Evaluating the Influence of Nutrient Solution Temperatures on Nutrient Uptake, Utilization, and Biomass Production of Hydroponically Grown Tomatoes

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Abstract

In addressing the global food security challenges, hydroponic agriculture emerges as a promising and resource-efficient cultivation method. The HypoWave+ project aims at producing food using wastewater. This study focuses on elucidating the effects of nutrient solution (NS) temperature on nutrient uptake, biomass production, and physiological effciency (PE) in hydroponically grown tomatoes, specifically examining two cultivars, Sweeterno and Saluoso. Conducted at the University of Hohenheim, the experimental setup employed a Deep Water Culture Hydroponic System and exposed the plants to three different NS temperature treatments: 17°C, 21°C, and 27°C. Daily assessments over a 30-day period encompassed phenological status, nutrient levels in the NS, and biomass parameters.

Our findings revealed that temperature significantly impacts nutrient uptake patterns; the 21°C treatment yielded the highest uptake of nitrate across both cultivars. Moreover, the Sweeterno cultivar consistently outperformed Saluoso in terms of biomass production and PE across all temperature conditions. This suggests that Sweeterno is more adaptable to varying NS temperatures, and can potentially be a cultivar of choice for resource-efficient hydroponic farming. Interestingly,

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1 Introduction

The global food security trilemma, characterized by an unstable food supply, resource shortage, and environmental degradation, is being exacerbated by an increasing urban population and an aging demographic (Kozai et al., 2018). Hydroponic agriculture has emerged as a potential solution to these challenges, allowing for high-yield cultivation in urban settings with minimized resource usage and environmental impact (Barbosa et al., 2015).

Food security is a multifaceted issue, encompassing not only social factors and distribution, but also environmental sustainability, economic viability, and technological innovation. In this context, the HypoWave+ project, under the leadership of the Technical University of Braunschweig, is exploring new agricultural cultivation methods with reduced water consumption. The project aims to reduce drinking water consumption in the agricultural industry by using recycled wastewater from sewage treatment plants. In this innovative cultivation method, crops are grown in hydroponic containers without soil and are continuously supplied with a nutrient solution (NS) from treated wastewater. The project is currently planning to produce tomatoes and peppers using this method (Institute for Social-Ecological Research (ISOE) GmbH, 2022).

In the context of climate change, this cultivation method offers farmers a new way to produce crops while conserving water. The plants only extract water from the system, and no water is lost through seepage or evaporation. The cultivation of crops in greenhouses also allows for year-round cultivation. Additionally, the quality of wastewater is improved as the plants extract excess nutrients (Institute for Social-Ecological Research (ISOE) GmbH, 2022).

This bachelor thesis, which is part of the HypoWave+ project, focuses on the impact of NS temperature on nutrient use efficiency (NUE) and biomass in hydroponically grown tomatoes. The temperature of the NS is a critical factor in hydroponic systems, influencing nutrient uptake, plant growth, and overall crop yield (He et al., 2022).

In many agricultural soils around the world, estimates of the overall efficacy of applied fertilizer have been estimated to be around or lower than 50% for Nitrogen, less than 10% for Phosphorus, and around 40% for Potassium (Baligar et al., 2007). Using hydroponic systems could help improve the efficiency of fertilizer, thus tackle the global food security trilemma. Understanding the impact of NS temperature in hydroponic systems and using best management practices will help create sustainable agricultural systems that safeguard and improve the quality of the soil, water, and air. (Kozai et al., 2018)

In the pursuit of sustainable food systems, nutrient cycling has been identified as a key component, particularly within the framework of a circular economy, as highlighted by the Food and Agriculture Organization (Food and Agriculture Organization of the United Nations, 2018). In horticulture, nutrient cycling can refer to the management and recycling of nutrients within a cultivation system to minimize waste and ensure that plants receive the necessary nutrients for optimal growth, often through the reuse of organic matter and water. By integrating innovative recycling fertilizers into the NS and recirculating it, hydroponics could significantly decrease the reliance on synthetic mineral fertilizers in horticulture (Halbert-Howard et al., 2020). This approach not only promotes the efficient use of resources but also contributes to closing nutrient cycles in contemporary circular agri-food systems.

Tomatoes were selected as the subject of this study due to their status as one of the most widely cultivated vegetables worldwide (Andrade-Linares et al., 2013). Their rapid and consistent growth, along with their extensive use as a model organism in scientific research, further underscores the practical relevance of this investigation.

In spite of extensive research into the effects of soil temperature on plant growth (DeLucia et al., 1992; Peng and Dang, 2003; Stone et al., 1999), the impact of NS temperature within hydroponic systems remains an inadequately explored domain, thereby revealing a lacuna in existing scientific literature. The present study endeavors to address this knowledge deficit by posing the subsequent research inquiries: (1) How does the temperature of the nutrient solution modulate biomass production in hydroponic growth systems? (2) What is the influence of nutrient solution temperature on nutrient use efficiency in hydroponic settings? Resolving these questions bears significance for the HypoWave+ Project, serving dual functions: it elucidates the consequences of varying nutrient solution temperatures and lays a foundation for future research in this domain.

The significance of this study transcends the academic sphere, holding potential to contribute to more efficient urban agricultural practices. This research is particularly pertinent in regions facing challenges such as water scarcity and urbanization. In a world where global agriculture confronts unprecedented obstacles, the insights from this study may lead to timely and innovative solutions, optimizing hydroponic cultivation methods, promoting sustainable agricultural practices and adressing the global food security trilemma.

2 Theory and State of Research

2.1 Nutrient solution Temperature

2.1.1 Importance of Root zone Temperature

The root zone temperature, referring to the temperature of the NS in hydroponic systems, plays a pivotal role in plant growth, nutrient uptake, and overall biomass production. It is a crucial parameter that can significantly influence the physiological and biochemical processes of plants, thereby affecting their growth and productivity (He et al., 2022).

In hydroponic systems, the NS temperature can be precisely controlled, allowing for optimization of plant growth conditions. This is particularly important in arid climates, where high ambient temperatures can stress plants and reduce crop yields. By controlling the temperature, it is possible to mitigate the effects of high ambient temperatures and maintain optimal growth conditions for the plants (Kozai et al., 2018).

The temperature of the NS exerts an influence not only on plant growth parameters but also on the propagation of plant diseases. A plethora of plant pathogens flourish in conditions characterized by elevated temperature and humidity, conditions frequently encountered in hydroponic systems. By modulating the temperature within the root zone, one can engender an environment less conducive to the proliferation and dispersal of such pathogens, thereby mitigating the occurrence of plant diseases (Marschner, 2012).

Additionally, root zone temperature plays a pivotal role in nutrient dynamics within the NS. As the NS temperature ascends, the solubility of specific nutrients may enhance, thereby facilitating their uptake by plant root systems. In contrast, a reduction in NS temperature may compromise nutrient solubility, thereby posing constraints on their bioavailability for plant uptake (Marschner, 2012).

Previous studies have shown that NS temperature can affect nutrient uptake and use efficiency in hydroponic systems (He et al., 2022). Moreover, temperature can influence the interaction between different nutrients in the NS. For instance, the uptake of ammonium and nitrate by plants is often inversely related, with an increase in the uptake of one leading to a decrease in the uptake of the other. This interaction can be influenced by temperature, with changes in temperature potentially affecting the balance between ammonium and nitrate uptake (Britto and Kronzucker, 2002). Therefore, understanding the effects of NS temperature on nutrient uptake and NUE could provide valuable insights for optimizing hydroponic cultivation practices.

2.1.2 Temperature and Disease control

Maintaining an optimal root zone temperature is crucial for ensuring efficient nutrient uptake and use, as well as for promoting healthy plant growth and high crop yield. High ambient temperatures can lead to heating up the NS. This can negatively affect plant growth and nutrient dynamics, potentially leading to reduced crop yield and quality (He et al., 2022).

High temperatures can also exacerbate challenges related to disease and pest control. Elevated water temperatures in hydroponic systems can lead to increased susceptibility to root diseases such as Pythium and Fusarium, as well as facilitate the growth of harmful algae and bacteria (Kumazaki, 2022). Moreover, high temperatures can accelerate the evaporation of water and nutrients, requiring more frequent replenishment and dislocating the ion balance inside the NS, increasing labor and resource costs (Hendrickson et al., 2022). Therefore, effective temperature management is not only essential for optimizing plant growth but also for minimizing risks associated with diseases and resource utilization.

The empirical evidence underscores the importance of temperature control for disease mitigation. For instance, a study by Schuerger and Hammer (1995) demonstrated that the prevalence of Tomato Mosaic Virus in hydroponically grown pepper plants (*Capsicum annuum*) was minimized at a root zone temperature of 18°C and maximized at 32°C. Another study, done by Gold and Stanghellini (1985) revealed that the growth rate of *Pythium aphanidermatum*, a soil-borne oomycete pathogen notorious for causing root rot in hydroponic systems, increased with rising temperatures. This pathogen thrives in warm, oxygen-poor conditions and can rapidly spread through the nutrient solution, leading to symptoms such as root browning, wilting, and stunted plant growth. These studies highlight the importance of maintaining optimal temperature conditions to control the spread of pathogens in hydroponic setups.

Hydroponic systems offer the advantage of precise control over the root zone temperature, allowing for the optimization of nutrient dynamics and plant growth under different climatic conditions. This is particularly relevant for global food security, as hydroponic systems can be used to cultivate crops in areas where traditional agriculture is not feasible due to harsh environmental conditions.

2.2 Nutrient Uptake and Use Efficiency

2.2.1 Introduction to Nutrient Uptake and NUE

Nutrient uptake is a critical process in plant growth and development, involving the absorption of essential nutrients from the growth medium, in this case, the NS in hydroponic systems. The nutrients absorbed are used in various metabolic processes, contributing to the overall health, growth, and productivity of the plant. NUE, on the other hand, refers to the plant's ability to convert the absorbed nutrients into biomass. High NUE is desirable as it indicates that a plant can produce more biomass with a given nutrient input, which is particularly important in hydroponic systems where nutrient supply is carefully controlled (Kozai et al., 2018).

2.2.2 Sustainability and Circular Economy

In the context of sustainability and circular economy, nutrient uptake and NUE are of paramount importance. Efficient nutrient uptake and use can reduce the need for synthetic fertilizers, which are energy-intensive to produce (Lubkowski, 2016) and can lead to environmental pollution when not managed properly (European Commission, 2023). Moreover, high NUE can contribute to the circular economy by reducing waste and promoting the recycling of nutrients within the system. This is particularly relevant in hydroponic systems, where the NS can be recirculated, thus minimizing nutrient waste (Food and Agriculture Organization of the United Nations, 2018).

2.2.3 Role of Key Nutrients

The nutrients under investigation in this study Ammonium (NH_4^+), Phosphate (PO_4^{3-}), and Nitrate (NO_3^-) are fundamental to plant physiology, metabolism, and growth. Their roles are elaborated below to provide context for their inclusion in this study.

Ammonium (NH_4^+)

Ammonium is one of the primary forms of nitrogen available to plants. It is directly assimilated into amino acids via the GS-GOGAT (Glutamine Synthetase-Glutamine Oxoglutarate Aminotransferase) pathway, bypassing the need for nitrate reduction, a process that consumes energy (Lea and Miflin, 2006). These amino acids are the building blocks for proteins, which serve various functions including enzymatic catalysis, structural roles, and signaling. Moreover, ammonium is a component of chlorophyll, the pigment essential for photosynthesis, and nucleic acids, which are vital for the storage and transmission of genetic information (Crawford, 1995).

Nitrate (NO_3^-)

Nitrate is another primary source of nitrogen for plants and is abundant in most soils. Unlike ammonium, nitrate needs to be reduced to ammonium in the plant cells before it can be incorporated into amino acids, a process that involves the enzymes nitrate reductase and nitrite reductase (Stitt, 1999). Nitrate also serves as a signaling molecule, affecting root architecture, stomatal opening, and flowering time among other developmental processes (Wang and Tsay, 2018).

Phosphate (PO_4^{3-})

Phosphorus, in the form of phosphate ions, is indispensable for plant growth and development. It is a component of ATP, the primary energy currency in cells, and is involved in the phosphorylation reactions that regulate many metabolic pathways. Phosphorus is also a structural component of nucleic acids and phospholipids, the latter of which make up cell membranes. In addition, phosphate is crucial for the activation of enzymes and is involved in signal transduction pathways (Marschner, 2012; Raghothama, 1999).

2.2.4 Forms of Nutrient Use Efficiency

NUE manifests in various forms including Agronomic Efficiency and Agrophysiological Efficiency, among others. The efficiency ratio of crops is subject to modulation by both external and plant intrinsic factors. In this investigation, particular attention is accorded to the impact of an external factor - NS temperature, on Physiological Efficiency (PE).

The PE offers insight into how the plant's biomass is associated with the nutrients taken up. It is an essential parameter that connects the nutritional status of the plant with its growth and developmental characteristics. The equation for calculating PE will be presented in the Material and Methods section and used in the results section.

The interpretation of PE helps in identifying the plant's efficiency in converting absorbed nutrients into biomass. A higher PE indicates a more efficient conversion of nutrients into dry matter, reflecting a more optimal use of nutrients. This could be indicative of a plant's ability to thrive in nutrient-limited conditions, whereas a lower PE might suggest a less efficient utilization of nutrients, which could have implications for fertilization strategies.

Nutrient uptake and use efficiency are critical factors in hydroponic cultivation, with significant implications for sustainability and the circular economy. By investigating the effects of NS temperature on these processes, this study aims to contribute to the development of more efficient and sustainable hydroponic cultivation methods (He et al., 2022; Marschner, 2012).

2.3 Impact of Temperature on Nutrient Dynamics

2.3.1 Temperature's Role in Nutrient Solubility

Temperature is a key environmental factor that significantly affects the physiology of hydroponically grown tomatoes, influencing everything from nutrient absorption to enzymatic reactions and metabolic efficiency (He et al., 2022). This section delves into the intricacies of these interactions, aiming to provide a comprehensive understanding of the subject.

Ammonium, nitrate, and phosphate are all soluble in water, and their solubility can be influenced by temperature. As the temperature of the NS increases, the solubility of these nutrients generally increases, making them more readily available for uptake by the plant roots (Marschner, 2012). However, the relationship between temperature and nutrient solubility is not linear and can be affected by other factors such as power of hydrogen (pH), electrical conductivity (EC), Oxygen (O_2) concentration and the presence of other ions in the solution.

According to Tindall et al. (1990), the optimal root-zone temperature for *Lycopersicon esculentum*, a type of cherry tomato, was found to be 24°C. Plants growing in this temperature had the highest nutrient uptake and overall growth. The functionality of various enzymes such as nitrate reductase, glutamine synthetase, and phosphatase are at their peak. These enzymes are instrumental in converting absorbed nutrients like Nitrate, Ammonium, and Phosphate into biologically useful forms like amino acids and nucleic acids. Enzyme kinetics favor this temperature range, achieving maximal catalytic efficiency, which in turn supports a higher rate of metabolic reactions. At these temperatures, ion transporters like NRT (Nitrate Transporters) and AMT (Ammonium Transporters) are highly active, facilitating rapid nutrient uptake (Marschner, 2012).

When root-zone temperatures fall below 20°C, enzymatic activities, particularly those of nitrate reductase and phosphatase, are markedly reduced. This diminishes the plant's capacity to convert absorbed nutrients into usable forms. At temperatures above 25°C, enzymes can become denatured, and transporters like NRT and AMT lose their selectivity, potentially causing nutrient imbalances and toxicities (Ruiz et al., 2002).

2.3.2 Nutrient Uptake Mechanisms

Nitrate is generally absorbed through two types of transport systems—high-affinity transport system (HATS) and low-affinity transport system (LATS)—depending on its concentration in the nutrient solution. NS temperature impacts the efficiency of these systems: lower temperatures slow down transporter kinetics, while higher temperatures might compromise transporter selectivity. Ammonium uptake is facilitated primarily via Ammonium transporters (AMT), whose efficiency is also regulated by temperature. The temperature-sensitive nature of these transporters impacts not just the rate of uptake but also intracellular processing, affecting the assimilation of Nitrogen into amino acids through the GS-GOGAT pathway (Orsel et al., 2006).

Phosphate is taken up by the plant using phosphate transporters (PHT). Like NRT and AMT, PHTs are also influenced by root-zone temperature, affecting the plant's ability to integrate Phosphate into energy molecules like ATP.

2.3.3 Effects on Ammonium and Nitrate

Ammonium and Nitrate are two primary forms of nitrogen that are crucial for plant growth and development. The availability and dynamics of these nitrogen forms in the NS are highly dependent on temperature, which in turn affects various biochemical and microbial processes.

Interestingly, the uptake of Nitrate can be inhibited by the presence of Ammonium. This phenomenon is attributed to the crosstalk between NRT and AMT, which are integral membrane proteins responsible for the uptake of these nutrients. These transporters are not only involved in nutrient uptake but also play a role in downstream signaling pathways that regulate nutrient assimilation (Hachiya and Sakakibara, 2017).

High levels of Ammonium in the root zone can lead to the repression of nitrate reductase, an enzyme crucial for the conversion of nitrate to nitrite, thereby affecting the assimilation of Nitrate into organic forms. This repression is often mediated through complex signaling pathways that involve both transcriptional and post-transcriptional modifications (Hachiya and Sakakibara, 2017).

The interplay between Nitrate and Ammonium uptake has significant implications for plant growth and development. It also raises questions about the optimization of nutrient ratios as well as NS temperature in agricultural settings, especially in the context of sustainable farming practices.

Impact on Nitrification

Nitrification is a two-step aerobic process involving the conversion of ammonium to nitrite (NO_2^-) and subsequently to nitrate, primarily carried out by nitrifying bacteria such as Nitrosomonas and Nitrobacter. At lower temperatures, the metabolic activity of these bacteria slows down, leading to reduced rates of nitrification (Marschner, 2012). As a result, ammonium may accumulate in the NS, posing a risk of toxicity to plants. Symptoms of ammonium toxicity include leaf chlorosis, root stunting, and overall reduced plant growth (Britto and Kronzucker, 2002).

Impact on Denitrification

Conversely, at higher temperatures, the metabolic activity of nitrifying bacteria increases, accelerating the nitrification process. This can potentially lead to a depletion of ammonium levels and an increase in nitrate concentrations in the NS. While nitrate is generally less toxic to plants, its excessive accumulation can lead to imbalances in nutrient uptake and potential health risks when consumed (Santamaria, 2006).

Denitrification is the anaerobic conversion of nitrate to nitrite and then to nitrogen gas (N_2) or other nitrogenous gases, primarily carried out by denitrifying bacteria. In hydroponic systems, the role of denitrification is less pronounced compared to soil-based systems due to the generally aerobic conditions and lower microbial diversity. However, at higher temperatures, any denitrifying bacteria present may become more active, potentially leading to a decrease in nitrate levels in the NS.

2.3.4 Effects on Phosphate

Another vital nutrient, Phosphate, has its solubility in the NS affected by temperature. At lower temperatures, phosphate solubility decreases, potentially leading to a reduction in availability for plant uptake, resulting in deficiency symptoms such as reduced growth and dark green leaves. Conversely, higher temperatures increase phosphate solubility, potentially enhancing its availability for plant uptake, playing a crucial role in energy transfer and storage within the plants (Marschner, 2012).

Interactions in interplay between nutrients can be influenced by temperature, with changes in temperature potentially affecting the balance between ammonium and nitrate uptake. Similarly, the uptake of phosphate can be affected by the levels of ammonium and nitrate in the NS, with high levels of these nutrients potentially inhibiting phosphate uptake (Marschner, 2012). In this study, nutrient concentrations were carefully managed to avoid toxicity issues associated with both high and low nutrient levels, ensuring optimal nutrient availability and uptake across the range of temperatures investigated.

2.3.5 Temperature-Dependent Equilibrium

It's crucial to emphasize that the variations in ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in the NS are not isolated phenomena. Instead, they are components of a broader dynamic equilibrium system. This system is in a constant state of flux, adjusting itself in response to various environmental and internal factors. The levels of these nitrogenous compounds are particularly sensitive to temperature changes, which can accelerate or decelerate their respective metabolic pathways within the plant (Winzor and Jackson, 2006).

To quantify this, consider the equilibrium equation for the ammonium-nitrate system in the NS:

$$K = \frac{[NH_4^+]}{[NO_3^-]} \tag{2.1}$$

where K is the equilibrium constant, and (NH_4^+) and (NO_3^-) are the concentrations of ammonium and nitrate, respectively.

In our study, temperature was identified as a significant variable influencing the equilibrium constant K in the hydroponic system. We conducted experiments under three distinct temperature regimes— 17°C, 21°C and 27°C—to rigorously assess its impact on nutrient concentrations. Subsequent calculations revealed that K values were 0.019, 0.018, and 0.025 for the respective temperature settings. Our observations are consistent with the predicted behavior, where an increase in temperature led to an increase in the value of the equilibrium constant K. Concurrently, nitrate levels showed a relative decrease, which could suggest an increased metabolic activity of bacteria involved in nitrogen transformations, if present.

This temperature-dependent change in K values and nitrate levels lends further support to the hypothesis that higher temperatures might stimulate microbial activities, such as denitrification, which could be reducing the nitrate concentrations in the nutrient solution (NS). It is important to consider that while hydroponic systems generally have lower microbial diversity compared to soil systems, the presence and potential activity of denitrifying bacteria cannot be entirely ruled out. This introduces complexities in the accurate computation of Physiological Efficiency, as will be discussed subsequently.

While temperature plays a significant role, it's not the only factor that impacts this equilibrium. The pH level of the NS can affect the solubility and availability of these nutrients. Electrical conductivity (EC) serves as an indicator of the total ion concentration in the NS, which can also influence nutrient uptake. Oxygen concentration is another critical factor, as it impacts root respiration and, consequently, nutrient absorption. Additionally, the presence of other ions in the NS can either compete with or facilitate the uptake of ammonium and nitrate (Winzor and Jackson, 2006). To stay inside the scope of this paper, we focus solely on the effect of the NS Temperature.

2.4 Oxygen and Nutrient Solubility

Oxygen solubility in the NS is another crucial factor influenced by temperature. Oxygen is vital for plant root respiration and the activity of beneficial microorganisms in the NS. As seen in Table 1, as temperature increases, the solubility of oxygen decreases, reducing the available dissolved oxygen for plant roots and microorganisms, which can limit their activity and potentially affect plant growth and NUE (Marschner, 2012).

Table 1: This table represents the solubility of various nutrients and oxygen in pure water at various temperatures. Taken from (Trejo-Tellez and Gomez-Merino, 2012) and (Sigma-Aldrich, 2023)

Temperature (°C)	**O_2** (mg/L)	**KNO_3** (g/100g)	**NH_4Cl** (g/100g)	**$NH_4H_2PO_4$** (g/100g)
0	14.6	13.3	29.7	22.7
20	9.1	31.7	37.56	36.8
40	6.4	63.9	46.0	56.7
60	4.9	109.9	55.3	82.9
80	4.0	169.0	65.6	120.7
100	3.3	245.2	77.3	174.0

While at the same time, solubility for ammonium, nitrate, and phosphate correlate positively with temperature. The compounds displayed in Table 1 represent commonly used forms of the key nutrients in hydroponic systems, which are often found in commercial fertilizers. Ammonium chloride (NH_4Cl) and ammonium dihydrogen phosphate ($NH_4H_2PO_4$) were selected to represent forms of nitrogen and phosphorus that are readily available for plant uptake. Potassium nitrate (KNO_3) was chosen to represent a key source of nitrate. These compounds were chosen based on their common use in hydroponic NS and their relevance to the nutrients under examination.

2.4.1 Oxygen Solubility in Water

Unlike solid minerals, the solubility of oxygen in water decreases with increasing temperature. This behavior can be explained by the kinetic theory of gases and the nature of intermolecular interactions. As temperature increases, the kinetic energy of oxygen molecules also increases, reducing the attractive forces between the oxygen molecules and water. Consequently, fewer oxygen molecules are able to dissolve in the water at higher temperatures. (Verberk et al., 2011)

Additionally, the increased movement of water molecules at higher temperatures creates less favorable conditions for gas molecules to dissolve. This phenomenon is consistent across different pressures and salinity levels, as observed in both fresh and seawater. The careful management of temperature in hydroponic systems is thus essential to maintain the optimal solubility of oxygen, ensuring sufficient availability for plant roots and microorganisms (ToolBox, 2005).

In the present study, the mean oxygen concentrations were found to be 4.82 mg/L, 4.13 mg/L, and 3.46 mg/L for the temperature treatments of 17°C, 21°C, and 28°C, respectively. These empirical findings are in alignment with the established literature, corroborating the inverse relationship between oxygen solubility and temperature.

2.5 Biomass Production

Biomass production in plants refers to the synthesis and accumulation of organic matter, primarily carbohydrates, proteins, lipids, and nucleic acids, through various metabolic processes. In hydroponic systems, plants absorb essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) from the NS. These nutrients are vital for the synthesis of amino acids, nucleic acids, and other organic compounds that contribute to biomass production.

The primary process responsible for biomass production is photosynthesis, where light energy is converted into chemical energy in the form of glucose. This glucose is then used as a building block for other organic compounds, contributing to the overall biomass of the plant (Taiz et al., 2015).

Plant hormones such as auxins, cytokinins, and gibberellins play significant roles in regulating biomass production. They influence cell division, cell elongation, and differentiation, thereby affecting the overall growth and development of the plant. Signaling pathways involving these hormones interact with nutrient signaling pathways, allowing the plant to coordinate nutrient uptake with growth processes (Sakakibara, 2006).

2.5.1 Carbon and Nitrogen Metabolism

The interplay between carbon and nitrogen metabolism is central to biomass production. Carbon skeletons derived from photosynthesis are used to assimilate nitrogen into amino acids, which are then incorporated into proteins and other nitrogen-containing compounds. The balance between carbon and nitrogen assimilation is regulated by key enzymes and is sensitive to environmental factors, including NS temperature (Coruzzi and Bush, 1999).

2.5.2 Impact of Root-Zone Temperature on Biomass Production and Nutrient Dynamics

The temperature of the root-zone in hydroponic systems serves as a linchpin in the intricate web of factors that govern biomass production. It not only influences the physiological state of the plant but also modulates the biochemical pathways that are central to nutrient uptake and assimilation.

One of the most compelling pieces of evidence comes from (Tindall et al., 1990), which identified 24°C as the optimal root-zone temperature for *Lycopersicon esculentum*.

At this optimal temperature, key enzymes such as nitrate reductase, glutamine synthetase, and phosphatase operate at maximal efficiency. These enzymes are crucial for the conversion of absorbed nutrients like Nitrate, Ammonium, and Phosphate into forms that are biologically useful, such as amino acids and nucleic acids (Marschner, 2012). The heightened enzymatic activity at optimal temperatures enhances the plant's metabolic rate, leading to an increased rate of reactions that contribute to biomass production.

However, the effects of temperature on biomass production are not uniformly positive. Suboptimal temperatures can have a range of detrimental impacts. For instance, temperatures below 20°C can significantly reduce the activity of enzymes like nitrate reductase and phosphatase, thereby diminishing the plant's ability to convert absorbed nutrients into usable forms (Ruiz et al., 2002). On the other end of the spectrum, temperatures exceeding 25°C could lead to enzyme denaturation and a loss of selectivity in nutrient transporters like NRT and AMT, potentially causing nutrient imbalances and toxicities.

The role of root-zone temperature extends beyond the plant's internal biochemistry; it also affects the nutrient dynamics in the surrounding NS. For example, higher temperatures can increase the solubility of certain nutrients, making them more readily available for plant uptake. However, this can also lead to faster nutrient depletion rates, requiring more frequent replenishment of the NS (Kozai et al., 2018).

Given these complexities, effective management strategies are essential. These may encompass continuous monitoring of root-zone temperatures, the use of temperature-resistant plant cultivars, and dynamic adjustments to the NS formulation based on real-time temperature data. Such multi-pronged approaches can help in aligning the root-zone temperature with other environmental variables and nutrient requirements, thereby maximizing biomass production (Zhang, 2019).

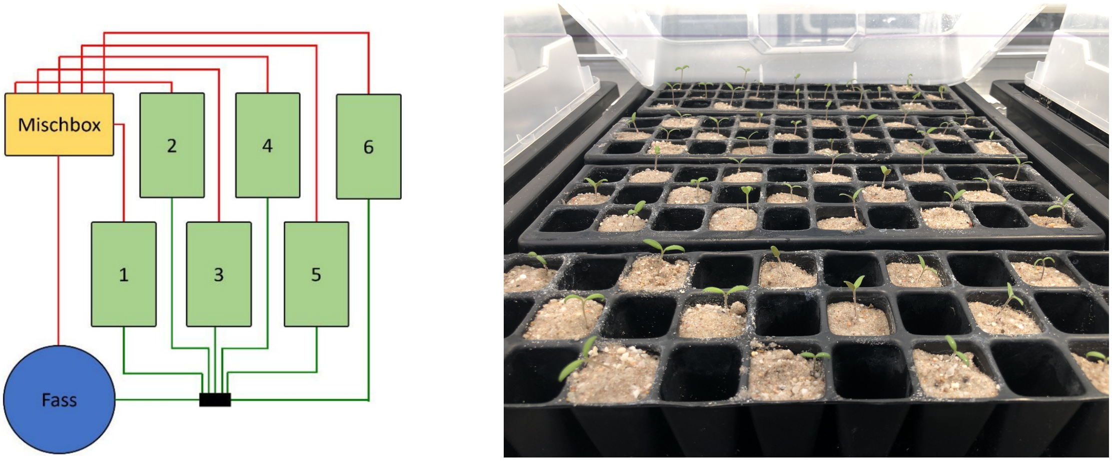
3 Materials and Methods

3.1 Plant Material and Growth Conditions

Two cultivars of tomatoes (*Solanum lycopersicum cv.* ”Sweeterno” (SW) and ”Saluoso” (SA), were sourced from Rijk Zwaan Zaadteelt en Zaadhandel B.V. (De Lier, Netherlands). The initiation of the seeding process began on the 30th of September, 2022, which is henceforth referred to as DAS 0 (Days After Sowing). This process was undertaken at the Phytotechnikum (PHT) facility of the University of Hohenheim, Stuttgart. After the primary root reached a span of 3 cm, which occurred six days post sowing (DAS 6), the saplings were transferred to seeding trays that contained sand and were covered with a humidity dome. The trays were organized in a checkered pattern to mitigate any possibility of shade. Throughout the first five weeks of their growth, the plants were supplemented using a 20% NS (20 mg Nitrogen per Liter), with an EC of 450 $\frac{\mu\mathrm{S}}{cm}$ and a pH of 6.0.

3.1.1 Configuration of the Hydroponic System

On the 8th of November, 2022 (Days After Transplanting, abbreviated as DAT 0), the plants were transferred from the seeding trays to a Deep Water Culture Hydroponic System. Each treatment consisted of one system including seven boxes each measuring 30 x 20 x 16 cm, sourced from AUER Packaging (Amerang, Germany). Out of these, six boxes were designated for plant cultivation while the remaining box was assigned the role of a ”mixing unit” used to take probes of the NS as seen in figure 1. These boxes were connected to a 60-liter barrel, which was equipped with a water pump and a unit for heating/cooling. Each system held a NS measuring 101.8 liters, which was circulated by a pump (compactON 1000, EHEIM, Deizisau, Germany) at the rate of 200 liters per hour. Each box was planted with a single tomato plant, leading to the establishment of three tables, each hosting six plants. This resulted in a flow rate of 33.33 liters per hour per plant. The tables were placed 85 cm above ground level with the boxes placed atop, resulting in a total planting height of 100.5 cm. Four Ceramic metal-halide lamps (CHD Agro 400, DH Licht GmbH, Wülfrath, Germany) were installed at a height of 150 cm from the table, each placed 90 cm apart from the next. To characterize the lighting experienced by the plants, Photosynthetic Active Radiation (PAR) was measured at different distances from the light source: 20 cm, 60 cm and 90 cm. The recorded PAR values at these respective distances were 243, 300, and 600 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$



(a) System Setup taken from Fischer (2023) (b) Seedlings under humidity Dome

Figure 1: Complete setup with System Setup and Seedlings under humidity Dome

3.1.2 Preparation and Maintenance of Nutrient Solution

The base formulation of the NS was meticulously crafted in the lab, following the recipe provided by Kreij et al. (2003). This resulted in the production of multiple Stock solutions labeled A through H, containing a diverse range of salts and micronutrients, as outlined in Table 2. The constituents were accurately measured using a volumetric flask and were brought to a final volume of one liter with the use of deionized water ($\frac{\mu S}{cm}$ = 3.8).

The experiment called for a 40% NS, equating to 40 mg Nitrogen per Liter, which was devised in a sizable 60-liter container. This led to the addition of 24 mL of each base solution into the container.

Table 2: Composition of the nutrient solution with stock solutions (SS) A to H, the reagents with the molecular formula, the nutrient of interest in this reagent, and the weight measured for one liter of base solution (BS).

SS	Formula	Nutrient	BS [g/L]
A	$(NH_4)_2H_2PO_4$	NH_4, P	21
B	$Ca(NO_3)_2 \times 4H_2O$	Ca, NO_3	490
C	KNO_3	K, NO_3	271
D	K_2SO_4	K, S	60
E	KH_2PO_4	K, P	90
F	$MgSO_4 \times 7H_2O$	Mg, S	170
G	$CaCl_2 \times 2H_2O$	Ca, Cl	21.5
	KCl	K, Cl	10
H	$C_{10}H_{12}FeN_2NaO_8 \times 3H_2O$	Fe	5.3
	$MnSO_4 \times H_2O$	Mn	1.9
	$ZnSO_4 \times 7H_2O$	Zn	1.3
	$CuSO_4 \times 5H_2O$	Cu, S	0.25
	$(NH_4)_6Mo_7O_{24} \times 4H_2O$	Mo, NH_4	0.09
	H_3BO_4	B	2.9

In the field of hydroponic cultivation, selecting the right formulation of NS is paramount for optimal plant growth. Different researchers

Table 3: The form of nutrients absorbed by plants and the compositions of nutrients as proposed by various scientists.

Element	**Form**	**Hoagland** (mg/L)	**Hewitt** (mg/L)	**Cooper** (mg/L)	**Steiner** (mg/L)	**De Kreij** (mg/L)
Nitrogen	NH_4^+, NO_3^-	210	168	200-236	168	100
Phosphorus	HPO_4^{2-}, $H_2PO_4^-$	31	41	60	31	25.8
Potassium	K^+	234	156	300	273	162.7
Calcium	Ca^{2+}	160	160	170-185	180	89
Magnesium	Mg^{2+}	34	36	50	48	16.9
Sulfur	SO_4^{2-}	64	48	68	336	33.3
Iron	Fe^{2+}, Fe^{3+}	2.5	2.8	12	2-4	0.8
Copper	Cu^{2+}	0.02	0.064	0.1	0.02	0.05
Zinc	Zn^{2+}	0.05	0.065	0.1	0.11	0.3
Manganese	Mn^{2+}, Mn^{4+}	0.5	0.54	2	0.62	0.6
Boron	H_3BO_3, BO_3^-, $B_4O_7^{2-}$	0.5	0.54	0.3	0.14	0.05
Molybdenum	MoO_4^{2-}	0.01	0.04	0.2	Not considered	0.5

Source: (Hoagland and Arnon, 1938); (Hewitt, 1996); (Cooper, 1988); (Steiner, 1984); (Kreij et al., 2003);

have proposed various formulations over time, each designed to meet specific requirements and conditions. Table 3 offers a comprehensive comparison of these, detailing the forms of nutrients absorbed by plants and the compositions as recommended by distinguished scientists such as Hoagland and Arnon (1938), Hewitt (1996), Cooper (1988), Steiner (1984), and Kreij et al. (2003). The particular formulation employed in this study is a 40% solution of Kreij et al. (2003) found in the last column. Utilizing this NS formulation consistently ensured a uniform nutrient environment, thus contributing to the reliability of the results.

To facilitate the computation of plant uptake, a daily sample of 20 mL was extracted from the NS and underwent laboratory analysis to determine the remaining concentrations. If the concentration of nitrate in a set dropped below 5 $\frac{mg}{L}$, the NS was fully replenished. This specific procedure was undertaken on DAT 22, 26, and 29. The NS was consistently maintained by supplementing with deionized water every other day and adjusting the pH to lie between 5 and 7 by the addition of Hydrochloric acid (HCl) or Sodium hydroxide (NaOH).

3.1.3 Management of Root Temperature

This investigation was structured as an experiment featuring three distinct conditions. Each treatment consisted of a different NS temperature during daylight hours and involved 6 plants, 3 of each cultivar. The NS temperature was set on 17°C, 21°C and 27°C. Ambient temperature has been uniform for all three treatments with a mean of 21.09°C during the 30 day experimental period.

To emulate greenhouse conditions in different environments, the heating/cooling units were activated synchronously with the lighting from 8:00 to 22:00 each day. The root zone temperature as well as ambient air temperature and Humidity was chronically logged every 5 minutes utilizing TinyTag Data Loggers (TinyTag Plus 2 TGP-4500, Gemini Data Loggers UK Ltd., Chichester, United Kingdom). The temperature time-series data of each treatment during the 30-day trial is detailed in Figure 2. Other Parameters of the NS such as Oxygen concentration, pH and EC can be seen in Table 4.

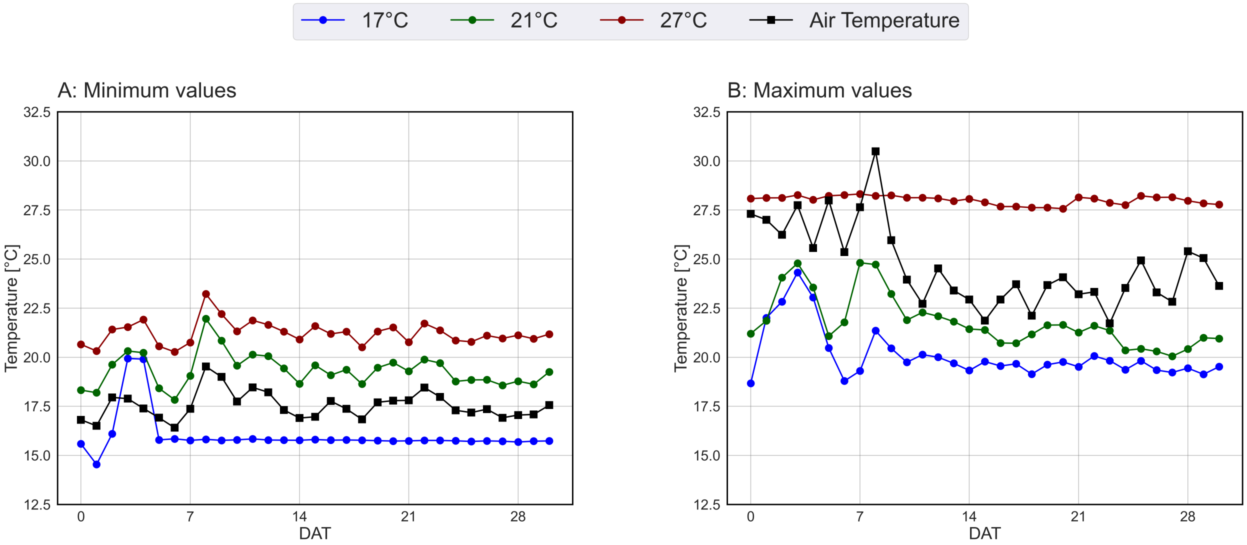


Figure 2: Time series of Root zone temperatures (RZT) and air temperature, starting from November 7, 2022 (= DAT 0). A shows the minimum, B the maximum value for each day.

Table 4: Minimum, mean, and maximum values for Oxygen concentration (mg/L), Temperature (°C), pH, and EC (μS/cm) for different treatments over the duration of the experiment.

Category	Treatment	Minimum	Mean	Maximum
Temperature	17°C	14.54	16.67	24.33
	21°C	17.80	20.65	24.78
	27°C	20.31	26.94	28.3
	Air	16.41	21.09	30.49
Oxygen conc.	17°C	3.77	4.82	5.61
	21°C	1.51	3.89	5.42
	27°C	0.91	3.29	4.93
pH	17°C	4.96	6.15	7.01
	21°C	5.2	6.12	7.03
	27°C	5.3	6.28	6.95
EC	17°C	169.0	390.47	520.0
	21°C	104.0	376.53	550.0
	27°C	149.0	379.25	508.0

3.2 Measurement Procedures

3.2.1 Parameter Assessment Throughout the Experiment

Measurement of pH and Electrical Conductivity (EC)

Daily monitoring of pH and EC levels in the nutrient solution was conducted using a ProfiLine pH/Cond 3320 probe (Xylem Analytics, Weilheim, Germany). (Figure 3).

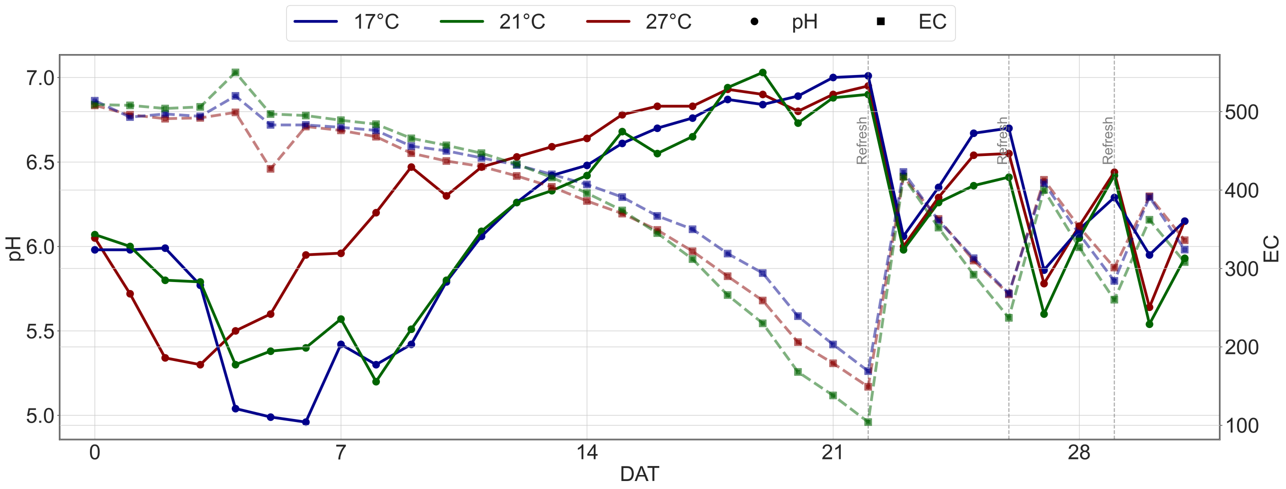


Figure 3: Time-series analysis of pH and Electrical Conductivity (EC) levels throughout the experimental period.

Nutrient Analysis and Monitoring

From DAT 0 up to DAT 30, the tomato plants' phenological status was inspected daily, with any extraneous shoots being removed. Laboratory testing of the NS samples (Department of Management of Crop Water Stress in the Tropics and Subtropics (490g), Garbenstr. 13, Building 03.33, 70599 Stuttgart-Hohenheim) was conducted using a flowsys Autoanalyser (Alliance Instruments, Salzburg, Austria), enabling the quantification of ammonium, nitrate and phosphate concentrations. Special attention was paid to nutrient concentrations to determine NS replacement dates (nitrate concentration threshold: 5 $\frac{mg}{L}$) and shed light on the dynamics of plant nutrient absorption.

To determine the correct nutrient uptake for calculating the physiological efficiency, the plants' nutrient uptake was segmented into four distinct intervals, representing the periods DAT 0 to 22, 22 to 26, 26 to 29, and 29 to 30, corresponding to the three times the NS was replenished when the nitrate threshold was reached. Within each segment, let $S_{i,j}$ denote the initial nutrient concentration of the unused solution, and $S_f(t)$ the nutrient concentration at time t. The formula to calculate the total nutrient uptake over the experiment is thus expressed as:

$$\text{Total Nutrient Uptake} = \sum_{j=1}^{4} \sum_{t=t_{start,j}}^{t_{end,j}} (S_{i,j} - S_f(t)) \tag{3.1}$$

Here, the outer sum ranges over the four intervals defined by replenishment days, and the inner sum calculates the nutrient uptake within each interval. The variables $t_{start,j}$ and $t_{end,j}$ are the starting and end in days of interval j, respectively. The equation will be used in the results section.

3.2.2 Parameter Assessment after the Experiment

At DAT 30, the plants were harvested and their organs separated for further analysis. The samples were dried at 70°C for 48 hours. Plant parameters including plant height, the number of flowers and leaves, the mass of roots, stems, petioles, rachis, leaf blades, full leaves and flowers, as well as the Leaf Area (LA) of every single plant was measured. To characterize the biomass distribution within the leaves, we systematically selected the 4th and 11th leaves, counting acropetally from the base of the plant. These leaves were then dissected into their constituent parts: rachis, petiole, and leaf blade. LA measurements were done using the LI-COR 3100 Area Meter (LI-COR, Inc., Lincoln, USA). To determine the mass, each organ was weighed separately on a digital scale. The masses were added up to gain insights on the total biomass per treatment and cultivar.

The physiological efficiency (PE) was assessed to understand how effectively the plants utilized the nutrients absorbed during the growth period. The equation for calculating PE is as follows and has been altered from Baligar (2008):

$$PE = \frac{DM}{S} \tag{3.2}$$

In the presented equation, DM denotes the total dry mass of the plant, measured in grams. This value was ascertained following the drying of the individual plant organs at $70°C$ for a duration of 48 hours. Subsequently, an average was computed for each distinct Cultivar-Treatment pair. The nutrient uptake, S, expressed in grams, was derived utilizing the formula for total nutrient uptake as outlined in the preceding section. The calculation of PE was performed considering all analyzed nutrients, and was again applied to establish a correlation between total nutrient uptake and biomass. This equation will be integral to the analysis in the results section.

3.2.3 Computational Tools Employed

For the computational aspects of this research, Python (Version 3.10.4) was employed as the main programming language for data analysis. The Pandas library (Version 2.0.3) was used for its advanced data manipulation and cleaning capabilities. Data visualization tasks were conducted using the Matplotlib library (Version 3.7.2). Microsoft Excel (Version 2309) served for preliminary data sorting and recording. The document was composed and formatted using TeXworks (Version 0.8.6) to adhere to academic writing standards. Furthermore, ChatGPT-4 (Version gpt-4-0613) was utilized to optimize sentence structures and refine the overall textual content of the study. Statistical analyses were conducted using ANOVA to determine the significance of the results, followed by a post-hoc 5% t-test to evaluate pairwise differences among treatment means.

4 Results

This study examined two tomato cultivars—Saluoso and Sweeterno—subjected to three distinct NS temperature treatments: 17° C, 21° C, and 28° C. Harvested at 30 days after transplanting (DAT 30), key metrics such as nutrient uptake, biomass production, and nutrient uptake efficiency (PE) were quantitatively assessed. Statistical analysis was performed to compute mean values, standard error and statistical difference for metrics across different cultivars and temperature conditions.

4.1 Nutrient uptake

The nutrient uptake efficiency was assessed by calculating the total uptake of nitrate, ammonium, and phosphate of each treatment as explained in section 3.2.1. Plants under the 27° C treatment had the highest uptake of nitrate (37.74 g), while those under the 17° C treatment had the highest uptake of ammonium (2.61 g). The 27° C treatment had the lowest uptake of ammonium and nitrate but the highest uptake of phosphate (6.43 g). Overall, the plants in the 27° C treatment took up most nutrients.

Table 5: Total Nutrient Uptake (values in g) by Treatment for both cultivars over the duration of the experiment using the equation 3.1

Treatment	Ammonium	Nitrate	Phosphate	Total
17°C	2.61	28.85	4.73	36.19
21°C	1.97	35.22	5.20	42.39
27°C	1.38	37.74	6.43	45.55

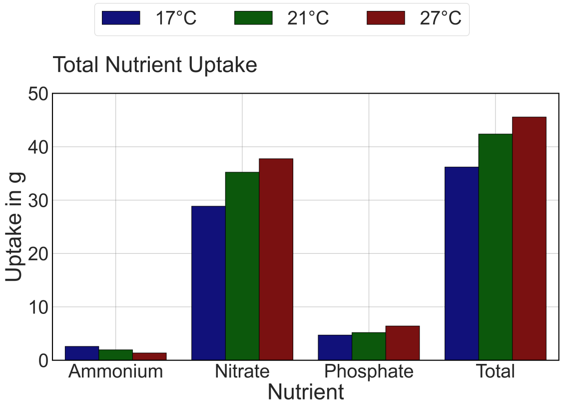


Figure 4: Comparison of Total Nutrient Uptake

4.2 Biomass production

After drying the isolated Plant organs, they were weighed to determine Biomass production. Cultivar Sweeterno generally had higher mean values than cultivar Saluoso across all treatments. Findings regarding

4.2.1 Biomass Production Across Cultivars and Treatments

Upon analyzing the biomass data, a notable variation in root weight across different temperature treatments was observed for the Saluoso cultivar, peaking at 21° C. Conversely, the Sweeterno cultivar exhibited relative stability in root weight across all temperature regimes. Saluoso showed the highest Stem weight at 21° C while Sweeterno consistently manifested higher stem weights across all temperature treatments, peaking at 27° C. Interestingly, leaf weight in Sweeterno displayed a positive correlation with increasing temperatures. In contrast, Saluoso achieved its maximum leaf weight at 21° C, diverging from the trend observed in Sweeterno. Flower weights remained relatively constant for both cultivars across varying temperatures, with minor reductions at 21° C with Sweeterno while Saluoso reached its peak Flower weight. The Sweeterno cultivar outperformed Saluoso in total biomass consistently across all temperature treatments, corroborating its generally higher mean values for individual plant organs. The highest biomass accumulation was recorded at 27° C for Saluoso (31.06 g) and 21° C for Sweeterno (26.86 g).

Table 6: Mean dry mass leaf values with standard error and statistical differences from a 5% significance level t-test (values in g) for both cultivars and all treatments.

Cultivar	**Treatment**	**Root**	**Stem**	**Leaf**	**Flower**	**Total**
SA	17°C	$5.37 \pm 0.96a$	$5.34 \pm 0.95b$	$10.42 \pm 1.08c$	$0.11 \pm 0.02d$	$21.24 \pm 7.49e$
	21°C	$7.02 \pm 0.70\textbf{x}$	$6.04 \pm 0.63b$	$13.65 \pm 2.66c$	$0.15 \pm 0.02d$	$26.86 \pm 3.90e$
	27°C	$2.84 \pm 0.37a$	$4.20 \pm 0.46b$	$8.25 \pm 0.47c$	$0.10 \pm 0.03d$	$15.39 \pm 2.05e$
SW	17°C	$4.98 \pm 0.40a$	$8.23 \pm 0.50b$	$14.22 \pm 0.33c$	$0.08 \pm 0.01d$	$27.51 \pm 4.01e$
	21°C	$5.36 \pm 0.38a$	$8.57 \pm 1.39b$	$15.32 \pm 0.88c$	$0.07 \pm 0.01d$	$29.32 \pm 5.78e$
	27°C	$4.84 \pm 0.81a$	$8.77 \pm 1.10b$	$17.36 \pm 0.88c$	$0.09 \pm 0.02d$	$31.06 \pm 8.69e$

4.2.2 Non-Weight Attributes

Sweeterno plants were consistently taller than Saluoso across all temperature treatments, with both cultivars achieving their maximum height at 27° C. The leaf area of Saluoso displayed a decreasing trend with an increase in temperature, unlike Sweeterno, which maintained a comparatively stable leaf area across all treatments. Both cultivars exhibited their highest leaf count at 21° C and demonstrated relatively uniform flower counts across all temperature treatments, with Saluoso slightly surpassing Sweeterno. However, no statistically significant difference could be observed.

Table 7: Mean non-mass attributes with standard error and statistical differences from a 5% significance level t-test (values in cm, cm^2, or count) for both cultivars and all treatments

Cultivar	Treatment	Height (cm)	Leaf Area (cm^2)	Leaf amount	Flower amount
SA	17°C	$74.00 \pm 3.61a$	$487.93 \pm 103.66b$	$16.66 \pm 0.88c$	$3.00 \pm 0.58d$
	21°C	$70.67 \pm 5.49a$	$472.26 \pm 51.90b$	$19.33 \pm 0.33c$	$3.33 \pm 0.33d$
	27°C	$77.00 \pm 4.04a$	$342.63 \pm 46.98b$	$17.00 \pm 0.58c$	$2.67 \pm 0.33d$
SW	17°C	$84.33 \pm 3.18a$	$464.99 \pm 57.03b$	$16.33 \pm 0.33c$	$2.67 \pm 0.33d$
	21°C	$82.33 \pm 9.21a$	$465.98 \pm 57.08b$	$16.67 \pm 0.88c$	$3.00 \pm 0.00d$
	27°C	$85.50 \pm 6.60a$	$438.30 \pm 55.94b$	$15.33 \pm 0.88c$	$2.67 \pm 0.33d$

4.2.3 Detailed Leaf Biomass Fractionation

In both cultivars, the maximum petiole mass was observed at a thermal regimen of 21° C. Concurrently, the rachis mass in Saluoso also demonstrated a peak at this temperature. In contrast, Sweeterno manifested its maximal rachis and leaf blade mass at 27° C. Saluoso exhibited a pronounced decline in both leaf blade and rachis mass at 27° C, with its weight metrics approximately halving compared to those of Sweeterno

Table 8: Mean dry mass values with standard error and statistical differences from a 5% significance level t-test (values in g) for both cultivars and all treatments.

Cultivar	Treatment	Rachis	Petiole	Leaf blade
SA	17°C	$3.59 \pm 1.10a$	$1.51 \pm 0.27b$	$0.84 \pm 0.12c$
	21°C	$4.79 \pm 0.40a$	$2.13 \pm 0.04b$	$1.20 \pm 0.10c$
	27°C	$2.67 \pm 0.24a$	$1.52 \pm 0.15b$	$0.61 \pm 0.06c$
SW	17°C	$4.56 \pm 0.57a$	$1.91 \pm 0.12b$	$1.11 \pm 0.09c$
	21°C	$5.16 \pm 0.73a$	$2.28 \pm 0.26b$	$1.07 \pm 0.06c$
	27°C	$5.96 \pm 0.94a$	$1.74 \pm 0.22b$	$1.28 \pm 0.10c$

4.2.4 Cross-Table Observations

The data indicates distinct temperature optima for different attributes between the two cultivars. Saluoso displayed a more variable response to temperature changes, whereas Sweeterno was generally more stable across attributes, especially considering higher temperatures. The impact of the treatments was most evident in the differences in plant dry mass. While Sweeterno maintained similar biomass production across all treatments, Saluoso performed best at 21° C and worst at 27° C. In fact, Sweeterno produced twice the dry mass as Saluoso at 27° C. The differences between the two cultivars were minimized when the NS was maintained at 21° C. Both the 27° C and 17° C treatments demonstrated variance in dry mass, both within and between cultivars.

4.3 Morphological differences

The trial revealed visible differences between the two cultivars, which are substantiated by Figures 5 and 6. On average, Sweeterno exhibited higher growth in stem length compared to Saluoso across all treatments. Furthermore, Sweeterno developed thicker leaves, as indicated by a higher mean leaf weight while Saluoso developed larger leaves as idnicated by a higher Leaf Area. The root system of Sweeterno, illustrated in Figure 6, also demonstrated a greater dry mass accumulation, which could have led to a higher nutrient uptake efficiency, as we will elaborate on later.

Although these morphological changes did not appear to be significantly influenced by the temperature treatments, they were subject to varietal differences. Plants subjected to the 21° C treatment exhibited greater root hair density and a higher proportion of white roots than plants in other temperature treatments. Leaves from plants in the 28° C treatment were noticeably softer to the touch, as confirmed through tactile examination. The morphological disparities between the treatments were subtle and generally not readily discernible to the naked eye. However, the varietal differences were pronounced. In some instances, Saluoso plants were only half the size of their Sweeterno counterparts, particularly under varying temperature conditions, which suggests that Saluoso experiences growth challenges both at low and elevated temperatures.

(a) 17° C, 69cm height

(b) 21° C, 80cm height

(c) 27° C, 72cm height

Figure 5: Cultivar Saluoso pre-harvest

(a) 17° C, 5.63g root dry mass (b) 21° C, 4.76g root dry mass (c) 27° C, 5.86g root dry mass

Figure 6: Roots from Cultivar Sweeterno pre-harvest

4.4 Nutrient Uptake Efficiency

Efficiency in nutrient uptake is calculated in terms of the amount of biomass produced per milligram of nutrient absorbed, which is key in understanding the plant's use of available nutrients. In this study, we use the physiological efficiency as explained in Section 3.2.2. This efficiency is inversely related to the quantity of the nutrient absorbed: the more a nutrient is absorbed, the lower its efficiency, indicating that the plant requires a greater quantity of that nutrient to produce the same amount of biomass. The specific values for Physiological Efficiency are detailed in Table 9, while Figure 7 provides a visual representation of these values.

Table 9: Physiological Efficiency (g Biomass/mg Nutrient) for different treatments and cultivars.

Cultivar	**Treatment**	**Ammonium**	**Nitrate**	**Phosphate**	**Total**
SA	17°C	8.14	0.74	4.50	0.59
	21°C	13.67	0.76	5.17	0.63
	27°C	11.17	0.40	2.39	0.34
SW	17°C	10.54	0.95	5.82	0.76
	21°C	14.91	0.83	5.64	0.69
	27°C	22.55	0.82	4.83	0.68

Ammonium Uptake: For ammonium, Saluoso cultivar showed efficiencies of 8.14, 13.67, and 11.17 $\frac{g}{mg}$ at 17° C, 21° C, and 27° C, respectively. Similarly, Sweeterno cultivar exhibited efficiencies of 10.54, 14.91, and 22.55 $\frac{g}{mg}$ across the same temperatures, indicating a trend of increasing efficiency with rising temperatures, particularly notable in Sweeterno.

Nitrate Uptake: The nitrate uptake efficiency remained relatively low for both cultivars across all temperatures, with the highest efficiency observed in SW at 21° C (0.83 $\frac{g}{mg}$). This suggests a

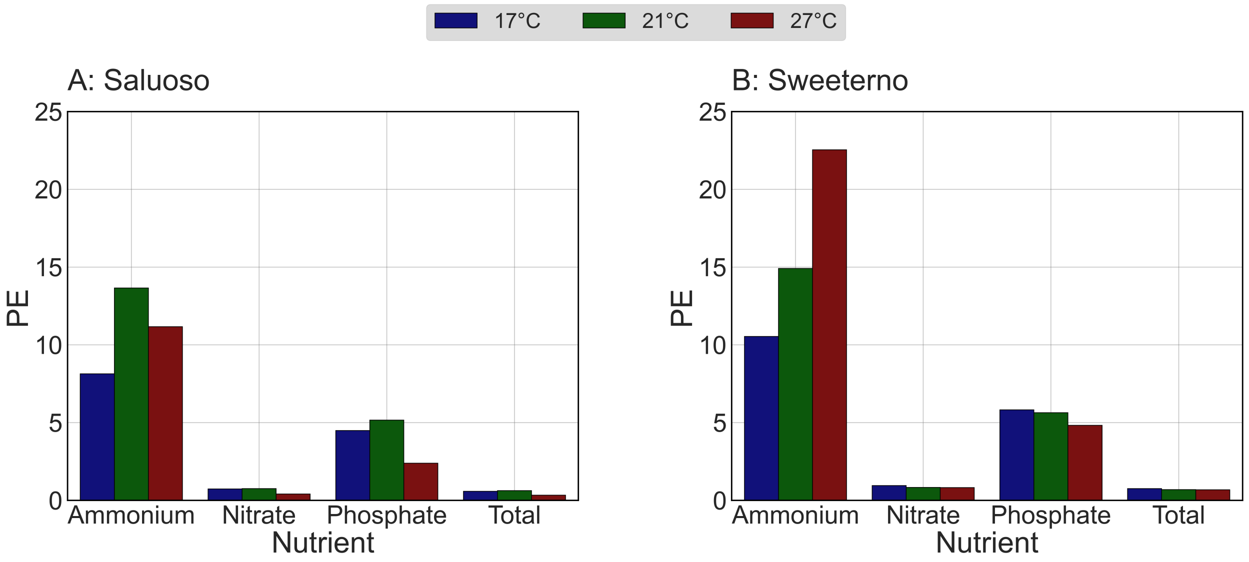


Figure 7: Comparison of Nutrient Uptake Efficiency (g Biomass/mg Nutrient)

consistent and significant reliance on nitrate for growth.

Phosphate Uptake: Phosphate efficiencies were intermediate, with Sweeterno generally showing higher efficiency than Saluoso. The highest phosphate efficiency was observed in Sweeterno at 17° C (5.82 $\frac{g}{mg}$).

Total Nutrient Efficiency: Overall, Sweeterno consistently demonstrated higher total nutrient efficiency across all temperatures, with a peak at 17° C (0.76 $\frac{g}{mg}$). This indicates a more balanced utilization of nutrients in the Sweeterno cultivar compared to Saluoso, particularly under cooler conditions. Notably, the least efficient performance observed in Sweeterno (27° C, 0.68 $\frac{g}{mg}$) still surpasses the lowest efficiency recorded for Saluoso (17° C, 0.63 $\frac{g}{mg}$).

5 Discussion

5.1 Interpreting Nutrient Uptake Rates

The primary objective of this study was to determine the impact of NS temperature on nutrient uptake and biomass production in two tomato cultivars. To deepen our understanding of how NS temperature influences these variables, and subsequently, crop yield, further research is warranted, particularly within the context of the HypoWave+ Project. Our experimental findings revealed that nitrate uptake peaked at 27° C, while optimum uptakes for ammonium and phosphate occurred at 17° C and 27° C, respectively. This complex pattern of nutrient uptake at different temperatures complicates the formulation of clear-cut conclusions.

It is important to consider that elevated temperatures can stimulate nitrification, the process responsible for converting ammonium to nitrate, primarily facilitated by nitrifying bacteria (Marschner, 2012). This heightened microbial activity at higher temperatures may contribute to a nutrient solution with reduced ammonium levels and elevated nitrate concentrations, influencing our observed nutrient uptake pattern.

This study measured changes in the NS's nutrient concentration, not the actual plant mineral content. Given that both cultivars underwent each treatment, nutrient uptake figures are approximations. These allow for comparing the impact of temperature treatments, with cultivar differences noted as estimates.

5.2 Impact on Biomass Production

Concrete evidence exists regarding the temperatures at which these specific cultivars attain maximum biomass; however, given the differential outcomes, it is challenging to generalize the findings to all tomato plants. A noteworthy observation was the root biomass of Saluoso, which peaked at 21°C with a value of 7.02 g—statistically significantly higher compared to the other temperature treatments. The acknowledged optimal root zone temperature of 24°C (Tindall et al., 1990) in soil mediums appears to also be the optimal NS temperature in hydroponic systems, as a marginal trend towards increased biomass accumulation at this temperature was observed. In particular, cultivar

Saluoso exhibited optimal performance at 21°C, while Sweeterno did so at 27°C.

It is noteworthy that the 21°C treatment yielded more consistent results across both treatments and cultivars, in contrast to the 27°C and 17°C treatments which displayed more extreme variations. This suggests that while higher or lower temperatures may foster enhanced outcomes for certain cultivars, the consistency afforded by a 21°C nutrient solution temperature represents a reliable and potentially superior choice for hydroponic cultivation of these tomato varieties.

5.2.1 Impact on Biomass Distribution

5.2.2 Root

The experimental results revealed a noticeable trend in root biomass distribution. Specifically, the root biomass exhibited an enhancement in the 21°C and 17°C treatments compared to the 27°C treatment. This observation can potentially be attributed to variations in oxygen solubility at these temperatures.

As elaborated in Section 2.4, the solubility of oxygen in nutrient solutions is inversely proportional to temperature. Therefore, lower temperatures, such as 17°C and 21°C, could facilitate higher oxygen concentrations in the nutrient solutions. This inference is corroborated by the study of Cherif et al. (1997), which demonstrated that tomato plants cultivated in nutrient solutions with elevated oxygen concentrations tend to accumulate greater root biomass.

5.2.3 Flower and Fruit

Interestingly, despite Sweeterno's higher values in both total biomass and PE, Saluoso demonstrated superior flower biomass, as evidenced by increased mean flower biomass for the cultivar across all treatments. This observation suggests that Saluoso may transition into its reproductive phase more rapidly than Sweeterno. In a related study, Amaliah (2018) explored the effects of cooling the root zone in hydroponic curly chili cultivation, revealing that a cooling treatment (NS at 14°C) resulted in elevated fruit weights. However, in contrast to these findings, Gosselin and Trudel (1986) noted that bell pepper reached its peak fruit weight at 30°C. A lower root zone temperature induced earlier flowering, whereas higher temperatures favored vegetative growth. **?** indicated that the growth and yield of two cocktail tomato cultivars were not significantly affected by root cooling. In contrast, our findings suggest that the dry mass of the plant's vegetative parts is influenced by root cooling and heating.

5.3 Implications for Nutrient Use Efficiency

The physiological efficiency was quantified using an adapted equation derived from the work of Baligar (2008), as denoted in Equation 3.2. The selection of this methodology was based on its conceptual clarity and computational simplicity. Remarkably, the results revealed substantial differences in PE values between the two tomato cultivars across varying NS temperatures. Sweeterno consistently outperformed Saluoso in terms of PE across all temperatures, with a notable peak at 17°C (0.76 $\frac{g}{mg}$). This superior performance, even under less optimal conditions (27°C, 0.68 $\frac{g}{mg}$), compared to Saluoso's lowest efficiency (17°C, 0.63 $\frac{g}{mg}$), underscores the importance of cultivar selection in agricultural practices. It is important to note that the nutrient use efficiency findings between the cultivars, like the nutrient uptake, are estimates and should be interpreted with this consideration in mind.

It's imperative to note that although higher temperatures can generally foster faster growth and nutrient uptake, our results indicate that this is not uniformly beneficial across all cultivars. This differential response to temperature among cultivars underscores the importance of selecting the appropriate plant genotype for specific environmental conditions. It also accentuates the need for a nuanced understanding of how NS temperature affects PE and could induce flowering.

While biomass production and nutrient uptake are often considered an important metric, it is essential to distinguish it from nutrient use efficiency. Our study highlights that the latter may be the more impactful variable, particularly when it comes to sustainable agricultural practices in controlled environments like hydroponic systems.

5.4 Practical Applications

The insights derived from our study have several practical applications for improving nutrient use efficiency in hydroponic systems. Firstly, the observed variations in PE values among different cultivars at specific NS temperatures can guide growers in selecting the most efficient tomato cultivars for their hydroponic setups. Secondly, our findings can assist in optimizing nutrient solution recipes tailored to specific cultivars and temperature regimes, thus minimizing nutrient waste. Lastly, given that PE values were found to be more consistent at 21°C across both cultivars, maintaining the NS at this temperature could provide a reliable and efficient strategy for hydroponic cultivation, thereby contributing to sustainable agricultural practices.

5.5 Future Research Directions and Enhancements

Given the substantial body of literature on the temperature dependence of nutrient transporters and nutrient solubility (Sigma-Aldrich, 2023), extending this study to encompass a broader spectrum of temperatures, including more extreme conditions, is recommended. As **?** demonstrated, maintaining lower root temperatures (around 10°C) can increase sugar and vitamin C levels in tomato fruits. However, this response can vary depending on the cultivar, similar to the temperature-related effects observed in our research. Exploring more extreme temperature differences could provide additional insights into the subject.

Furthermore, investigating the presence and interactions of bacteria, such as Nitrosomonas and Nitrobacter, within the NS could provide additional insights. This expanded approach is likely to align more closely with established theories and enhance our understanding of the influence of NS temperature on nutrient uptake and biomass production in hydroponically grown tomatoes especially in the context of the HypoWave+ Project. The project will utilize water from sewage treatment plants, which is expected to contain a higher concentration of bacteria compared to the deionized water used in our studies (Ruiz et al., 2002) (Orsel et al., 2006) (Institute for Social-Ecological Research (ISOE) GmbH, 2022).

Another key area for future research is the impact of temperature on yield, particularly fruit weight. While our study did not extend to evaluating fruit weight, future studies could explore how root heating might impact fruit yield. Understanding this relationship is crucial for optimizing hydroponic agriculture, as optimal biomass production does not always equate to maximum yield. Future studies should focus on the yield responses of different tomato cultivars to varying temperatures, to develop more efficient and sustainable hydroponic farming practices.

6 Conclusion

This study delved into the impacts of NS temperature on hydroponically grown tomato cultivars Sweeterno and Saluoso, uncovering critical insights. A key discovery was the identification of 21°C as the optimal NS temperature for both cultivars, which effectively balances nutrient uptake and biomass production. This finding challenges existing guidelines and presents new possibilities for hydroponic cultivation,. especially considering cultivar-dependency of nutrient use efficiency.

In terms of cultivar performance, Sweeterno emerged as particularly efficient in biomass production and nutrient use, suggesting its suitability for hydroponic farming. Interestingly, the study did not reveal significant differences in biomass accumulation across different temperature treatments. This observation implies that soil cultivation recommendations regarding root zone temperature might be applicable to hydroponic systems, offering a fresh perspective for agricultural practices.

Despite its comprehensive nature, the study had limitations, including a focus on vegetative growth and a limited sample size as well as overlookin gthe important aspect of bacterial interactiosn within the NS. Future research should broaden the scope to encompass various temperatures, cultivars, bacteria and fruit production, to fully optimize hydroponic systems.

Overall, this research contributes significantly to the field of hydroponic agriculture. It not only provides new insights into the optimal NS temperature for growing tomatoes but also underscores the importance of cultivar selection, with Sweeterno demonstrating particular efficiency. These findings are instrumental in enriching the HpoWave+ project, advancing sustainable agricultural practices in hydroponic systems and aligning with broader goals of global food security.

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