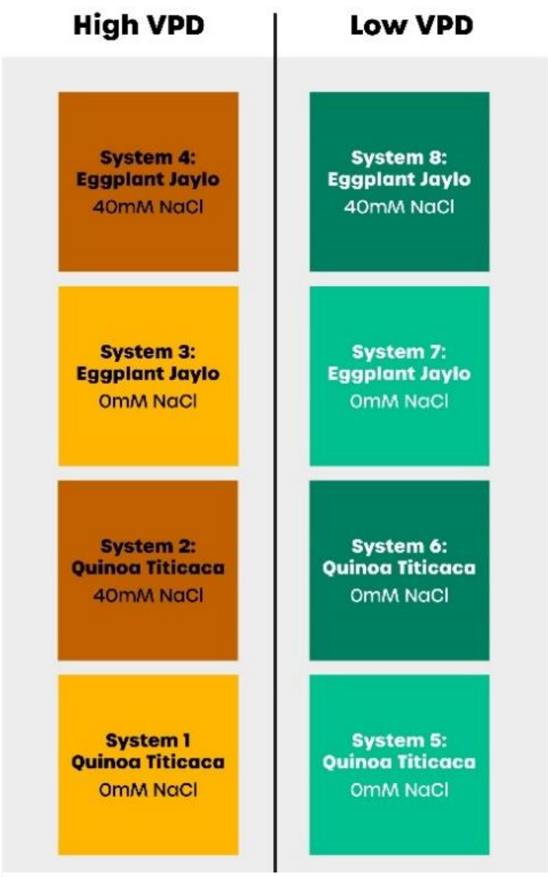

Figure 2: Schematic visualization of the experimental setup inside the chamber

2.2.2 Hydroponic system setup

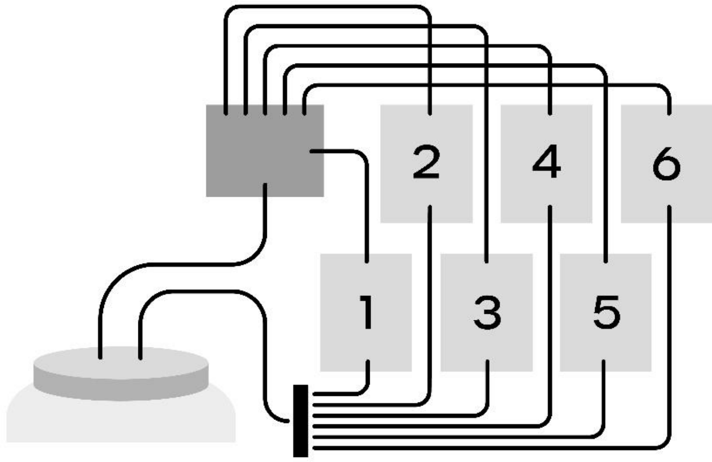

Figure 3: Schematic visualisation of the hydroponic system

Each hydroponic system, as shown in Figure 3, consists of seven plastic containers (Eurobehälter geschlossen 30x20x12 cm, Auer GmbH, Amerang, Germany) and a plastic barrel with a filling volume of 60l, connected with hoses to form a circuit through which 102 l of Yoshiba nutrient solution (Tab. 2) flowed constantly. The nutrient solution was exchanged twice throughout the experiment, the first exchange took place 22 days and the second 29 days after transplanting the plants into the systems. Each container as well as the barrel were closed with a lid to prevent evaporation and algae development. The containers holding a plant had a hole in the middle of their lid, sealed with a foam-stopper to stabilize the plants.

From the barrel the nutrient solution was distributed into the six containers carrying a plant using a pump (compactON 1000, EHEIM, Deizisau, Germany) to move the solution through the hoses. The hoses on the container inlet were attached in a certain way so that the impact of the water created air bubbles to supply the roots with oxygen. After the solution flowed through the containers it was led through the outlet hoses into the seventh container, where the six streams connected again. The solution flowing through this container was used for nutrient solution sampling and other daily measurements. After flowing through the seventh container the solution was led back into the barrel.

Table 2: Composition of the nutrient solution from the stock solutions A-G (modified after Yoshida et al., 1976)

	Element	Chemical	Stock [g/L]	Stock final [ml/L]	Solubility [g/L]
A	N	NH_4NO_3	114,29	1	2089
B	P	$NaH_2PO_4 * 2H_2O$	50,37	1	850
C	K	K_2SO_4	89,14	1	111
D	Ca	$CaCl_2 * 2H_2O$	146,73	1	986
E	Mg	$MgSO_2 + 7H_2O$	405,73	1	710
F	Fe	FeNa+- EDTA	15,080	1	n.n
G	Mn	$MnCl_2 * 4H_2O$	1,875	1	700
	Zn	$ZnSO_4 * 5H_2O$	0,044		965
	Cu	$CuSO_4 * 4H_2O$	0,393		203
	Mo	$(NH_4)_6Mo_7O_{24} * 4H_2O$	0,092		430
	B	H_3BO_3	11,675		50

2.3 Daily measurements

The daily measurements were taken in the morning around 10:30 am. They started the day after the NaCl was added into half of the systems and continued until the day of the harvest, therefore the measurement days amount to 31 days.

2.3.1 water loss

With a permanent marker a line was drawn 7.5 cm below the edge of the barrel of each system, to visualize the height of the water level inside the barrel when 102 l of solution are circulating through the system. Every morning the barrel was filled up to the marked line with a measuring cup to refill the system back up to 102 l. The refilled quantity was determined as daily water loss. With this data the cumulative water loss was calculated.

2.3.2 Nutrient solution sampling

After refilling the systems to their fixed filling quantity of 102 l there was a 30 min wait before the nutrient solution samples were taken, to make sure the nutrients were well distributed throughout the whole solution. To collect the samples a plastic vial with a 20 ml volume (nerbe plus GmbH & Co. KG, Winsen, Germany) was filled with nutrient solution taken out of the seventh container. The vials were labelled with consecutive numbers and then transferred and stored in a fridge in the lab of the Department of Management of Crop Water Stress in the Tropics and Subtropics (490g) until they were analysed for the nutrient concentration. On the two days the nutrient solution in the systems was exchanged two samples were taken, one before exchanging the solution and one afterwards.

2.4 Harvest

After being cultivated in the hydroponic system for 33 days the plants were harvested. Each plant was taken out of their container and cut into their individual plant parts. The roots and leaves were cut off the stem, the diameter and length of which was then measured with a meter stick. The petioles were separated from the leaf blades.

The harvesting process differed between the two plant species. For each eggplant the leaves were counted, and each leaf blade and petiole were put individually in separate paper bags. Some eggplant plants developed flowers, those were separated from the plant and put into paper bags as well. Because quinoa plants develop more leaves than eggplant plants, the lower half of the expressed leaf blades and petioles were determined as old leaves and the upper half as young leaves. The leaf blades and petioles of each category were put into labelled paper bags.

After the harvesting process the labelled paper bags were transferred into a dry chamber (ED 400, BINDER GmbH, Tuttlingen, Germany) where the plant material was dried at 70°C for 72 hrs for the following dry weight determination.

2.5 Plant measurements

2.5.1 Leaf area

The leaf area was determined during the harvesting process. After the leaf blades were separated from the petioles the leaf area was measured using a Leaf Area Meter (3100 C Area Meter, LI-COR Environmental GmbH, Bad Homburg, Germany), before the leaf blades were put into the labelled paper bags. The leaf blades of the eggplant plants were measured individually, while the leaf blades of the quinoa plants were measured in the two determined categories of young and old.

2.5.2 Dry weight

After the drying process the dry plant material was weighed with a precision scale (ABJ-NM/ABS-N, KERN & SOHN GmbH, Balingen-Frommern, Germany). The contents of each bag were weighed individually, afterwards the dry plant material was transferred back into the bags, which were then stored inside a cupboard inside the greenhouse for further evaluations.

2.6 Sample analysis

The collected nutrient solution was analysed for its Na^{+}, Cl^{-}, NO_3^{2-}, PO_4^{3-} and K^{+} concentration. The NO_3^{2-}, PO_4^{3-} and Cl^{-} contents of the nutrient solution were evaluated with a flow analyser (Technicon Autoanalyzer II, SEAL Analytical GmbH, Norderstedt, Germany). For that the sampler was loaded with 2 ml of nutrient solution sample. For the Cl^{-} evaluation samples taken from systems with salt treatment had to be diluted 1:50 or 1:100, depending on the nutrient concentration, for the determined values not to overshoot. Overshot samples had to be diluted to a higher degree in order to receive clear results. The Na^{+} and K^{+} contents of the nutrient solution were determined with a flame photometer (PFP-7, Jenway, United Kingdom). Because of their high nutrient concentration, the Na^{+} samples taken from systems with salt treatment had to be diluted 1:20 for the evaluation.

2.7 Data and statistical analysis

The collected tinytag data was sorted in Microsoft Excel and mean values where calculated. The RH data was then converted to VPD using the following formulas (Wilhelm, 1976):

$VPD = Es(T)\ [kPa] - Ea$	VPD = water pressure deficit
$Es(T) = 613{,}75\ \times exp\frac{17{,}502\ \times T}{240{,}97 + T}$	Es(T) = saturation vapour pressure
$Ea = Es(T)\ \times \frac{rH}{100}$	Ea = actual water pressure

For the statistical analysis the collected raw data and measured values were sorted in Microsoft Excel. For the analysis of the dry weight, stem measurements and leaf area the mean values, standard deviation and standard error were calculated, and the values of water loss and nutrient uptake were cumulated using Microsoft Excel as well.

For the descriptive statistics graphs were plotted with the calculated data using SigmaPlot 12.5. To visualize the dry weight, stem measurements and leaf area bar graphs of the mean values including the standard error were plotted. The cumulated water loss and nutrient uptake values were visualized using spine line graphs. To confirm significant differences between the different environmental conditions and treatments a two-way ANOVA test was carried out also via SigmaPlot 12.5. The significance level was set at $p < 0.05$.

3. Results

3.1 Dry weight

Figure 4 shows the average dry weight of the total plants in g, as well as their individual plant parts (root, stem and leaves) for each system. The total plant dry weight of quinoa showed no significant difference between salt treatment and humidity level. Nevertheless, plant growth benefitted from the salt treatment in both humidity levels. Plants without salt treatment grown under high VPD reached a dry weight of 17.2 g on average, while the plants grown under saline conditions reached an average dry weight of 20.8 g. A similar positive effect is seen for the plants grown under high VPD where plants without salt treatment reached a dry weight of 19.1 g on average, while the plants grown under saline conditions reached an average dry weight of 2.2 g. Not just the saline conditions had a positive effect on plant growth, a low VPD further enhanced growth, which lead to quinoa plants grown under saline conditions and low VPD experiencing the biggest growth. For eggplants the salt treatment had a significant impact on plant growth in both humidity levels ($p<0.001$). While eggplants without the salt treatment reached a dry weight of 24.4g on average under high VPD, the plants grown under saline conditions only reached an average dry weight of 4.2 g. Plants grown under saline conditions and low VPD suffered even more and only reached a dry weight of 3.5 g on average, while VPD didn´t have an effect on plant growth for plants that weren´t treated with salt and reached a dry weight of 24.5 g on average. Therefore, the combination of growing under saline conditions in a low VPD environment had the strongest negative effect on plant growth for eggplants in contrast to quinoa, where plants under these conditions were thriving the most.

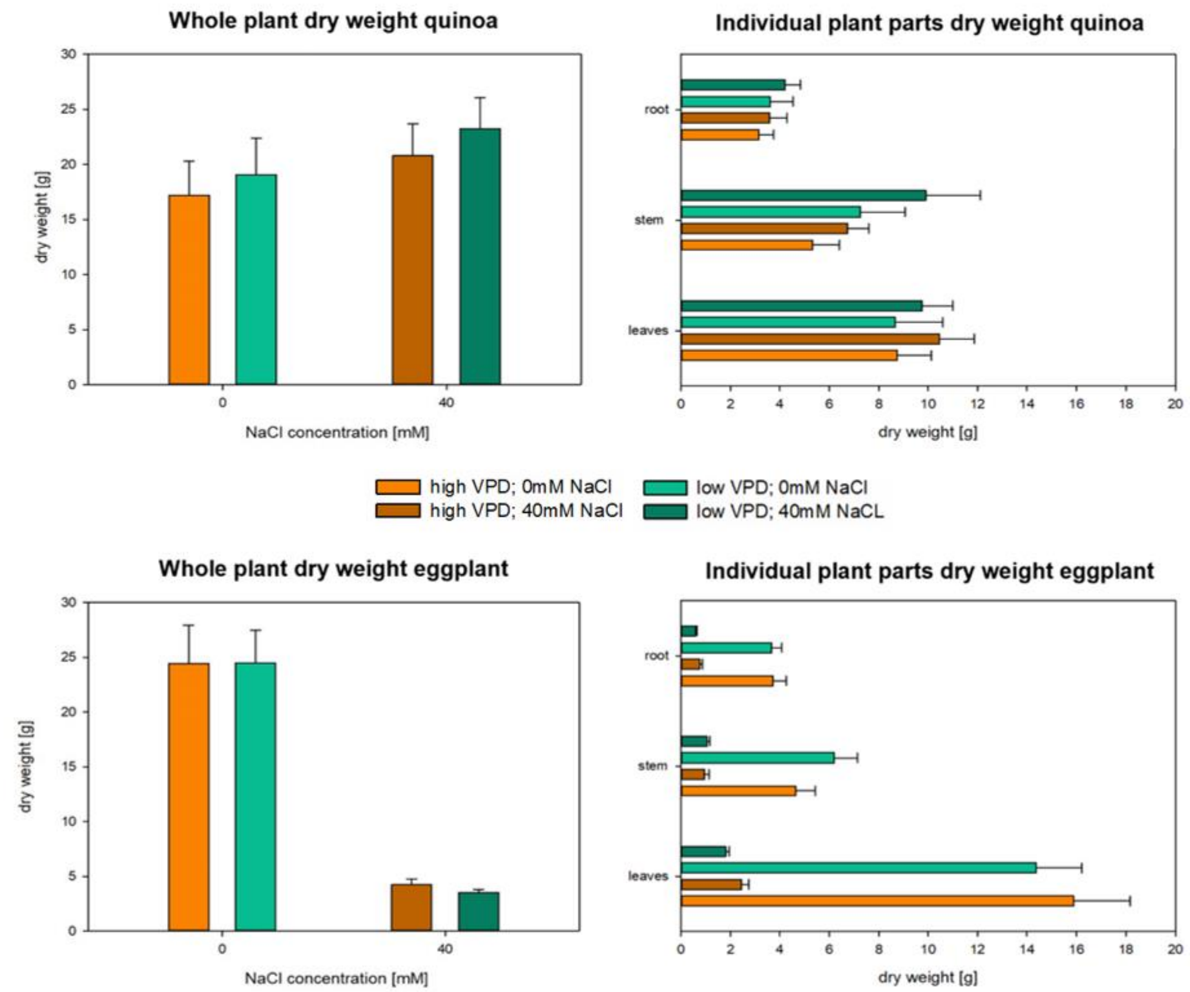

Figure 4: Barplots showing the average dry weight in g *of the whole quinoa plants, individual quinoa plant parts, the whole eggplant, and individual eggplant parts, respectively. The dry weights are divided into high VPD, 0 mM NaCl (orange); high VPD, 40 mM NaCl (brown); low VPD, 0 mM NaCl (turquoise); and low VPD, 40 mM NaCl (green), the individual parts of the plants were roots, stems, and leaves. Standard errors are indicated by whiskers, Plots were generated using SigmaPlot.*

This tendency is seen when looking on the individual plant parts in most cases as well, although some plant parts showed a different trend as to be seen when looking at the total plant dry weight. Especially the roots displayed the same reaction to salt treatment and different humidity level in both species. For the root dry weight of quinoa plants neither the salt treatment nor the humidity level had a significant impact on growth. As seen in the total plant dry weight the root growth of quinoa plants grown under saline conditions benefitted from the treatment with plants grown under high VPD reaching a dry weight of 3.6 g on average and low VPD enhancing root growth to an average dry weight of 4.2 g. The low VPD enhanced root growth of plants without salt treatment as well, with roots reaching a dry weight of 3.6 g on average, while roots growing under high VPD only reached a dry weight of 3.2 g on average. Viewed as in the total plant growth of eggplants the salt treatment had a significant impact ($p<0.001$), while the humidity level didn’t lead to a significant difference on root growth. Eggplant roots without salt treatment reached the same dry weight of 3.7 g on average for both humidity conditions. The roots of plants growing under saline conditions and high VPD reached a dry weight of 0.8 g on average and plants under low VPD reached an average dry weight of 0.6 g. It is shown again that in contrast to quinoa plants whose roots were experiencing the biggest growth under saline and low VPD conditions, eggplant roots suffered most under these conditions.

Just as with root growth neither the salt treatment nor the different humidity levels had a significant impact on leaf growth in quinoa plants. Nevertheless, the salt treatment had a bigger impact on leaf growth than the humidity level with plants grown under saline conditions the leaves of quinoa plants reached a dry weight of respectively 10.5 g under high VPD and the leaves growing under low VPD reached a dry weight of 9.8 g on average. The leaves of quinoa plants were the only plant part that benefited from high VPD under saline conditions. Quinoa leaves without salt treatment reached a dry weight of 8.7 g for both humidity levels. Eggplant leave growth reacted in a similar way to the different treatments and humidity levels as the roots. The most leaf growth was reached under non-saline conditions and high VPD with a dry weight of 15.9 g on average, while leaves growing under low VPD reached an average dry weight of 14.4 g. Eggplant leaves under saline conditions reached a dry weight of 2.5 g on average under high VPD, while the leaf growth under low VPD suffered most with reaching a dry weight of 1.8 g on average. While the impact of the relative air humidity levels on leaf growth was minor in quinoa plants, eggplant leaves benefited from a high VPD environment.

In both plant species the stem growth was impacted in a different way, especially from the relative air humidity, than the other plant parts. While the salt treatment for quinoa plants didn’t show a significant difference in stem growth for both humidity levels, the relative air humidity had a significant impact ($p=0.035$) for stem growth. The quinoa stems grown under high VPD reached a dry weight of 5.3 g on average under non-saline conditions, while plants grown under low VPD reached an average dry weight of 7.3 g. Stems growing under saline conditions reached a dry weight of 6.7 g on average under high VPD and a dry weight of 9.9 g on average under low VPD. The least stem growth happened under non-saline conditions with high VPD, the most beneficial environment was under saline conditions and low VPD. Although this follows the same reaction pattern than root and total plant growth, a different trend could be seen because the stem was the only plant part which benefitted more from a low VPD environment than saline conditions. Eggplant stems showed a different reaction to growing conditions as the other plant parts as well. Under non-saline conditions a low VPD had a significant impact ($p=0.022$) on plant growth, which is the only occasion where the VPD had a significant impact for plant growth in eggplants. As seen in the other plant parts the salt treatment had a significant impact ($p<0.001$) on plant growth in both humidity levels. Eggplant stems without salt treatment reached a dry weight of 4.7 g on average under high VPD and an average dry weight of 6.2 g under low VPD. Under saline conditions the stems reached an average dry weight of 1 g for both humidity levels. The stem growth of eggplants was the only plant part that benefitting from low VPD, while a high VPD didn't impact the growth in a positive way under saline conditions.

Overall the dry weight data shows that quinoa Plants thrived the most under saline conditions in a low VPD environment and suffered most under non-saline conditions in a high VPD environment, which is in contrast to the reaction of eggplant growth to the different growing conditions, with eggplants thriving the most under non-saline conditions in a high VPD environment and plant growth being restricted the most under saline conditions in a low VPD environment.

3.2 Leaf area

Figure 5 shows the average leaf area in cm^2 of each system. Eggplants showed a significant difference between salt treatments on both humidity levels ($p<0.001$). Eggplants grown under high VPD and non-saline conditions developed a leaf area of 3679.9 cm^2 on average while plants grown under saline conditions had an average leaf area of 610.4 cm^2. Eggplants grown under low VPD and non-saline conditions developed a leaf area of 3640.1 cm^2 while the eggplants grown under saline conditions had an average leaf area of 452.6 cm^2. There was no significant difference for leaf area development between the different air humidity levels, in both environments the salt treatment had a significantly negative effect on the leaf area development.

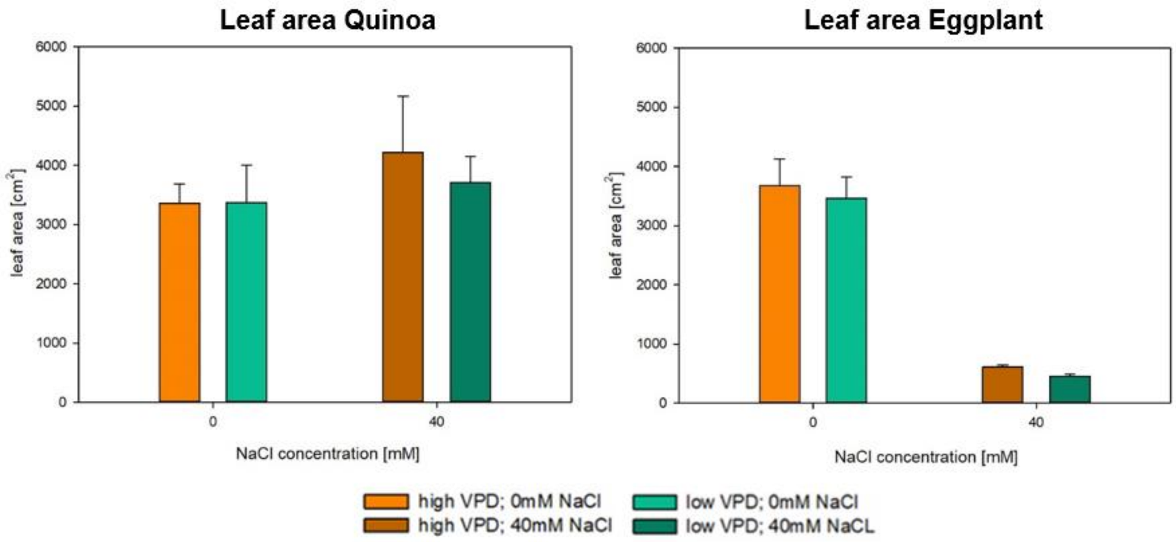

Figure 5:Barplots showing the average Leaf area in cm² *of Quinoa (left) and Eggplant (right). Results are divided into high VPD, 0 mM NaCl (orange); high VPD, 40 mM NaCl (brown); low VPD, 0 mM NaCl (turquoise); and low VPD, 40 mM NaCl (green). Standard errors are indicated by whiskers, Plots were generated using SigmaPlot.*

Quinoa plants didn´t show a significant difference between treatments or air humidity levels. Quinoa plants grown under high VPD developed a leaf area of 3363.6 cm^2 on average while quinoa plants grown under saline conditions had an average leaf area 4223.4 cm^2. Quinoa plants grown under low VPD developed a leaf area of 3366.9 cm^2 on average while plants grown under saline conditions had an average leaf area of 3713.6 cm^2. Although there was no significant difference, the salt treatment had a slightly beneficial effect on the leaf area development under both air humidity conditions.

3.3 Stem measurements

Figure 6 shows the stem measurements taken directly after the harvest in cm. As seen in the dry weight data, the relative air humidity had a significant impact on stem growth in both plant species. In quinoa plants the relative air humidity had a significant impact on stem length for both treatments ($p<0.001$). In the high VPD environment the stem length of quinoa plants measured 64.1 cm on average for plants without salt treatment, plants grown under saline conditions reached an average stem length of 74.2 cm. In the low VPD environment the stem length measured 59.5 cm on average for plants without salt treatment, plants grown under saline conditions reached an average stem length of 75.1 cm. The stem length development is the only growth parameter, that didn’t get enhanced from salt treatment in the high VPD environment, while in low VPD environment the salt treatment still had a beneficial effect on stem length. In the stem length development of eggplant, the salt treatment had a significant effect ($p<0.001$) in both humidity levels, while humidity only showed a significant impact on plants without salt treatment, while the low VPD environment still showed a positive effect ($p=0.120$) on stem length. Under high VPD the stem length of eggplants measured 32.5 cm on average for plants without salt treatment, plants grown under saline conditions reached an average stem length of 23.9 cm. Under low VPD the stem length measured 44.5 cm on average for plants without salt treatment, plants grown under saline conditions reached an average stem length of 26.7 cm. While the salt treatment limited the stem length development in eggplants, a higher relative air humidity could counteract this limitation.

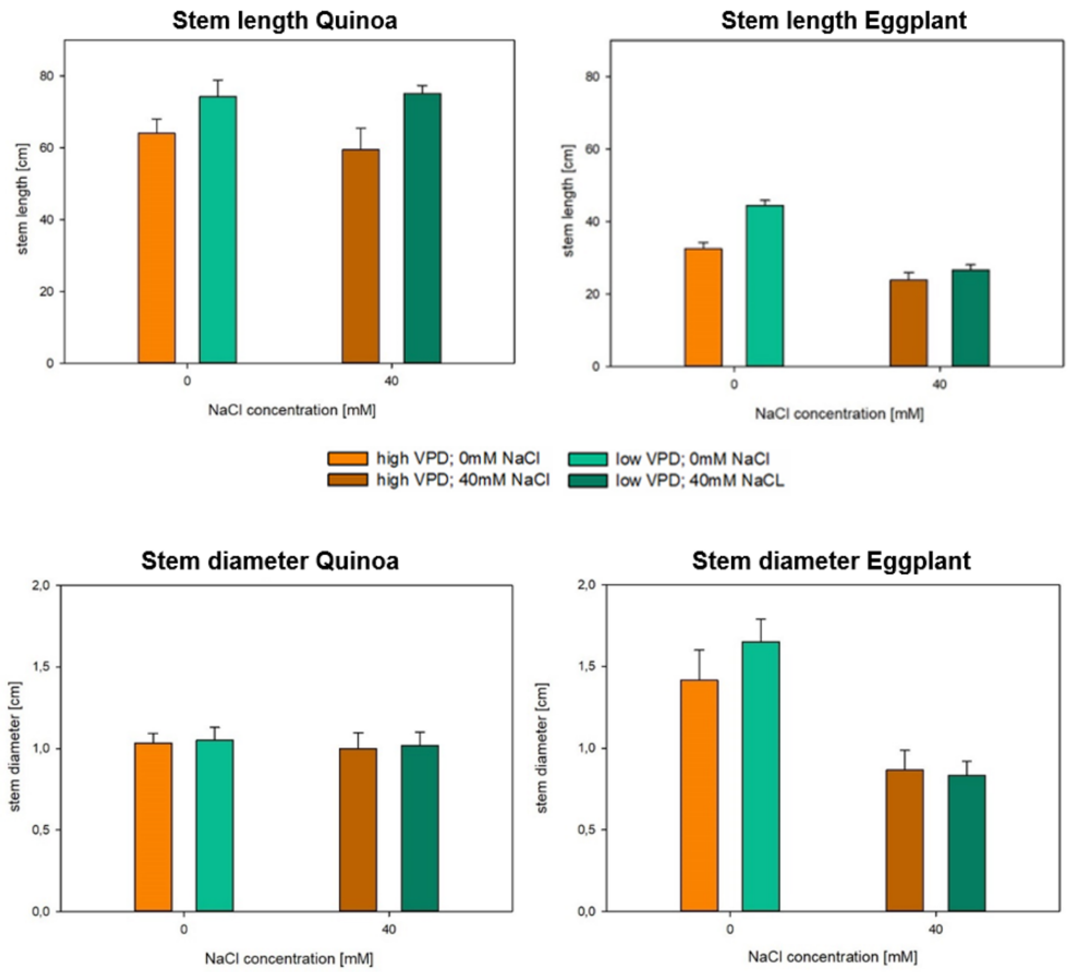

Figure 6: Barplot showing the Stem measurements in cm *for Quinoa (left) and Eggplant (right). The upper graphs show the average stem length in cm, the bottom graphs show the average stem diameters in cm. Results are divided into high VPD, 0 mM NaCl (orange); high VPD, 40 mM NaCl (brown); low VPD, 0 mM NaCl (turquoise); and low VPD, 40 mM NaCl (green). Standard errors are indicated by whiskers, Plots were generated using SigmaPlot.*

For the stem diameter development in quinoa plants neither the treatment nor the relative air humidity had a significant impact, as the plants developed a stem diameter of 1 cm on average in all systems. The stem diameter development in eggplants was significantly affected by the salt treatment in both humidity levels ($p<0.001$), while the humidity level didn't affect the stem diameter development significantly. Eggplants grown under high VPD developed a stem diameter of 1.4 cm on average in non-saline conditions, while under saline conditions the stem diameter was 1.7 cm on average. Eggplants grown under low VPD developed a stem diameter of 0.9 cm on average under non-saline conditions, while under saline conditions the stem diameter was 0.8 cm on average. While under non-saline conditions a low VPD had an enhancing effect on stem diameter development, under saline conditions a low VPD didn't have an impact.

3.4 Cumulative water loss

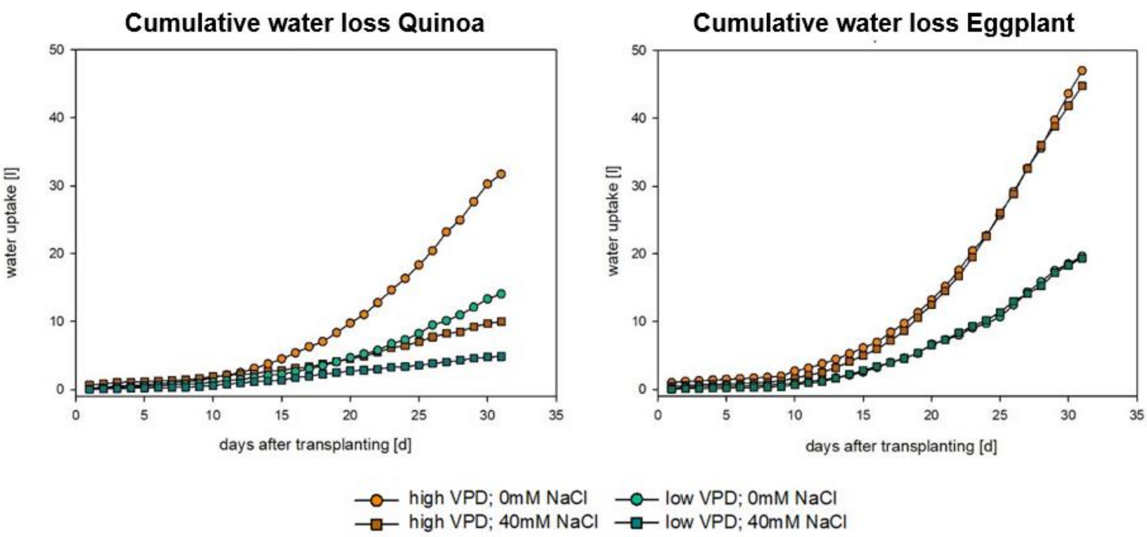

Figure 7: Line graph showing the cumulative water loss in liter *for Quinoa (left) and Eggplant (right) from 0 until 35 days after transplanting. Results are divided into high VPD, 0 mM NaCl (orange); high VPD, 40 mM NaCl (brown); low VPD, 0 mM NaCl (turquoise); and low VPD, 40 mM NaCl (green). Plots were generated using SigmaPlot.*

Figure 7 shows the cumulative water loss of each system in litre for the duration of the cultivation. In quinoa plants the water uptake of the plants was strongly affected by the relative air humidity, while the salt treatment only had a minor effect. In the contrary the water uptake of eggplants was affected strongly by the salt treatment as well as the relative air humidity level. Quinoa plants grown under high VPD and non-saline conditions had an average water uptake of 47 l, while under saline conditions the plants took up 44.8 l of water during the experiment on average. Quinoa plants grown under low VPD took up much less water. Under non-saline conditions the quinoa plants had an average water uptake of 19.6 l, while under saline conditions the plants took up 19.4 l of water during the experiment on average. Eggplants plants grown under high VPD and non-saline conditions had an average water uptake of 31.7 l, while under saline conditions the plants only took up 10 l of water during the experiment on average. Eggplants plants grown under low VPD and non-saline conditions had an average water uptake of 14 l, while under saline conditions the plants only took up 4.9 l of water during the experiment on average. Although the saline treatment and the relative air humidity had an impact on the water uptake of eggplants, saline conditions had a bigger effect than the VPD.

3.5 Nutrient uptake

Table 3 shows the average nutrient uptake rates (NUR) per plant for each system. The NO_3^{2-} and K^+ uptake rates were clearly influenced by the different treatments and growing environments. The PO_4^{3-} uptake rate, on the other hand, was only influenced by the salt treatment in eggplants while quinoa plants showed the same NUR for each growing condition, with an PO_4^{3-} uptake rate of 0.01 mol/g. Eggplants growing under non-saline conditions had the same PO_4^{3-} NUR as quinoa, while eggplants growing under saline conditions had double the PO_4^{3-} uptake rate, taking up 0.02 mol/g. Furthermore, while eggplants growing in the high VPD environment without salt treatment showed the lowest NUR for NO_3^{2-} (0.13 mol/g) and K^+ (0.28 mol/g), quinoa plants had the lowest NUR for NO_3^{2-} (0.14 mol/g) and K^+ (0.30 mol/g) in the low VPD environment with salt treatment. Overall, it is seen that NUR in eggplants was enhanced through the salt treatment in both humidity levels, while the NUR in quinoa plants was inhibited through the salt treatment in both humidity levels. Eggplants showed the highest NO_3^{2-} NUR (0.19 mol/g) in the low VPD environment under saline conditions, while the highest K^+ NUR (0.39 mol/g) under saline conditions in the high VPD environment. In quinoa plants the NUR of NO_3^{2-} was hardly affected by VPD or salt treatment with the uptake rates ranging from 0.14 mol/g to 0.16 mol/g in the different growing conditions. The K^+ NUR of quinoa plants on the other hand was affected more by the different growing conditions, with the high VPD environment enhancing the NUR by 0.05 mol/g for both treatments and the salt treatment further enhancing the NUR by 0.08 mol/g in both humidity levels. Eggplants under saline conditions in the high VPD environment had a bigger NUR of Na^+ (6.01 mol/g) than Cl (5.90 mol/g), while eggplants under saline conditions in the low VPD environment showed the contrary effect of taking up more Cl^- (6.22 mol/g) than Na^+ (4.75 mol/g). Quinoa plants treated with salt in the low VPD environment had a bigger NUR of Na^+ (1.21 mol/g) and Cl^- (1.50 mol/g) than the plants in the high VPD environment under saline conditions. Generally, it is seen that for both plant species the salt treatment had a bigger effect on the NUR than the VPD, although the NUR of Eggplants was more susceptible to the NUR being influenced by the different growing conditions.

Table 3: Average nutrient uptake rates (NUR) *per plant species, per treatment, for NO_3^{2-}, PO_4^{3-}, K^+, Na^+, and C^{l-}*

Plant	Treatment	NO_3^{2-} [mol/g]	PO_4^{3-} [mol/g]	K^+ [mol/g]	Na^+ [mol/g]	Cl^- [mol/g]
Eggplant	High VPD 0mmol NaCl	0,13	0,01	0,28	0,06	0,05
	High VPD 40mmol NaCl	0,18	0,02	0,39	6,01	5,90
	Low VPD 0mmol NaCl	0,14	0,01	0,31	0,07	0,08
	Low VPD 40mmol NaCl	0,19	0,02	0,36	4,75	6,22
Quinoa	High VPD 0mmol NaCl	0,16	0,01	0,47	0,09	0,17
	High VPD 40mmol NaCl	0,15	0,01	0,35	1,21	1,50
	Low VPD 0mmol NaCl	0,16	0,01	0,42	0,10	0,12
	Low VPD 40mmol NaCl	0,14	0,01	0,30	1,07	0,97

4. Discussion

4.1 Effects of salinity

Increased Salinity in soils and other growing substrates leads to stress reactions in plants, resulting in growth inhibition and low productivity for most crops. Especially the productivity and yield of glycophytes, a salt sensitive group representing most crops in agriculture, is significantly restricted by salt stress. For glycophytes a concentration of 100-200 mM NaCl generally leads to complete inhibition of plant growth (Brenes et al., 2020).

4.1.1 Salinity effects on plant growth

Plant growth is the most general and rapid effect of salt stress, since plants under saline conditions redirect their resources from biomass accumulation to the activation of defence mechanisms, in order to ensure survival. Therefore, comparison of salt induced inhibition of growth represents an appropriate criterion for the tolerance of salinity in different plant species and cultivars (Brenes et al., 2020).

The plant growth of eggplants was significantly affected by salinity in all morphological characteristics, with eggplants grown under saline conditions being restricted by more than 80% in total plant growth. This result is consistent with the findings of Hanachi et al. (2014). Their research showed that significant growth reduction is already present in low salinity levels for eggplant, although the cultivars being used in their research were restricted to a smaller degree by salinity. This is probably due to the fact that different cultivars show different levels of salinity tolerance, resulting in the chance to breed eggplants with higher tolerance towards salinity through genetic crossing with wild relatives or cultivars with higher salinity resistance (Brenes et al., 2020).

One of the first observational responses to salinity stress is the reduction of shoot growth and leaf expansion. Due to osmotic stress and Na^+ accumulation at a toxic level in the leaves shoot growth is restricted and new leaves and lateral buds emerge more slowly, resulting in fewer branches and lateral shoots (Munns et al., 2008). This is reflected in the reaction of eggplants to salinity, with leaf development being most restricted under saline conditions.

Quinoa plants have shown an opposite reaction to salinity, with plant growth under saline conditions being enhanced about 20%. This was to be expected, since quinoa plants are facultative halophytes, meaning they thrive under saline conditions (Jacobsen et al., 2003). Although the quinoa plant growth was enhanced by salinity, the treatment didn't show a significant effect. This could be due to the relatively low NaCl concentration of 40 mM. Research of Hariadi et al. (2011) has shown that the optimal plant growth of the Titicaca cultivar of quinoa is achieved at NaCl concentrations of approximately 100 mM. Even plants subjected to 500 mM NaCl were able to complete their life cycle and produce seeds.

The stem dry weight of quinoa plants experienced the biggest enhancement, although the stems were shorter and didn't differ in their diameter. The reduction of shoot length under saline conditions was described by Hariadi et al. (2011) as well. This could be the result of resource allocation from biomass accumulation to activating defence or tolerance mechanisms as well. One tolerance mechanism observed in quinoa plants is the osmotic adjustment taking place under saline conditions. Rather than only accumulating and compartmentalizing Na^+ in the leaves, the ions are being translocated to the shoot. Halophytes can use inorganic ions such as Na^+, K^+ and Cl^- as osmotica in shoot tissues to maintain turgor and meet the external osmotic stress (Adolf et al., 2013). Further tolerance mechanisms in quinoa are reduced stomata density to reduce transpiration and the development of salt bladders on the epidermis to further reduce water loss and store excess Na^+ and Cl (Adolf et al., 2013).

4.1.2 Salinity effects on nutrient uptake

Nitrogen and Phosphate are the most important elements for plant growth and development, while Potassium is important in protein synthesis, transport of water and nutrients in the xylem, stomatal activity and photosynthesis (Hu and Schmidhalter, 1998). Salinity decreases the adsorption of those elements, because of the Na^+ and K^+ competition at uptake sites in roots, the Cl^- and NO_3^{2-} competition and the reduction of PO_4^{3-} uptake through the presence of Cl^- (Hu and Schmidhalter, 1998). This results in nutrient deficiency or imbalance, further inhibiting plant growth.

Although the NUR of eggplants increased under saline conditions it is important to note that the uptake of NO_3^{2-}, PO_4^{3-} and K^+ ions significantly decreased under saline conditions (Fig. S1, Fig. S2), according to Hu and Schmidhalter (1998) and Bernstein et al., (1974). In Quinoa plants the NUR decreased under saline conditions, although the plants took up more NO_3^{2-} and PO_4^{3-} ions than the control group under non-saline conditions (Fig. S1). Furthermore, Halophytes are able to exclude the accumulation of Na^+ und Cl^- (Munns et al., 2008), which is seen when comparing the NUR of Na^+ and Cl^- in eggplant and quinoa. The NUR of Na^+ and Cl^- in Eggplants was 4-6 times higher than in quinoa plants. The ability of quinoa plants to regulate the accumulation of salts is another important factor in their resistance to salinity.

When evaluating the nutrient solution data, it should be taken into account that many samples had to be diluted and that further measurement errors may have occurred using the autoanalyzer and the flame photometer.

4.2 Effects of VPD

VPD describes the amount of gaseous water in the air, thus being a key driver for transpiration, which is regulated by stomatal movements. A high VPD results in declining stomatal conductance and increased transpiration, consequently reducing photosynthesis and plant growth. Since stomatal sensitivity and drought resistance are highly variable across species and in between their different cultivars, a high VPD doesn't necessarily lead to reduced plant growth (Grossiord et al., 2020). In this experiment eggplants and quinoa plants were grown hydroponically under two different RH conditions. One half of the plants were grown in an 40% RH environment (high VPD) and the other half in an 80% RH environment (low VPD).

4.2.1 VPD effects on plant growth

In general, VPD didn't show a significant effect on plant growth in both species, the only exception being shoot development. For eggplants a low VPD environment resulted in an increased stem dry weight of 32%, while the stem length increased by 37% and an increased stem diameter of 21%. Quinoa plants experienced an increase of stem dry weight of 38% in low VPD environment, with a stem length increase of 16%, while the stem diameter development wasn't affected by VPD. The increased shoot length of plants in low VPD environments could be related to the increment in water potential, resulting from these conditions, which enhances turgor driven cell enlargement due to the reduced transpiration rate (Amitrano et al., 2019). The leaf dry weight and leaf area development in eggplants were both increased in a high VPD environment, although not to a significant degree. This effect was also observed in tomatoes, by Zhang et al. (2017). While the root dry weight of eggplants wasn't affected by VPD, quinoa plants experienced an increase of 12,5% in the low VPD environment.

Both plant species experienced a similar increase of evapotranspiration in the high VPD environment, with eggplants showing an increase of 56% and quinoa plants showing an increase of 58%. Nevertheless, the overall plant growth of eggplants was less affected by different humidities than plant growth of quinoa plants.

4.2.2 VPD effects on nutrient uptake

The nutrient uptake in both plant species was only slightly affected by VPD. Studies have shown that nutrient uptake generally decreases under low VPD, due to the lower transpiration driven mass flow, allocating nutrients from the substrate towards the roots. Diffusion supplied nutrients such as K^+ seem to be less affected by transpiration driven mass flow (Zhang et al., 2017). The results of this experiment showed an opposing trend to Zhang et al.´s findings, with NUR either slightly increasing or not being affected at all under low VPD. This could be explained with the fact that nutrient acquisition is dependent on various factors besides VPD such as root physiological capacity, temperature and pH (Bassirirad, 2000).

4.3 Salinity and VPD interaction

While eggplants thrived the most under non-saline conditions and high VPD environment, the most beneficial growing environment for quinoa plants was under low VPD and saline conditions.

Research showed that air humidification in high VPD environments limit the salinity induced plant growth inhibition in tomato plants (Romero-Aranda et al., 2002), while in this experiment a low VPD further inhibited plant growth for eggplants. Since the ideal VPD for Solanaceous crops is around 1.5 kPa (Rasouli et al., 2022), the low VPD of 0.4 kPa in this experiment most likely put additional stress on the plants, resulting in the amplified growth inhibition in eggplants under saline conditions. In their experiment Romero-Aranda et al. (2002) contained a VPD of 1.4 kPa for the low VPD environment, which suggests that an optimal VPD can reduce the negative effects of salinity on plant development.

Since quinoa plants thrived under low VPD and under saline conditions, it was anticipated, that the interaction between these conditions lead to a positive synergetic effect for quinoa plant growth. In general, it is seen that quinoa plant growth was less impacted by the different treatments and environmental conditions than eggplants, highlighting the resistance to abiotic factors in this crop.

5. Conclusion

In this thesis the impact of salinity and relative air humidity on plant growth and nutrient uptake of hydroponically grown eggplant and quinoa were studied. Salinity significantly inhibited the plant growth of eggplants, while enhancing plant growth of quinoa plants, although not to a significant degree. These results support the stated hypothesis that quinoa plants are, due to their salinity resistance, more suitable for saline growth than eggplants.

Relative air humidity didn't have a significant effect on either of the studied species. Nevertheless, quinoa plants thrived under low VPD, while plant growth of eggplants under non-saline conditions wasn't affected from changing air humidity levels. Under saline conditions, a low VPD further inhibited plant growth of eggplants. Since none of the given air humidity levels were beneficial for eggplant growth, further research should be conducted to study the effect of an optimal VPD on eggplant growth under saline conditions, given that this could enhance the resistance of eggplants towards salinity. In this study it was observed that different plant species respond differently to changes in air humidity, supporting the second hypothesis as well.

To better understand the effects of salinity and relative air humidity it would be interesting to analyse the individual plant parts for their nutrient concentrations after the harvest. This would give further insight into tolerance mechanisms of quinoa and eggplants and thus offering opportunities for genetic modification, strengthening salinity resistance and providing optimal growing environments for these crops to increase yields.

6. Appendix

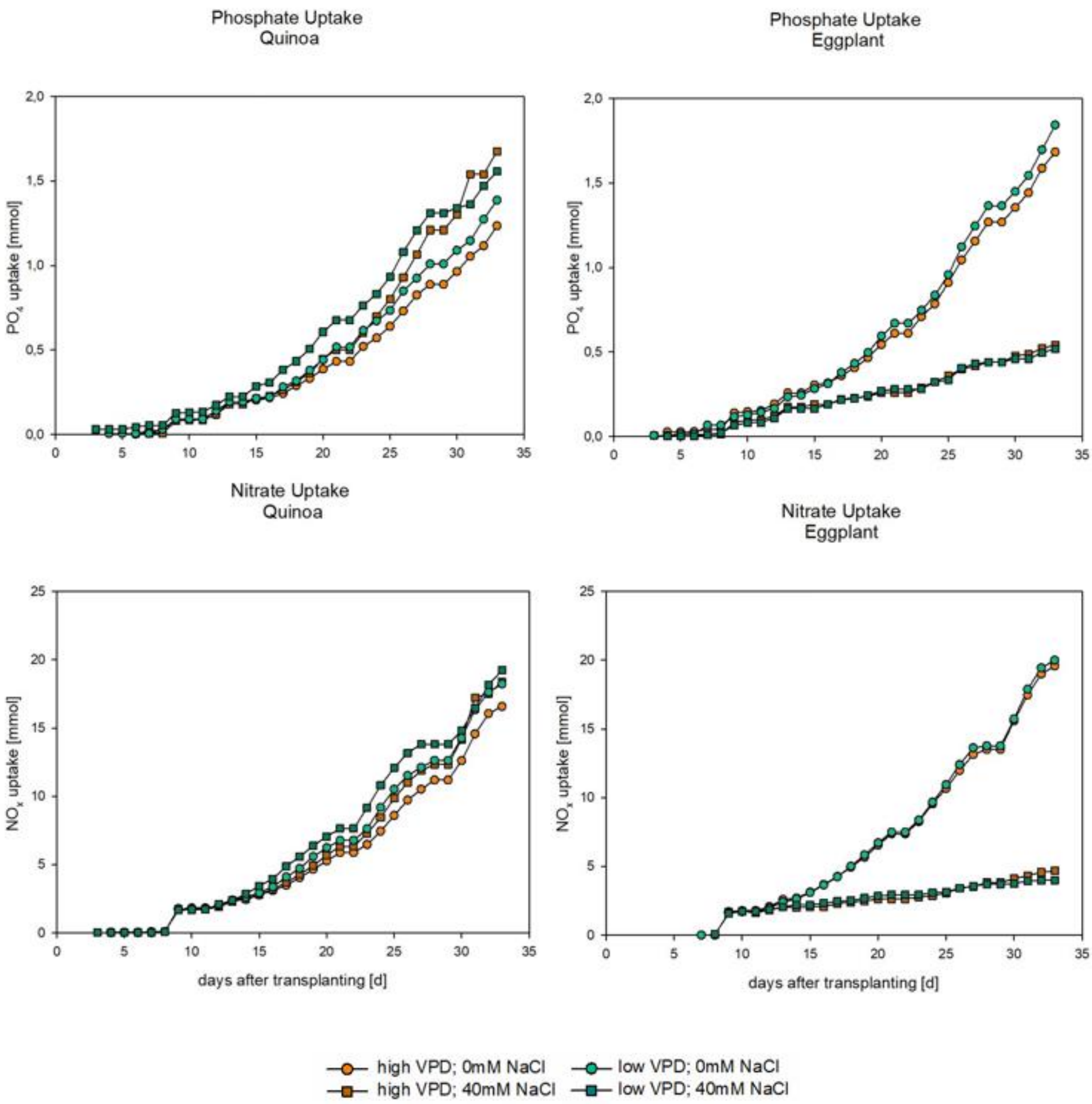

Figure S1*: Line graph showing the NUR in mmol of Phosphate and Nitrate for Quinoa (left) and Eggplant (right). Results are divided into high VPD, 0 mM NaCl (orange); high VPD, 40 mM NaCl (brown); low VPD, 0 mM NaCl (turquoise); and low VPD, 40 mM NaCl (green). Plots were generated using SigmaPlot.*

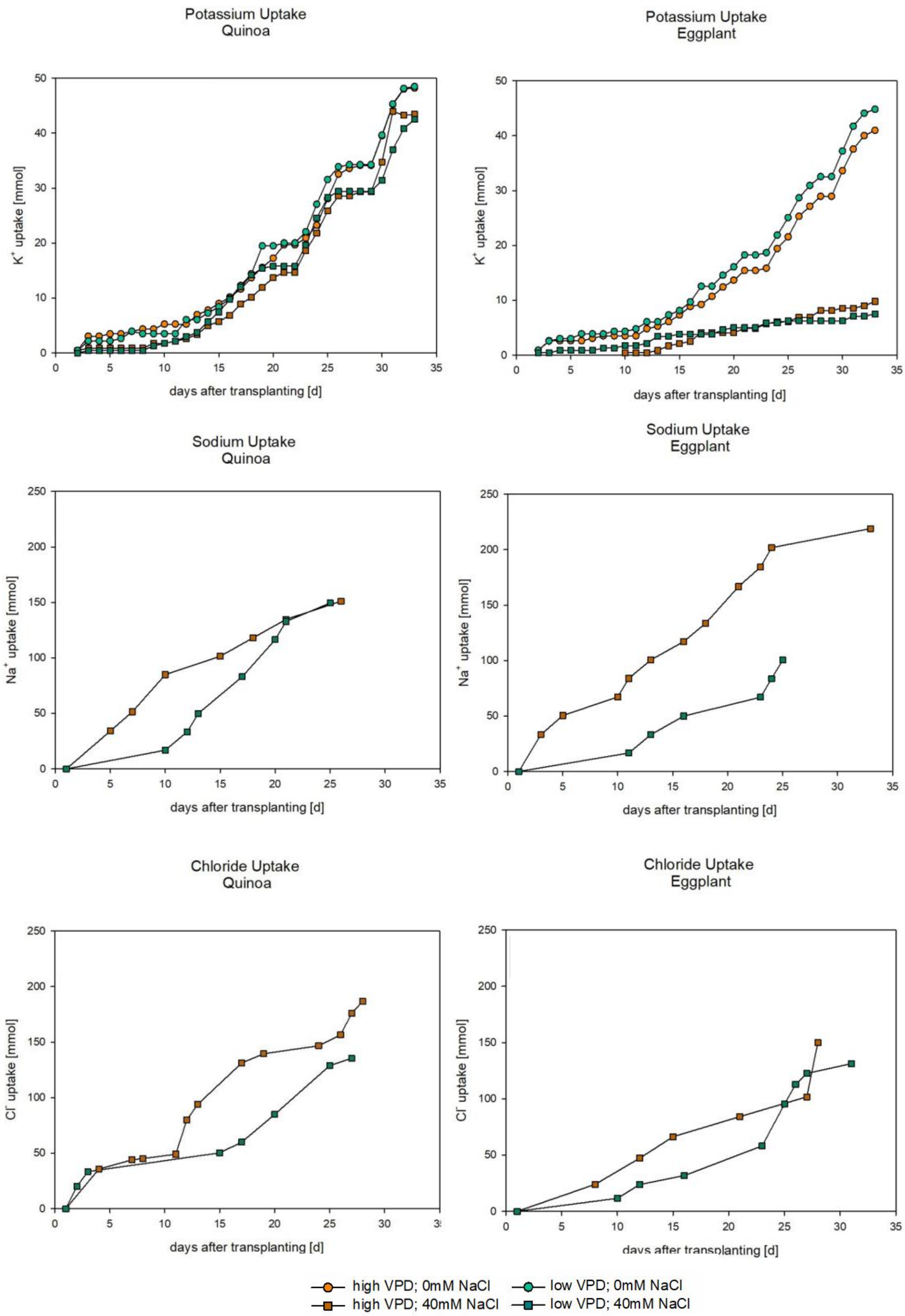

Figure S2*: Line graph showing the NUR in mmol of Potassium, Sodium, and Chloride for Quinoa (left) and Eggplant (right). Results are divided into high VPD, 0 mM NaCl (orange); high VPD, 40 mM NaCl (brown); low VPD, 0 mM NaCl (turquoise); and low VPD, 40 mM NaCl (green). Plots were generated using SigmaPlot.*

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