Influence of localized cooling on microclimatic conditions in a vertical hydroponic system

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Independent project in Horticultural Science • 30 credits
Swedish University of Agricultural Sciences, SLU
Department of Biosystems and Technology
Horticultural Science Master's programme
Alnarp, 2025

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Credits:	30 credits
Level:	Master's level, A2E
Course title:	Independent project in Horticultural Science
Course code:	EX0948
Programme/education:	Horticultural Science, MSc
Place of publication:	Alnarp, Sweden
Year of publication:	2025
Cover picture:	Vertical hydroponic system with *Lactuca sativa*. Photo: Anna Hallin Lundberg
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Keywords:	Climate control, Controlled environment, Lactuca sativa, Plant stress, Sustainable agriculture

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Department of Biosystems and Technology

Horticultural production systems

Abstract

Hydroponic production of vegetables is both resource and land efficient which gives the potential to manage some of the worlds many pressing issues, such as water scarcity, shrinking arable land and a need for sustainable food production (Kumar et al. 2024). Several of the United Nations sustainable development goals (SDG's), for example 2 "Zero hunger" and 13 "climate action", can be connected to the development and use of hydroponics. This by potentially enhancing food security, especially in places with high environmental stress and in densely populated areas while reducing crop productions climatic impact (Ngcobo et al. 2024). However, these controlled environment productions use a lot of energy consuming elements (Kumar et al. 2024). This is problematic in a world where energy prices are rising and most energy sources come from non-renewable resources (Ritchie et al. 2024). The main energy consumer in hydroponic greenhouse production is heating and cooling (Liantas et al. 2023). In this experiment two vertical hydroponic systems were set up in a temperature regulated growing chamber. One of the systems was integrated with a localized cooling system and one without. The aim was to improve the hydroponic systems performance in terms of productivity and energy use efficiency. This by providing a more beneficial microclimate enhancing plant growth and regulate the temperature on a smaller scale. The chosen crop was the lettuce, Batavia salad 'Lollo Rossa', *Lactuca sativa*, the chamber was set to 25°C and the cooling system 17°C During eight weeks data was collected on microclimatic variables to evaluate the localized cooling system. Statistical tests in the form of a two-way t-test and Pearson's correlation test were done at the end of the experiment. A statistical difference in fresh and dry weight was registered at the end of the experiment, where the system without the cooling system had higher values in both categories. This was contradictory to the stated hypothesis that implementing localized air distribution in a vertical system would improve its performance in terms of productivity and energy use efficiency. However, no statistical differences were found between the systems regarding temperature measured with data loggers during the growing period, or of the leaf temperature measured with an Infrared (IR) camera. The similarity in temperature between the systems can be explained by the measurements done on the outflow air in the cooling system, also using the IR camera. This showed a rise in temperature from bottom to top, indicating insufficient cooling. The lower fresh weight in the system with the integrated cooling most likely derived from indirect stress factors induced by the constant airflow. This work highlighted the linkage between different growth variables and even if the temperature regulations systems can be modified to lower energy consumption the other parts must also work together to maximize yield and lower the resource use efficiency necessary to achieve sustainability.

Keywords: Climate control, Controlled environment, Lactuca sativa, Plant stress, Sustainable agriculture

Table of contents

List of tables

List of figures

Abbreviations

EC	Electric conductivity
LED	Light Emitting Diodes
PFAL	Plant Factory with Artificial Light
PF	Plant Factory
RH	Relative Humidity
S1	System 1
S2	System 2

1. Background

1.1 Definition

A simple and rater strict definition of hydroponics is when plants are being grown in a nutrient solution, although there is some division of what the meaning of hydroponics is and should include (Raviv & Lieth 2007). In modern days hydroponics does in general include many kinds of soilless production, both where and where not a form of solid medium or substrate is being used as support (Morgan 2021).

1.2 Brief history

The variation of definition might be explained by, that although hydroponics is not regarded as a conventional way of farming, different forms has been around for 4000 years (Raviv & Lieth 2007; Morgan 2021). The first records of something defined as hydroponic was in Egypt, where plants were grown in containers above ground in what is believed to be in other substrates than soil. This was done in order to move trees from their native countries in order to be placed in the pharaohs palace (Morgan 2021). Further historic example is the Hanging gardens of Babylon around 2500 years ago, which was a system of terraces and roofs where plants were grown (Caputo 2022), these has also been descried as the first example of vertical farming (Van Gerrewey et al. 2022). In another part of the world around 800 years ago, the Aztec in Mexico created a kind of floating islands where crops were grown directly onto the river, called chinampas (Caputo 2022).

During the middle of the 1800s, Hydroponics became a tool in the research of essential plant nutrients and the development of nutrient formulas (Morgan 2021). During the beginning of 1900s, the term Hydroponic, from the Greek words *hydro* for water and *pono* for work, was coined by Frederick Gericke of the university of California (Morgan 2021). Frederick Gerickes published book “The complete guide to soilless gardening” laid a base for hydropnic cultivation (Van Gerrewey et al. 2022). Further studies was done at the university of California, showing promising

results and was regarded as having the potential to be used were soil fertility was declining and agricultural land scarce (Caputo 2022). Research was also conducted in other place in the US, England and France during the fallowing decades of the 1900s, which laid the base for future commercialization of hydroponics (Morgan 2021). In association with the second world war, the interest in hydroponics was raised (Morgan 2021) for example by the US army, which wanted to improve the self-sufficiency of secluded areas and in extreme environments (Caputo 2022). The US Airforce set up hydroponic systems in remote Islands were they had established military bases (Morgan 2021) and successfully grew vegetables, the majority was grown in open air (Caputo 2022).

In the 1960s, the principle of hydroponics in vertical farming systems was used by the Austrian engineer Otmar Ruthner in greenhouse towers. This application was an important part of the development of vertical farming systems but was set aside due to high maintenance and energy costs. The concept was not taken up again until the early 2000s, when it was suggested as part of a potential solution to improve food security and safety (Van Gerrewey et al. 2022).

An architectural development which has been a big contributor to the use of hydroponics in crop production is greenhouses (Morgan 2021). What can be seen as the first modern greenhouse was built in Italy during the 1500s, and greenhouses were later spread to other parts of Europe as well, they were used to display tropical plants mainly in botanical gardens. Other sources claim it was a French botanist during the 1800s that constructed a greenhouse to grow medicinal plants, that should be attributed as the first. Regardless of the first origin the construction was made of glass and metal (Caputo 2022). Glass was the most popular cover material up until the early 1990s, but glass is an expensive material which limited greenhouse production. In 1933 polyethylene was discovered, and in the 1950s it was developed into cover material for greenhouses. This made the constructions cheaper and lighter, which made greenhouse production spread and grow rapidly. Plastic film is today the most used cover material in different greenhouse productions (Nemali 2022).

1.3 The basic of the systems

All the essential plant nutrients need to be provided in proper amounts for the plant to complete its life cycle and develop correctly. There are 13 essential plant nutrients, divided into macro- and micronutrients depending on the amount needed in the plant. The macronutrients are Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg) and sulphur (S) while the micronutrients are Boron (B), Chlorine (Cl), Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo) and Zinc (Zn) (Kathpalia & Bhatla 2018). A hydroponic system needs to provide the crops with the essential nutrients; this is being done through the nutrient

solution. The composition of nutrients required depend on the different species of plant, there are different combinations available today on the market (Caputo 2022). A number of factors can affect the nutrient uptake of the plant such as pH, oxygen availability and temperature, these are usually controlled and monitored in a hydroponic system (Caputo 2022). How the nutrient solution is provided in the system is how they are generally classified. These can be ebb and flow, drip irrigation, aeroponic misting, capillary fed or continuous flow (Morgan 2021). They can also be categorized as an open system, where the nutrient solution is discarded after passing through the system, or a closed system, where the solution is being recirculated (Morgan 2021). Further distinguishing between systems are if they use growing medium, a solid usually inert substrate, or directly placed in the nutrient solution or in the air (Caputo 2022). There are a few different materials used for substrate or growing medium, e.g. sand, gravel, peat, vermiculite, coir dust, saw dust and coconut fibre (Sankhalkar & Jamuni 2024), rock wool is also commonly used. The media should ensure good aeriation, anchorage for the roots and be able to ensure the plant being supplied with the nutrient solution (Patil et al. 2020).

There are a variety of crops commercially grown in hydroponic systems today. The most common are tomatoes, cucumber, chilies and a variety of herbs, leafy vegetables and cut flowers (Khan et al. 2024).

1.4 Potential benefits

Hydroponic systems have some major benefits due to and depending on their construction. Today, most systems are closed which leads to a higher water and nutrient use efficiency because of the recirculation of water and nutrients (Morgan 2021). Soil-borne diseases, insects, pests and weed are severely limited which in turn can reduce the use of pesticides and potential toxicity. The non reliance of the local soil conditions leads to hydroponics being suitable in areas where other production methods would not be feasible (Sankhalkar & Jamuni 2024). Hydroponics is today mostly used for protected cultivation. Growing indoors provides the ability to produce crops all year round and in environments with high climatic stresses such as unreliable weather conditions, drought and cold (Sankhalkar & Jamuni 2024). For this reason, different kinds of hydroponics is seen as a way to grow crops in urban and densely populated areas providing the potential of locally produced food and a reduced transportation chain (Kumar et al. 2024).

The indoor setups range from very simple for home growers (Sankhalkar & Jamuni 2024) and crop production in greenhouses (Morgan 2021), to the highly technological systems called plant factories (PF). PF or plant factories with artificial lights (PFAL) controls more or less every climatic aspect in a closed room environment (Kozai 2020).

Vertical farming is another term usually used for indoor hydroponic production which once more differs in definition and usage. These systems are based on multiple growing modules stacked on the same surface and are usually associated with high environmental control technologies and artificial lights from LED light sources, like PFALs (Caputo 2022). PFAL is often associated with and referred to as a vertical farming system set up in an industrial building dedicated to crop production (Kozai, 2020). There are other vertical farming setups as well. Container farms are when a shipping container is set up with self-contained vertical farming systems. In-store farms are production units placed where the produce is consumed or purchased. Another example is appliance farms, which are growing systems adapted for homes or offices (Kozai, 2020). Vertical farming is not always strictly vertical, it can include other setups as well and it doesn't necessarily have to be hydroponics either. However, today vertical farming is closely associated with hydroponics, climate control, and artificial light. (Van Gerrewey et al. 2022).

The development of artificial light, especially more efficient and cheaper LEDs, has been a big factor in the spread and increased use of vertical farming (Kozai, 2020; Van Gerrewey et al., 2022). The expansion of vertical farming has in turn increased research on controlled environment agriculture, which also benefits more established greenhouse production (Kozai, 2020).

1.5 Microclimate

Monitoring and alteration of microclimates are part of all hydroponic production, ensuring optimum resource use efficiency (Perone et al. 2023). The microclimate are composed and effected by environmental variables such as temperature, humidity and radiation (Jones 1993). Monitoring and controlling the microclimate directly affects plant health which in turn has consequences for quality and yield. There are various sensoring technologies available to monitor e.g. humidity, temperature and light intensity in the production system (Wang et al. 2024b). Air and root zone temperature is an environmental factor which strongly affects plant growth and yield. Too high or too low air temperatures can negatively affect physiological processes such as respiration and photosynthesis, and temperature in the root zone can affect nutrient and water uptake (Levine et al. 2023).

1.6 Potential downsides

Hydroponics can be seen as a valuable tool in addressing many agricultural and environmental issues seen today, but the systems still face drawbacks. The level of technology components leads to high initial costs and a need of comprehensive

understanding of specialized techniques (Kumar et al. 2024). Hydroponically grown crops cannot be classified as organic within EU due to regulations, and similar discussions are ongoing in the US and UK (Caputo 2022). An extensive understanding of the market is needed to be able to get a return on the investments connected to the initial costs and not all crops are economically viable in hydroponic systems (Kumar et al. 2024). Even though soilborne pests and diseases are reduced in hydroponic systems, there are still challenges. In closed systems, diseases can spread rapidly through the recirculating nutrient solution. There is also a risk of accumulation of toxic compounds due to root exudates. The special environment of hydroponic systems needs specialized research and solutions to be effective as well (Prakash et al. 2025).

The major issue with indoor farming is energy consumption. The hydroponic systems used today often have many energy consuming elements such as artificial light, ventilation mechanisms and environmental control systems (Kumar et al. 2024). Hydroponic production in greenhouses have heating and cooling as its major energy consumer, especially in temperate climates (Liantas et al. 2023). They have in general higher energy demand compared to conventional systems (Abbass et al. 2022) resulting in a larger environmental footprint (Casey et al. 2022). Only a small proportion of the energy consumed today derives from renewable energy and the energy production, which mainly comes from the burning of fossil fuels, stand for circa three-quarters of the global greenhouse gas (GHG) emissions (Ritchie et al. 2024). Between 13-27% of global GHG-emissions from human activities derives from the agricultural sector (Chen et al. 2020; Gołasa et al. 2021; Abbass et al. 2022) and when it comes to horticultural crops energy consumption is the major hotspot (Gołasa et al. 2021).

The worlds energy prices has risen drastically a lot due to the outbreak of COVID (Livia & Ada 2024). More recent events and effects on the rising energy prices can be tracked to the ongoing conflict in Ukraine which has contributed to the energy crisis (Sun et al. 2024). In Europe between 2020 and 2022 the average wholesale electricity price per megawatt-hour increased over 400% (Wang et al. 2024a). The global electricity demand grew by 4,3 % during 2024 and is predicted to keep rising by approximately the same figure up until at least 2027 (Çam et al. 2025).

Since the late 1900s and early 2000, greenhouse production has increased drastically and spread from being focused to the northern hemisphere to 119 different countries, with China having the majority on over 60% of the world's greenhouse area. The global area is ca 1,3 million ha which includes both simple structures covered in plastic film and more complex greenhouses (Tong et al. 2024). Hydroponic production systems in greenhouses is still growing and is predicted to keep rising with 11,3% until 2028 (Benko et al. 2023). Vertical farms has also been increasing significantly since the early 2000s but have now stagnated and only

occupies ca 30ha worldwide (Zhuang et al. 2022). Food demand is rising while conventional agricultural practices is threatened and indoor farming have an advantage going into an uncertain future (Cowan et al. 2022). However, there is a risk that rising energy prices causes stagnating crop production in controlled environments. This leads to a necessity to find ways to reduce energy demand in these production systems (Liantas et al. 2023).

1.7 Aim and Hypothesis

Hydroponic production could be a great asset in sustainable food production but needs to be more energy efficient. The heating and cooling systems have the potential to be altered in a way which lowers energy demand without risking the wellbeing of the crops. The aim of the present study is to implement a modified cooling system, which more directly targets the plants, in a hydroponic system. The aim is to optimize the microclimate and growth while laying the base for a potentially more energy efficient climate regulation that can be implemented regardless of growing facility and geographical location.

Questions examined in this paper were: Does implementing a localized cooling system improve productivity in a vertical hydroponic system in the form of plant growth? How does localized air distribution affect microclimatic factors such as temperature and humidity? And what impact does localized air distribution have on plant stress indicators and nutrient uptake?

Hypothesis – Implementing localized air distribution in a vertical system will improve its performance in terms of productivity and energy use efficiency.

2. Material and method

Two identical vertical hydroponic systems were set up in the same temperature regulated growth chamber (Figure 1). One of the systems was serving as the control and is referred to as System 1 or S1. The other had an integrated localized cooling system, referred to as System 2 or S2 (figure 2). The systems used recirculating nutrient solution. The capacity was 64 plants in each system. The only climatic factor regulated was the temperature in the growth chamber set to 25°C. LED light sources (Valoya B150, spectrum AP673L, Valoya, Helsinki, Finland) was installed in vertical and horizontal position placed 65-75 cm from the plants on each side and from above, of S1 and S2 with a light interval of 06am to 22pm. The light intensity (photosynthetic photon flux density, PPFD) was measured in five different spots on each side of each system using Skye Quantum Sensor (Skye Instruments Ltd., Llandrindod Wells, UK). The light varied between 77 to 275 µmol m^{-2} s^{-1} within the systems (figure 1 & table 1)

The cooling system included a portable air condition (AC). The cold air was distributed on the plants via seven 20 mm PVC pipes from 100 mm main duct connected to the AC. The smaller pipes were drilled with 56 holes, 5 mm in diameter, which were directed towards the plants and placed in between the growing towers. Each plant had two holes for air distribution except for the plants on the edges of the system which only had one. The airflow going into the system via the AC was measured using an anemometer (model TSI VelociCalc 9535, Taiwain). The measurement showed airflow in the main duct of 0,34 m s^{-1}. The airflow out of the 56 5 mm holes, directed towards the plants, was calculated with the assumption that the airflow of the system was equal and potential pressure drop occurring were neglectable due to the small size of the system. The airflow was converted to L s^{-1} and showed an outgoing flow of 0,048 L s^{-1}, see appendix for full calculation. It was assumed that the warm air flowing from the backside of the AC, which remained inside the growing chamber, would help maintain a temperature of 25 °C. This warm air was expected to compensate for the cold air distributed in S2.

Figure 1: The temperature regulated growing chamber showing system 1(S1), without localized cooling system, closes to camera and system 2 (S2) further back with the cooling system. Left picture showing before planting of lettuce. Right picture showing the final week of the growing period. Photo: Anna Hallin Lundberg.

The temperature of the inflowing air in the localized cooling system was set to 17°C. Data loggers (HOBO U12, Onset computer corp., Bourne, MA USA) were placed in each system to record the temperature (figure 2). The cultivar chosen was a red lettuce, Batavia salad 'Lollo Rossa', *Lactuca sativa*, suitable for hydroponics. They were pre-cultivated for three weeks in rockwool plugs in 21°C under LED light then transferred to the systems. New seeds were planted after the first batch had been transferred.

Each system had a water capacity of 50 L, and to this a solution of 4L of stock solution (100g/L Kristalon, Yara, Oslo, Norway) with the NPK ratio of 9 ,11, 30 and 4 dl of 100g/L Calcinite (Yara, Oslo, Norway) was added. Electric conductivity (EC) was around 2.4 mS cm^{-1} and pH 6,1 during the experiment. pH was adjusted by adding phosphoric acid (H_3PO_4).

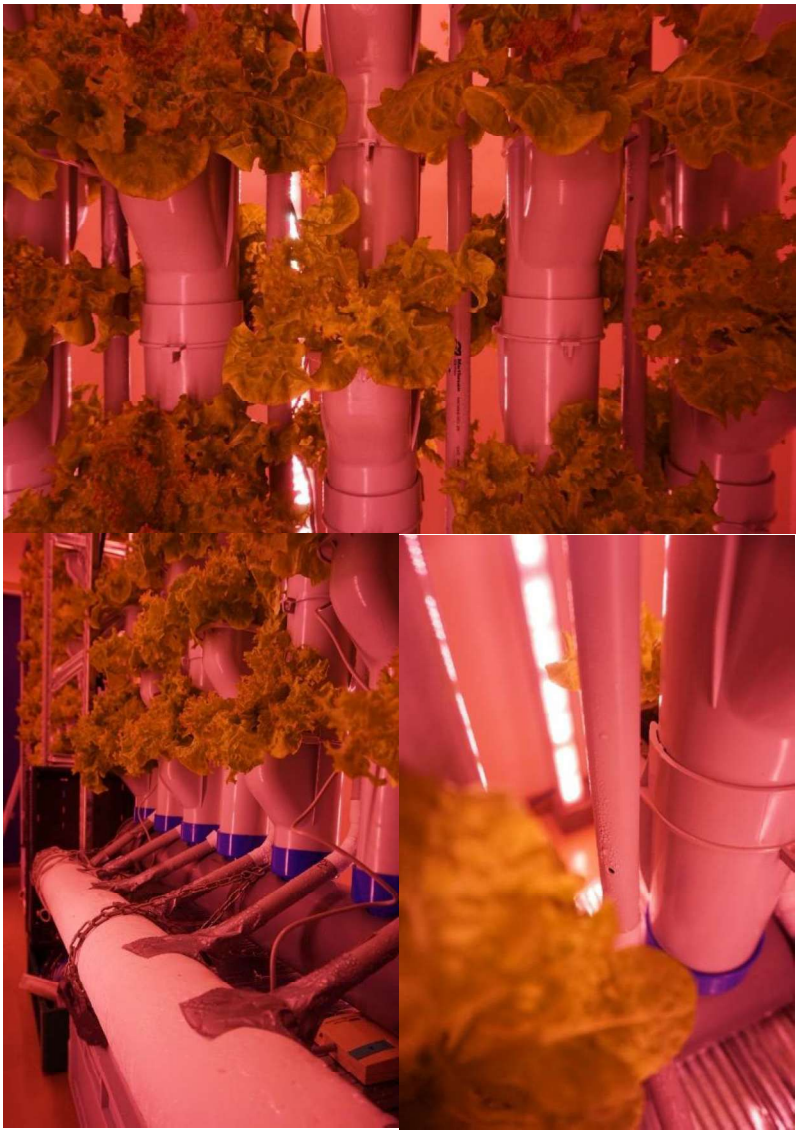

Figure 2:Hydroponic System 2 (S2) with the integrated cooling system. Top pic. showing positioning of 20mm pipes between growing towers. Lower-left pic. Showing the 20mm pipes connecting to the 100mm main duct leading to the AC providing the cool air. Lower right shows one of the outflow holes directed towards the lettuce. Photo: Anna Hallin Lundberg.

To evaluate the system, different variables were measured. During ca eight weeks visual observations of leaves, roots and general growth were made, as well as record of EC and pH before adjustments were made, as well as water level. Measurements of the microclimate was done, this included temperature around the plants and relative humidity (RH), using the previously mentioned dataloggers. Temperature measurements of the leaves were performed by using an IR camera, (FLIR i3, Estonia). Same camera was used to register temperature of the outgoing air from the localized cooling system. Further data of the plants' performance and stress level was collected through chlorophyll fluorescence measurements and photosynthesis registration.

The chlorophyll fluorescence was measured using a PAM-2500 instrument (Heinz Walz GmbH, Effeltrich, Germany). This measurement was done to provide an image of the impacts of abiotic stresses and tell if there was ongoing photoinhibition. Photoinhibition is when efficiency in the photosynthetic reactions has been reduced (Guidi et al. 2019).

The photosynthetic activity was measured by using a LCPro photosynthesis instrument (ADC Bioscientific, Hoddesdon, UK). The working principle of the instrument was by enclosing part of the leaf in a chamber estimating the concentration of gases (CO_2 and H_2O.) passing through the leaf stomata (Hunt 2003). Data was collected of CO_2 assimilation rate (μmol CO_2 m^{-2} s^{-1}) and of Stomatal conductance (H_2O m^{-2} s^{-1}).

At the end of the growing period, fresh weight as well as dry weight, after drying in paper bags for 36 hours at 75°C in a forced-air drying oven, was measured on 32 plants randomly selected from the systems.

Data was collected in excel. Two sample-T-test, with a significance level of 0,005, were performed in Minitab (Minitab inc., State College PA USA) to determine if there were a statistical significance difference between the systems and the different factors. Pairwise Pearson Correlations, with a significance level of 0,005, were made to conclude potential correlations within the systems. The tests were done on 12 randomized samples from each system. Mean values for chlorophyll fluorescence, photosynthetic activity and fresh and dry weight were calculated from randomized samples. The mean values for temperature and relative humidity were calculated of all the data from the dataloggers.

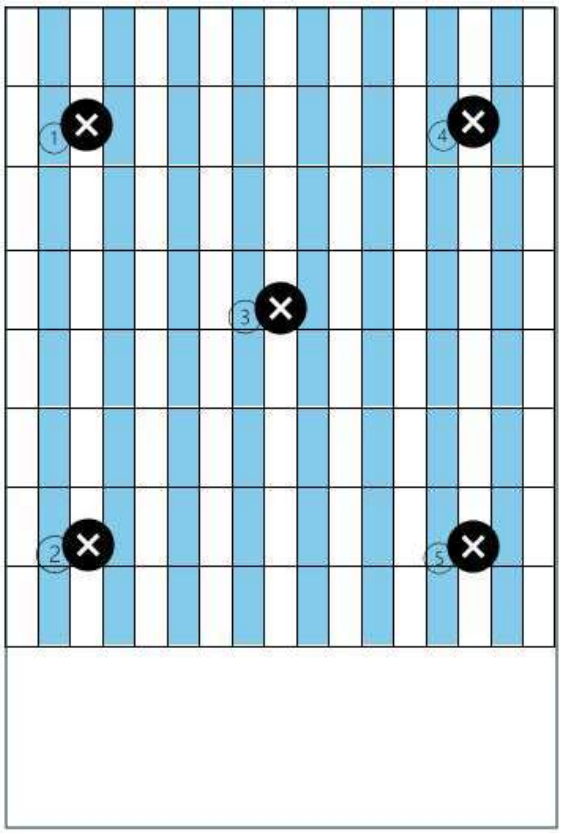

Figure 3: Figure showing the spots of light measurements in the vertical hydroponic system.

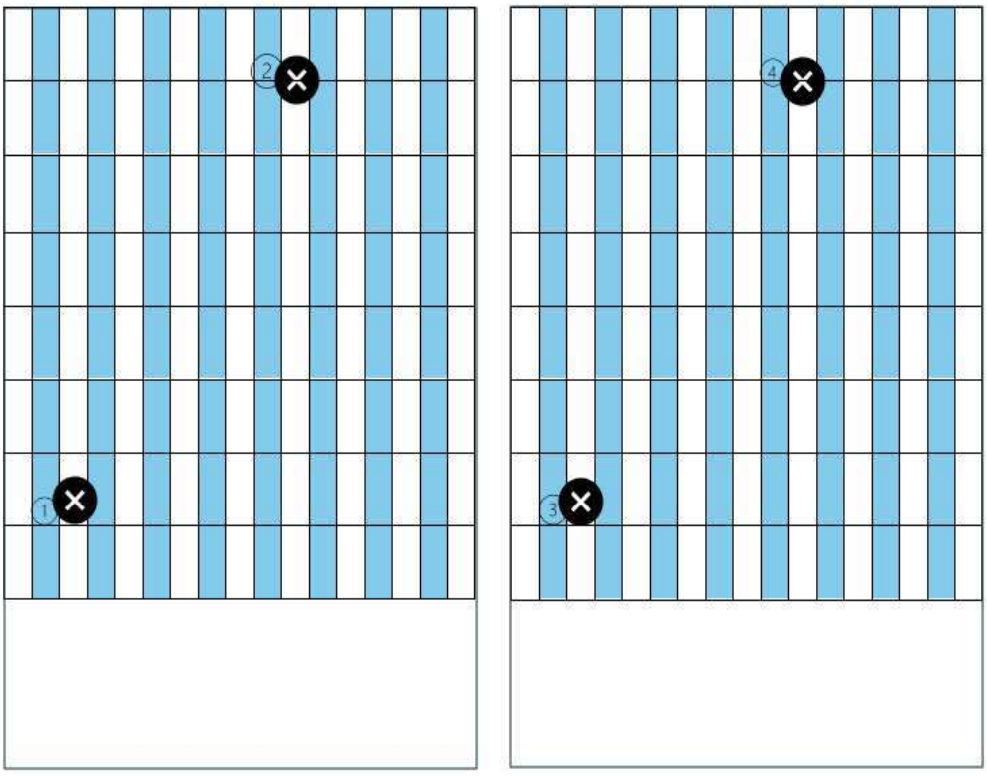

Figure 4: Placement of dataloggers in the systems. From left to right S1 with dataloggers 1 and 2, S2 with dataloggers 3 and 4

Table 1: Photosynthetic photon flux density (PPFD) measured in five spots (Spots 1–5) within System 1 (S1) and System 2 (S2), on the first side (x:1) and second side (x:2), using a Skye Quantum Sensor (Skye Instruments Ltd., Llandrindod Wells, UK). Measurements were taken from above and the side of the systems. Values are in µmol m^{-2} s^{-1} and represent single-point measurements.

Spot	1	2	3	4	5
µmol m^{-2} s^{-1}					
S1:1 Above	110	77	110	127	97
S1:2 Above	240	96	170	212	131
S1:1 Side	111	91	139	112	97
S1:2 Side	150	112	180	139	112
S2:1 Above	132	95	100	104	88
S2:2 Above	234	110	275	165	108
S2:1 Side	106	96	135	85	101
S2:2 Side	175	97	172	126	120

3. Results

Temperature was one of the main aspects measured in this experiment. Temperature-related parameters were the temperature of the leaves, the temperature of the room, and the temperature of the outflow air from the localized cooling system. No statistically significant difference was found between the systems when it came to room temperature, which is also supported by the weekly mean temperatures (Figure 5). The weekly mean temperature rarely went over 25 °C, which might not have been enough on its own to cause any stress in the lettuce.

Differences between the systems were mainly observed in fresh and dry weight. S1 showed higher mean values for both, indicating better growth overall, despite having a slightly higher mean temperature than S2. Even though the mean temperature in S2 was slightly lower (23.7 °C) than in S1 (24.8 °C), the difference was not statistically significant. S2 also had a higher mean leaf temperature, and this difference was statistically significant.

Temperature measurements performed on the outflow air from the localized cooling system showed a rising temperature from the bottom outflows compared to the top outflows (Figure 3). Dataloggers showed fluctuations in temperature over time, with weekly mean temperatures between 23.6 °C and 24.7 °C, and weekly relative humidity (RH) between 50.3% and 72.3% (Figure 5). Slow growth was noted during the first five weeks. Around this time, the roots were observed to have callus formations and no visible root hairs. During the final three weeks, more normal growth of leaves and roots was observed (Figures 6–7). Mean water level was 16,2cm in S1 and 15,1cm in S2.

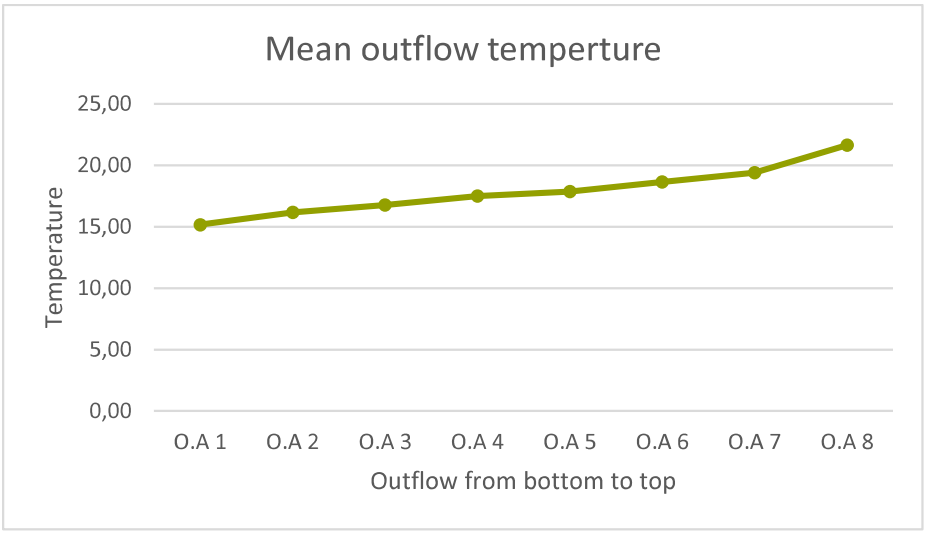

Figure 5: Mean outflow air temperatures (O.A) measured at different heights (O.A1 to O.A8, from bottom to top) within the hydroponic system integrated with the localized cooling system. The data were collected using an infrared camera (FLIR i3, Estonia), and mean values were calculated in Excel. The temperatures increased from the bottom to the top, indicating a reduced cooling effect at higher levels.

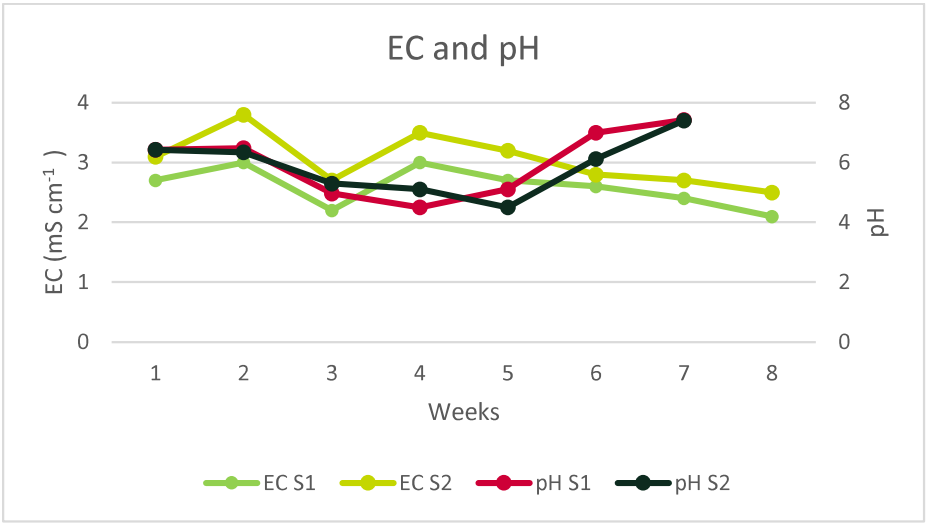

Figure 6: Weekly measurements of electrical conductivity (EC) and pH in the nutrient solution for System 1 (S1, without localized cooling) and System 2 (S2, with localized cooling), recorded before adjustments were made. Fluctuations in both EC and pH were observed across the eight-week period

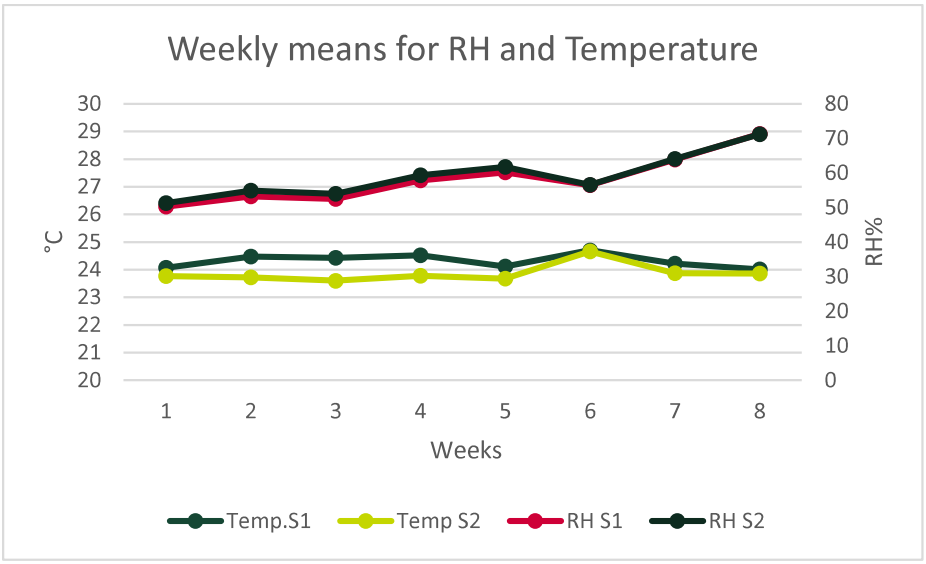

Figure 8: Figure showing the weekly means of relative humidity (RH) and temperature (Temp.) collected from dataloggers during eight weeks in the two hydroponic systems. S1 represent System 1 and was without localized cooling system. S2 represent System 2 and was with localized cooling system. Temperatures ranged from 23.6 °C to 24.7 °C, and RH varied between 50.3% and 72.3%.

Figure 7: Pictures taken from the 5th growing week and from the 8th. Photo: Anna Hallin Lundberg.

Figure 9: Pictures showing the roots from the 5th growing week, with callus formations, and from the 8th growing week. Photo: Anna Hallin Lundberg.

The two-way T-test indicated a statistical significant difference between the systems in Leaf temperature, RH, Fresh weight and Dry weight. The other measured parameters did not indicate any statistical significant difference (table 2). Pairwise Pearson Correlations performed in S1 indicated a negative correlation between RH and Leaf temperature and a positive correlation between CO_2 assimilation rate and Stomatal conductance, and between CO_2 assimilation and Dry weight. No statistical significant correlation was shown between the other parameters. In S2 statistical significant positive correlations were shown between, Fresh weight and CO_2 assimilation rate, CO_2 assimilation rate and Stomatal conductance, and Stomatal conductance and Temperature in the room. Between the other parameters there was no statistical significant correlation. Full statistical table see appendix.

Table 2: Table showing mean values from the measured parameters from System 1(S1) and System 2 (S2) and P-values from two-way T-test. Values of 0,005> indicates a statistical significant difference between the systems.

Parameter	Mean S1	Mean S2	P-value
Leaf temperature °C	21,77	22,16	0,045
Room temperature °C	24,76	23,71	0,201
Relative humidity (RH) %	54,78	56,15	0,003
Chlorophyll fluorescence Fv/Fm	0,808	0,811	0,615
CO_2 assimilation rate µmol CO_2 m^{-2} s^{-1}	11,17	10,13	0,106
Stomatal conductance H_2O m^{-2} s^{-1}	0,31	0,25	0,064
Fresh weight gram	27,33	19,91	0,044
Dry weight gram	1,19	0,72	0,032

4. Discussion

The results showed that S1 had a greater fresh weight than S2, this goes against the stated hypothesis that implementing localized air distribution would improve the system's performance in terms of productivity. This might be explained by a disadvantage in S2 that could be explained by enhanced stress and an inability to utilize the nutrients. The Pearson correlation test showed a strong positive correlation between CO_2 assimilation and fresh weight, which can indicate that the factors affecting CO_2 assimilation could directly influence biomass production. The constant airflow in S2 might have contributed to lower CO_2 assimilation, thereby reducing fresh weight. In a study on tomato plants they found that increasing air velocity can be beneficial for CO_2 assimilation to a certain point and highlighted the importance of controlling the airflow (Kitaya et al. 2003). However, the t-test did not show a statistically significant difference in CO_2 assimilation between the systems, indicating that there was no meaningful difference between S1 and S2.

The measurement of the cooling systems outflow air showed a rise in temperature from bottom to top. The top temperatures had a mean of 21,6°C which indicates that the localized cooling system did not have a temperature lowering effect. It is therefore not relevant to draw any direct conclusions about its influence on the growth of lettuce. The reason is probably related to the airflow of 0.34 m s^{-1}, which did not provide enough velocity to keep the outflow air cool throughout the system. A study done to form a model on light intensity and air velocity's effect on microclimatic parameters in a plant canopy, showed that the radiation from the light source had a greater effect on the microclimate then the airflow if the velocity was below 0.57 m s^{-1} (Gu & Goto 2024). This could further explain the lack of cooling effect in S2. Considering this, a localized cooling system could benefit from a higher air velocity to provide enough effect.

Although the localized cooling system likely did not provide enough airflow to significantly affect CO_2 assimilation, or to lower the temperature, the constant airflow may still have affected plant growth indirectly.

The water level in S2 could be seen to lower slightly quicker than S1 which could be a consequence of higher transpiration rate due to constant airflow. Both systems had relatively high pH in the beginning of the growing period which can derive from the high pH of rockwool used as substrate. To high pH can lead to that certain essential nutrients are unavailable for the plants to utilize (Kudirka et al.

2023). The mean EC in S2 before alteration were 3,16mS cm^{-1} compared to 2,59mS cm^{-1} in S1. Lettuce is salt sensitive and EC between 2,5-6,5mS cm^{-1} has been seen leading to moderate salinity stress but does not necessarily result in effects on fresh weight (Kappel et al. 2021). It's not unusual for nutrient imbalance to occur in closed hydroponic systems, due to water loss occurring by evapotranspiration, which results in higher nutrient concentrations and rising EC levels (Fathidarehnijeh et al., 2024). Salinity stress due to high EC could be the explanation of the callus formation on the roots. In a study performed on abscisic acid signalling gates in plant roots under salt stress, cell damage and root swelling was seen under conditions of high salinity (Lamers et al. 2025). Regular monitoring of EC levels is important to prevent potential phytotoxicity and reduction in yield. Refreshing the nutrient solution could be a way to manage potential negative effects (Fathidarehnijeh et al., 2024). In this experiment, a more thorough refreshing of the nutrient solution could have proven beneficial regarding the reduction of negative effects related to increased EC levels.

Bad growth was noted in both systems the first 5 weeks, this likely derived from insufficient light, this could be part of the inability for the lettuce to utilize the nutrients leading to accumulation and symptoms of salt stress. After more lights were added both leaves and roots showed enhanced growth and EC levels started to decline (figure 4). The measurements for chlorophyll fluoresce and photosynthesis were done after the added lights and did not indicate stress. This strengthens the belief that insufficient light was the main factor for slow growth.

The Insufficient light probably limited the photosynthetic process during the first five weeks. This is part of explaining the poor growth and the nutrient accumulation seen as high EC. Without enough light, the plants couldn't utilize the nutrients, leading to stress. The light probably affected the RH as well. After week five, the RH could be seen to increase from around 55–60% to 70% (Figure 7), indicating increased transpiration and a recovery from previous stress (Jones, 1993). This could have been confirmed if measurements of chlorophyll fluorescence and photosynthetic activity had been performed both before and after the added lights, enabling comparisons.

A lower concentration of nutrients in the beginning could have been favourable for the growth of the lettuce as well (Vought et al. 2024). Optimized nutrients, lights and microclimatic factors could have minimized the potential negative impact these had on the growth, camouflaging potential effect deriving from the localized cooling systems.

Repeating the experiment would have provided more data and a more relabel result. Trying different temperatures to be able to conclude if the differences in growth had to do with the temperature or not. Putting a timer on the airflow could also have been tested and perhaps proved advantageous in reducing negative effects in S2. Further research could investigate measuring and comparing energy

consumption and looking into alternative sources of cooling or heating which could be more environmentally friendly. Also measuring other factors and comparing the effect of other inflow velocity and potential effects these could have, there might be an optimum airflow. Future studies should consider monitoring pipe temperatures and possibly using multiple cooling devices to ensure even distribution. A different design of the hydroponic system, in order to possibly manage the issue with insufficient cooling, could also be considered. For example, a more horizontal or stepped design could provide more even cooling, since the air wouldn't have to move as far up in the system.

The microclimatic factors related to this experiment that should be considered and optimized in future experiments are light, temperature, RH, EC, pH, and airflow velocity.

This experiment has further made it clear that the different factors are linked and need to be carefully considered. Even if the temperature regulations systems can be modified to lower energy consumption the other parts must also work together to maximize yield and lower the resource use efficiency connected to energy consumption. Finding energy saving solutions is necessary for hydroponic production to growth, especially in the eye of rising energy prices (Liantas et al. 2023). Crop production in controlled environments is going to be necessary to ensure food production when outdoor farming is at risk with rising climatic threats. Developing these systems are going to be steps in the aspiration of completing the SDGs 2 "Zero hunger" and 13 "climate action". This by ensuring growth of crops in all environments and by reducing the climatic impact from food production by lowering the usage of resources.

5. Conclusion

This study's hypothesis was that "implementing localized air distribution in a vertical system will improve its performance in terms of productivity and energy use efficiency". The results could not support this due to lower fresh weight in S2, the system with the implemented cooling, but the system did not have any significantly lower temperature either. Which makes it unreliable to draw any conclusions regarding the localized cooling systems effects on the microclimate and how this could have affected the productivity of the system.

Even if the airflow did not contribute to any noticeable temperature effects, its present likely influenced the growing conditions in S2. This highlighted the connection between different factors within a system. Factors, such as airflow or light, can affect the whole system and can cause stress but also enhance growth significantly. Future experiments should examine optimal airflow velocity, while keeping optimal growing conditions to maximize yield and resource use efficiency. This experiment's localized cooling system would need further work and research before it can be part of lowering energy consumption while optimizing the microclimate in order to maximize yield.

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Acknowledgements

I want to direct my gratitude towards Grow Pipes who provided the systems along with ideas, knowledge and support.

A great thanks to Partnerskap Alnarp who funded the project (1595/Trg/2025).

And last a big thanks to my supervisor for all the time, lending of equipment and very quick answering of emails.

Appendix

Calculation of airflow out of the system:

d = 100 mm = 0,1 m

d / 2 = r ⟶ r = 0,05 m

0,34 m/s

$A = r^2 \cdot \pi = 0{,}05^2 \cdot \pi \approx 0{,}00785\ m^2$

$m/s \cdot m^2\ (A) = 0{,}34 \cdot 0{,}00785 \approx 0{,}00267\ m^3/s$

$0{,}00267 / 56 = 0{,}0000476786\ m^3/s$

$\cdot 1000 = 0{,}048\ L/s$

Pairwise correlation test performed in Minitab, on the measured parameters of system 1 (S1)

S1 - Pairwise Pearson Correlations			0,95.%	Signifikant if p =	<0,05
Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
Fresh Weight	Dry Weight	12	0,339	(-0,291; 0,764)	0,281
Stomata conductance	Dry Weight	12	0,433	(-0,187; 0,807)	0,16
CO_2 assimilation	Dry Weight	12	0,715	(0,240; 0,914)	0,009
RH	Dry Weight	12	0,159	(-0,456; 0,672)	0,621
Temp Room	Dry Weight	12	-0,145	(-0,664; 0,468)	0,653
Clorophyll F	Dry Weight	12	0,438	(-0,181; 0,809)	0,154
Leaf.temp	Dry Weight	12	-0,355	(-0,772; 0,275)	0,258
Stomata conductance	Fresh Weight	12	0,12	(-0,488; 0,649)	0,711
CO_2 assimilation	Fresh Weight	12	0,042	(-0,545; 0,601)	0,897
RH	Fresh Weight	12	0,134	(-0,477; 0,657)	0,678
Temp Room	Fresh Weight	12	-0,112	(-0,644; 0,494)	0,73

Clorophyll F	Fresh Weight	12	0,19	(-0,431; 0,689)	0,554
Leaf.temp	Fresh Weight	12	-0,211	(-0,700; 0,413)	0,511
CO_2 assimilation	Stomata conductance	12	0,589	(0,023; 0,869)	0,044
RH	Stomata conductance	12	0,446	(-0,172; 0,812)	0,146
Temp Room	Stomata conductance	12	-0,111	(-0,644; 0,494)	0,73
Clorophyll F	Stomata conductance	12	-0,063	(-0,615; 0,530)	0,846
Leaf.temp	Stomata conductance	12	-0,37	(-0,778; 0,259)	0,237
RH	CO_2 assimilation	12	0,369	(-0,260; 0,778)	0,238
Temp Room	CO_2 assimilation	12	-0,278	(-0,735; 0,352)	0,382
Clorophyll F	CO_2 assimilation	12	0,102	(-0,501; 0,639)	0,751
Leaf.temp	CO_2 assimilation	12	-0,359	(-0,774; 0,271)	0,252
Temp Room	RH	12	0,425	(-0,197; 0,803)	0,169
Clorophyll F	RH	12	-0,534	(-0,848; 0,057)	0,073
Leaf.temp	RH	12	-0,765	(-0,930; -0,340)	0,004
Clorophyll F	Temp Room	12	-0,42	(-0,801; 0,203)	0,175
Leaf.temp	Temp Room	12	-0,198	(-0,693; 0,424)	0,538
Leaf.temp	Clorophyll F	12	0,361	(-0,268; 0,775)	0,248

Pairwise correlation test performed in Minitab, on the measured parameters of system 2 (S2)

S2 - Pairwise Pearson Correlations			0,95.%	Signifikant if p =	<0,05
Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
Fresh Weight	Dry Weight	12	0,258	(-0,371; 0,725)	0,418
Stomata conductance	Dry Weight	12	0,253	(-0,376; 0,722)	0,428
CO_2 assimilation	Dry Weight	12	0,338	(-0,293; 0,764)	0,283
RH	Dry Weight	12	0,325	(-0,306; 0,757)	0,303
Temp Room	Dry Weight	12	0,043	(-0,544; 0,602)	0,894
Clorophyll F	Dry Weight	12	0,09	(-0,510; 0,631)	0,78
Leaf.temp	Dry Weight	12	0,241	(-0,386; 0,716)	0,45
Stomata conductance	Fresh Weight	12	0,327	(-0,304; 0,759)	0,299
CO_2 assimilation	Fresh Weight	12	0,716	(0,240; 0,914)	0,009
RH	Fresh Weight	12	-0,389	(-0,787; 0,238)	0,211
Temp Room	Fresh Weight	12	-0,096	(-0,635; 0,506)	0,767
Clorophyll F	Fresh Weight	12	0,013	(-0,565; 0,583)	0,967
Leaf.temp	Fresh Weight	12	0,457	(-0,158; 0,817)	0,135
CO_2 assimilation	Stomata conductance	12	0,691	(0,194; 0,906)	0,013
RH	Stomata conductance	12	0,223	(-0,402; 0,706)	0,486
Temp Room	Stomata conductance	12	0,594	(0,031; 0,871)	0,042
Clorophyll F	Stomata conductance	12	-0,252	(-0,722; 0,376)	0,429
Leaf.temp	Stomata conductance	12	0,211	(-0,413; 0,700)	0,511
RH	CO_2 assimilation	12	-0,124	(-0,651; 0,485)	0,702
Temp Room	CO_2 assimilation	12	0,279	(-0,351; 0,735)	0,38

Clorophyll F	CO_2 assimilation	12	-0,247	(-0,719; 0,381)	0,44
Leaf.temp	CO_2 assimilation	12	0,344	(-0,286; 0,767)	0,273
Temp Room	RH	12	0,358	(-0,272; 0,773)	0,253
Clorophyll F	RH	12	0,212	(-0,412; 0,701)	0,508
Leaf.temp	RH	12	-0,379	(-0,783; 0,249)	0,224
Clorophyll F	Temp Room	12	-0,104	(-0,640; 0,500)	0,747
Leaf.temp	Temp Room	12	-0,269	(-0,730; 0,360)	0,397
Leaf.temp	Clorophyll F	12	0,004	(-0,571; 0,577)	0,99

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