RESPONSE OF TOMATO (*Solanum lycopersicum L.*) VARIETIES TO ELECTRICAL CONDUCTIVITY MODULATION IN A RECIRCULATING HYDROPONIC SYSTEM

BY

BUKARI MUSAH

(11007550)

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DECLARATION

I hereby declare that this thesis is the record of my original research and has not been presented elsewhere either in part or in whole for another degree. Works of other researchers have been cited and referenced. Also, all assistance received has been duly acknowledged.

Bukari Musah (Student) 10/06/2025

10/06/2025

Prof. George Oduro Nkansah (Principal Supervisor)

10/06/2025

Dr. Alex Willams Ayarna (Co-supervisor)

DEDICATION

This thesis is dedicated to all members of the Yidana family, especially my wife and my parents who supported me in diverse ways throughout my study. May God bless them.

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ABSTRACT

Tomato production in tropical countries, including Ghana, has remained low, threatening sustainable food security and nutrition. The demand for the produce far exceeds its supply, and this imbalance is expected to worsen as the population grows, and the impacts of climate change intensify. Tomato yields in Ghana have remained low despite the adoption of greenhouse systems, unlike in some developed countries. To bridge this production gap and improve sustainable productivity, efficient and adaptable technologies are required. One promising approach is the use of a low-substrate-volume hydroponic system with high-density planting, coupled with low-node order pinching. There is limited information on how nutrient solution electrical conductivity (EC) modulation affects tomato performance in this system. This study aimed to evaluate the effect of nutrient solution EC modulation on the physio-morphological, yield, fruit quality and water use efficiency responses of tomatoes. The study was conducted in the greenhouse at the University of Ghana's Forest and Horticultural Crops Research Centre (FOHCREC), Kade. Four EC modulation treatments were tested: high, low, high-low, and low-high. Plants in the high-low and low-high treatments received high or low EC during the vegetative stage and then switched to the reverse EC level during the reproductive stage. Two tomato varieties, Anna and Jaguar, were evaluated across these treatments. Two experiments, which followed a 2 x 4 factorial in a randomized complete block design, with three replications were conducted. The results showed that EC modulation significantly affected plant height, leaf number, and stem diameter, with variety Anna displaying greater height (30.3% to 38.1% higher) under high EC. High EC also promoted greater stem girth. Both varieties showed changes in photosynthetic efficiency and chlorophyll content, with Anna having higher chlorophyll levels at high EC, while Jaguar maintained stable chlorophyll content across EC modulations. Water use efficiency (WUE) was higher in high or high-low EC treatments, with Jaguar exhibiting superior WUE compared to Anna. Yield and fruit quality were also influenced by EC modulation. Anna had consistent fruit numbers across EC treatments, while Jaguar's fruit number decreased under high EC. However, Jaguar produced 36.7% to 45.3% higher yields than Anna. Anna had higher lycopene, vitamin C, and total soluble solids under high EC, while Jaguar exhibited less variation. Both varieties showed an increase in fruit pH with high EC. The study suggests that Anna is more stable under variable EC conditions and offers better nutritional content under high-low EC modulation, while Jaguar was better in water-use efficiency and yield, particularly under high or high-low EC. Achieving high yield, fruit quality, and resource efficiency depends on both nutrient solution EC levels and variety selection.

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CHAPTER ONE
INTRODUCTION

1.1 Background

Tomato (*Solanum lycopersicum L*) is a flowering plant in the Solanaceae family also known as the nightshades. Due to the fruit's superior taste, colour, flavour, and nutritional value, it is one of the most widely planted vegetable crops worldwide. It is a major part of the Ghanaian diet, providing essential nutrients such as vitamin C and antioxidants that help reduce the risk of chronic diseases (FAO, 2019).

According to the 2021 Population and Housing Census conducted by the Ghana Statistical Service, Ghana's population was 31 million, reflecting an increase in population (statsghana.gov.gh 2023). By 2050, the population is projected to reach 52.2 million, with 70% living in cities. Due to the increasing population, efforts to achieve the sustainable development goals (SDGs) for food security are crucial.

Currently, the output of tomato production in Ghana falls short of meeting the prevailing demand, and this is expected to worsen with population growth. Domestic tomato production rose from 318,000 tonnes in 2009 to over 420,000 tonnes in 2019 (FAOSTAT 2021, IFPRI 2020, Asselt *et al.* 2018), with average yields increasing from 8.1 to 8.6 tonnes per hectare (Melomey *et al*. 2019).

Despite this growth, domestic output has still fallen short of demand, resulting in the annual import of 100,000 tonnes of fresh tomatoes to meet market needs (Asselt *et al*. 2018). Fresh tomato imports account for about 30% of household consumption (Robinson *et al* 2010). Over 92,000 tonnes of tomato paste (UN, ITSD 2019) and significant amounts of other processed tomato products are imported from the USA, Spain, Italy, Portugal, and China in addition to fresh tomatoes (Boamah *et al* 2019). The International Food Policy Research Institute (IFPRI) estimates that Ghana would need an additional 736,000 tonnes of fresh tomatoes to reduce imports and meet both domestic and industrial demand.

The low tomato output in Ghana is primarily due to significant challenges, including high post-harvest losses and pressures from biotic factors (such as pests and diseases) and abiotic factors (including heat stress and low soil fertility) exacerbated by climate change. Furthermore, one of the main factors contributing to low productivity is the lack of high-yielding tomato varieties with superior fruit quality (Robinson *et al* 2010). Low productivity is strongly due to a poor traditional cultivation system among others. In Ghana, the traditional cultivation system is soil-based, which is highly laborious with a low output and inefficient resource use.

To ensure the sustainable productivity of tomatoes, an efficient and adaptable technology (cultivation system) is needed. The low node pinching order at a high-density planting system has been recommended as an efficient technology for increasing tomato productivity (Ayarna *et al.* 2020 and Takahashi *et al*. 2012). This technology is ultimately gaining popularity in Japan, employing recirculating hydroponic techniques, with a high level of resource use efficiency, and the ability to automate (Takahashi *et al.* 2012). Moreover, the period of cultivation spans 70 -120 days of which, the farmer can cultivate tomatoes at least three times per year.

The concentration of nutrients in the nutrient solution plays a pivotal role in shaping the growth, yield, and quality of crops, as highlighted in studies by Komosa *et al*. (2014) and Patil *et al*. (2020). This is particularly crucial in the context of hydroponic systems, which offers a promising solution for regions characterized by tropical climates, where issues related to soil quality challenges, and water availability frequently hinder conventional crop production, as noted by Hossain *et al*. (2016).

For achieving the best possible outcomes in terms of tomato growth, yield, and fruit quality, it is imperative to fine-tune the strength of the nutrient solution. Interestingly, research by Zhang *et al*. (2016) indicates that an increase in electrical conductivity (EC) within the nutrient solution can affect tomato growth, yield, and water uptake. Yang *et al*. (2017) suggest that a higher EC can lead to an increase in the photosynthetic rate of tomatoes.

Moreover, a higher EC has been associated with enhanced sugar and lycopene levels in tomatoes, as observed by Fanasca (2007). Various studies have conflicting findings on how the electrical conductivity of nutrient solutions affects tomato performance.

Krumbein *et al*. (2012) discovered that high electrical conductivity does not influence the lycopene content in tomatoes. Management of electrical conductivity in hydroponics and their influence on crop productivity necessitates a thorough understanding of the relationship between nutrient levels and crop reactions under different growing conditions.

1.2 Problem Statement

The demand for tomatoes in Ghana far exceeds the current production capacity, and this issue is projected to worsen due to the increase in population and the impacts of climate change (FAOSTAT 2021). Tomato production faces numerous challenges, with poor cultivation practices and insufficient nutrient management standing as key barriers to achieving optimal yields.

1.3 Research Justification

To address these challenges, adopting innovative and efficient technologies is crucial. A promising method is the hydroponic cultivation of tomatoes with low substrate volume and low-node order pinching at high-density planting. This approach has been proven to significantly enhance both yield and fruit quality (Takahashi *et al*. 2012; Ayarna *et al.* 2020).

However, there is a knowledge gap in the effective management of electrical conductivity (EC) for such tomato cultivation methods, especially in tropical regions like Ghana.

Balancing high fruit yield with exceptional fruit quality under EC management is crucial for bolstering food security and nutrition. This study focuses on evaluating the effect of nutrient solution EC modulation on the physio-morphological, yield, fruit quality and water use efficiency responses of tomatoes, bridging the knowledge gap in EC management for tropical regions like Ghana.

1.4 Objectives

1.4.1 General Objective

The general objective of this study was to evaluate the effect of nutrient solution EC modulation on the physio-morphological, yield, fruit quality and water use efficiency responses of tomatoes

1.4.2 Specific Objectives

The specific objectives were to:

1. Evaluate the growth of two tomato varieties as influenced by EC modulation.
2. Determine the physiological response of two tomato varieties to EC modulation.
3. Assess the yield of two tomatoes as influenced by EC modulation
4. Determine the water-use efficiency of two tomato varieties.
5. Evaluate fruit quality, including nutrients (Vitamin C), antioxidants, (lycopene), and sugar content of two tomato varieties

1.5 Significance of the Study

This study aims to contribute to the development of sustainable and efficient hydroponic cultivation system for tomato production in Ghana, ultimately enhancing food security and nutrition.

CHAPTER TWO

LITERATURE REVIEW

2.0 General Description of tomato

The tomato (*Solanum lycopersicum*) is a widely cultivated crop, typically grown annually in tropical and temperate climates. It is often cultivated in open fields or greenhouses, which is common for large-scale production (Nuez, 2001).

The growth habit of tomato plants varies from indeterminate to determinate, with heights reaching up to 3 meters. The plant has a primary root that can grow several meters in length, and its stem is angular and covered with hairy and glandular trichomes, giving it a characteristic smell. The leaves are alternately arranged on the stem, with lobed to compound shapes, typically comprised of five to nine leaflets (Britannica, 2024). The plant produces yellow, clustered pendant flowers, with fruits varying in diameter from 1.5 to 7.5 cm or more, and colours ranging from red and scarlet to yellow, with green and purple varieties also existing (Nuez, 2001).

Tomato plants are mainly self-compatible and inbreeding, with flowers exhibiting mechanisms for self-pollination. However, cross-pollination between varieties and even species is possible, especially through insect activity. Pollen viability and dispersal are affected by temperature, with high temperatures reducing pollen viability. The natural cross-pollination rates among commercial varieties range from 0.07% to 12%, with the rate decreasing as the distance from the pollen source increases (Richardson and Alvarez, 1957; Groenewegen *et al*., 1994; Accotto *et al*., 2005).

2.1 Taxonomy of Tomato

Tomatoes have been known by various names over the years, reflecting their cultural and historical significance. Before the advent of scientific nomenclature, tomatoes were commonly referred to as "pommed’or" or "pommed’amour" (Peralta *et al*., 2006). These names highlight the tomato's initial reception in Europe, where it was often associated with love and luxury. Miller proposed the name *Lycopersicum esculentum* (Taylor 1986). Miller's classification was based on morphological differences he observed, leading him to place tomatoes in a separate genus from the other poisonous nightshade species. This name, *Lycopersicum esculentum*, was widely accepted and used for many decades (Peralta *et al*., 2006).

Despite the longstanding use of Miller's classification, further advancements in genetic research led to a re-evaluation of the tomato's taxonomy. Modern genetic studies provided new insights into the relationships between different plant species, prompting taxonomists to reconsider tomato's classification. Based on these genetic analyses, tomatoes were reclassified under the genus *Solanum*, which is the same genus as the nightshade species (Blancard *et al*., 2009).

Today, while both names—*Lycopersicum esculentum* and *Solanum lycopersicum* can be found in various documents, *Solanum lycopersicum* is the most widely accepted and dominant name for the tomato plant. This reclassification aligns tomatoes more closely with other members of the *Solanaceae* family, reflecting their genetic and evolutionary relationships (Blancard *et al.*, 2009).

2.2 Importance of Tomatoes

Tomatoes (Solanum *Lycopersicon*) are one of the most widely consumed vegetables globally, renowned for their nutritional benefits and culinary versatility.

2.2.1 Biochemical Composition

Tomatoes are made up of about 95% water, yet they are packed with a wide array of nutrients, which can vary depending on the variety, growing conditions, and form of the product (fresh fruit, dried, paste, soups, or ketchup) according to Bedad *et al*., 2018. They are an excellent source of carbohydrates, proteins, fatty acids, minerals, vitamins, amino acids, and phenolic compounds (Pinela *et al*., 2012; Goka *et al*., 2021). Notably, tomatoes contain no cholesterol and only small amounts of lipids (0.3%) and proteins (1.1%) as indicated by Alhagdow *et al*., 2007). They are rich in a variety of vitamins, including A, C, K, B1 (thiamine), B2 (riboflavin), B3 (niacin), B5 (pantothenic acid), B6, and B9 (folate) (Chanforan, 2010).

Minerals in tomatoes, which make up 8% of their dry matter, include major elements such as magnesium, phosphorus, calcium, potassium, sodium, sulfur, and chlorine, and minor elements like iron, iodine, zinc, fluorine, cobalt, and manganese (Ali *et al*., 2021). Carbohydrates, primarily fructose (25%) and glucose (22%), constitute over 50% of the sugar content in dry matter (Ali *et al*., 2021). Organic acids, which contribute to the fruit's acidity, include citric acid (60%) and malic acid (4%) (Petit, 2013; Ali *et al*., 2021). Amino acids, representing 2 to 2.5% of the dry matter, significantly influence the fruit's flavour (Kader *et al*., 1978).

Additionally, tomatoes are rich in antioxidants such as lycopene, β-carotene, ascorbic acid, phenolic acids, anthocyanins, and flavonoids, which play crucial nutritional roles (Borguini and Ferraz 2009; Petit, 2013, and Ali *et al*., 2021).

2.2.2 Culinary Use and Nutritional Value

Tomatoes are a staple ingredient in many diets, consumed fresh in salads or cooked in sauces, soups, meat, or fish dishes (Outtara *et al*., 2024). They are also processed into pastes and ketchup, widely used to flavour food (Outtara *et al*., 2024). Preservation methods such as drying or canning ensure year-round availability.

Nutritionally, tomatoes provide significant health benefits. Consuming 100 grams of tomatoes offers up to 20 calories, about 1% of daily energy needs (Ali *et al*., 2021). They are known to reduce the risk of cardiovascular disease, cancer, and diabetes, primarily due to their antioxidant content and micronutrients (Lairon *et al*., 2005; Cheng *et al*., 2017., Ali *et al*., 2021). The fibres in tomatoes aid digestion and facilitate intestinal transit, while vitamins promote cell growth and overall health (Ali *et al*., 2021).

Tomatoes are particularly noted for their high vitamin content, which plays therapeutic roles in preventing deficiencies and diseases such as cancer, due to the antioxidant properties of vitamins C and E (Ali *et al*., 2021; Usman *et al*., 2023; Liu *et al*., 2023). The mineral content contributes to various bodily functions, including maintaining acid-base balance, nerve transmission, and blood pressure regulation (Ali *et al*., 2021).

Lycopene, a carotenoid in tomatoes, is beneficial against diabetes and cancers (Cheng *et al*., 2017). Studies show that dietary lycopene helps manage diabetes by improving insulin levels, reducing glucose levels, and enhancing lipid profiles (Liu *et al*., 2023; Rasal *et al*., 2023; Uchenna *et al*., 2023). It also improves kidney function and antioxidant activities (Usman *et al*., 2023; Liu *et al*., 2023).

2.2.3 Socio-Economic Importance

Tomato cultivation is economically significant, involving about 30% of vegetable farmers in Burkina Faso. It is highly profitable, generating significant income for producers and reducing seasonal unemployment in rural areas (MAHRH, 2007; Tapsoba *et al*., 2016; Goka *et al*., 2021). Despite susceptibility to pests and diseases, tomato farming provides additional income that improves living standards and contributes to resilience against poverty and food insecurity (Ba *et al*., 2019).

In Burkina Faso, tomato farming employs approximately 620,000 people, with 35% being women (Dione *et al*., 2021). The sector creates numerous jobs in transportation, processing, and commercialization, where women predominate (Dione *et al*., 2021). In 2018, tomato exports generated around 50 billion CFA francs, with Ghana being the largest importer (MAAH, 2019).

2.3. Production Trends and Challenges of Tomato

2.3.1 Global Tomato Production

Tomatoes are a vital agricultural commodity, grown in more than 170 countries around the world. In 2021, they ranked as the most-produced vegetable crop globally, with an estimated production of over 189 million tons. This figure surpasses the production of other major crops, such as onions (106 million tons), watermelons (101 million tons), and cabbages (71 million tons) (FAO, 2023). Between 1970 and 2021, global tomato production grew by nearly 500%, with much of the increase driven by a rise in production across Asia, which now accounts for

63% of the world's total. In comparison, the Americas and Europe each contributed around 13% of global production (FAO, 2023). Europe, (particularly countries like the Netherlands, Belgium, and Sweden), is noted for its high tomato yields.

2.3.2 Tomato Production in Africa

Africa ranks fourth in global tomato production, contributing 11% of the total output (FAO, 2023). The continent's production has grown significantly, from 3 million tons in 1970 to 21 million tons in 2021. However, despite this progress, tomato production in Africa remains relatively low compared to its potential and the needs of its population.

In 2021, Egypt became Africa's largest tomato producer, with an output of approximately 6 million tons, ranking eighth globally (FAO, 2023). Nigeria is the second-largest producer on the continent and the top producer in West Africa. Other notable tomato producers in West Africa include Ghana, Niger, and Burkina Faso (FAO, 2023). These countries have increasingly recognized tomatoes as a key strategic crop for reducing imports and promoting the growth of local processing industries.

2.3.3 Tomato production in Ghana

Ghana's tomato production has seen fluctuations in recent years. According to FAOSTAT (2023), the country produced 373,166.39 tons of tomatoes in 2018, with a slight increase to 383,220.13 tons in 2019, indicating a growth trend. However, production dipped to 379,798.89 tons in 2020 before recovering to 383,720.72 tons in 2021. By 2022, production experienced a minor decline again, reaching 382,246.58 tons (FAOSTAT 2024).

This pattern reflects a generally stable production trend, with only minor fluctuations. Ghana's status as one of West Africa's leading tomato producers highlights the crop's significance to the country's agricultural sector. Both the government and the private sector have increasingly invested in tomato production and processing infrastructure, recognising its potential to strengthen local economies and reduce dependence on imports.

2.3.4 Challenges facing tomato production in Ghana

Although tomato production in Ghana is on the rise, the sector continues to face several challenges. Tomato farmers in Ghana frequently struggle to access credit and essential inputs such as seeds, fertilizers, and pesticides, limiting their capacity to invest in farm improvements. Research by Osei *et al*. (2020) found that just 20% of tomato farmers in Ghana have access to credit, with an even smaller proportion able to obtain high-quality inputs.

The tomato production sector in Ghana faces substantial post-harvest losses, primarily due to inadequate storage and transportation infrastructure. Agyekum *et al*. (2017) found that these losses can account for 30-40% of total production, largely due to poor handling practices, inadequate storage facilities, and long transportation distances.

Pests and diseases, including the tomato leaf miner and bacterial wilt, represent major threats to tomato production in Ghana, resulting in reduced yields and compromised fruit quality. Gordon *et al*. (2015) highlighted the tomato leaf miner as a key pest, responsible for yield losses of up to 50%.

Climate change is shifting the growing conditions for tomatoes in Ghana, with rising temperatures and changing rainfall patterns affecting the growing season and leading to lower yields. Koranteng *et al*. (2018) predicted that climate change could result in a 20% decline in tomato yields by 2050.

Tomato farmers in Ghana face difficulties in accessing markets and are frequently impacted by price volatility, which undermines their ability to earn stable incomes. Asuming-Brempong *et al*. (2020) found that many farmers sell their tomatoes at low prices due to limited market access and price fluctuations, making it hard to invest in farm improvements and boost productivity.

2.4 Strategies for Enhancing Tomato Production

To tackle the numerous challenges in tomato production in Ghana, including pest and disease pressures, declining soil fertility, water management issues, and the effects of climate variability, various solutions have been introduced to boost productivity. These include the use of improved varieties, the adoption of advanced farming technologies, and the implementation of innovative agricultural practices. The development and adoption of disease-resistant tomato varieties have been a crucial strategy. Varieties such as 'Tima' and 'Rising Sun,' for instance, have been specifically bred for resistance to common diseases like bacterial wilt and blight (Asare-Bediako *et al*., 2020).

The introduction of high-yielding varieties such as 'Anna' and 'Jaquar' has contributed to increased productivity. These varieties have also been selected for their improved adaptation to local climatic conditions (Aidoo *et al*., 2018).

2.4.1 Nutrient management and resource use efficiency in hydroponic systems

Hydroponics gives growers more control over the factors that influence plant growth, such as nutrients. This control leads to the possibility of increasing the yield and improving the overall quality. Nutrient solutions used in hydroponic systems are highly efficient methods for delivering essential nutrients to plants, as they allow for precise control over the nutrient concentration and pH levels. This efficiency is especially pronounced when a recirculating system is adopted, as it minimizes nutrient waste by continuously recycling the solution through the root zone. In such systems, the excess solution that is not absorbed by the plants is filtered, and returned to the reservoir, ensuring that valuable nutrients are not lost and reducing the need for frequent replenishment.

This closed-system approach not only promotes sustainable resource use but also helps maintain a stable nutrient environment, which can enhance plant growth, improve yields, and reduce environmental impact. Recycling or reusing nutrient solutions is seen as important strategies for making agriculture more sustainable (Andriolo *et al*., 2006). This approach helps reduce the consumption of water and fertilizers (Alarcón, 2006; Nakano *et al*., 2010), minimizing waste and environmental impact while still supporting healthy crop growth.

The adoption of drip irrigation systems has enhanced water use efficiency by delivering consistent moisture to tomato plants, reducing water stress and boosting yields (Yeboah *et al*., 2021). Implementing proper fertilizer application schedules and techniques, such as fertigation, ensures optimal nutrient availability and uptake (Adomako *et al*., 2022). However, closed systems present challenges, such as nutrient imbalances caused by the accumulation of ions and dissolved salts in the recirculated solution, which can lead to growth and yield reductions (Tunali *et al*., 2009; Van Os, 2009).

Nutrient solutions are commonly applied through high-frequency drip irrigation, which allows excess solution to drain, helping to maintain stable nutrient concentrations (Sánchez *et al*., 2014). In open hydroponic systems, the excess nutrient solution that drains away is not recycled, leading to the continuous loss of both water and fertilizers. This results in significant resource wastage, as valuable nutrients and water are discarded, making this system less efficient. Such losses have both economic and environmental consequences, as growers must frequently replenish the solution, increasing costs and contributing to a larger ecological footprint.

In hydroponic systems utilizing inert substrates for tomato cultivation, it is imperative to maintain the nutrient solution pH within the optimal range of 5.5 to 6.5, and EC between 1.5 and 3 dS m^{-1}, to ensure optimal plant growth and adequate mineral nutrition (Adams, 2004).

The composition of the nutrient solution must be carefully balanced to prevent the formation of precipitates and the onset of nutrient antagonisms, both of which can impair the efficient uptake of water and essential nutrients (Sonneveld and Voogt, 2009; Velazco *et al*., 2012).

Elevated EC levels (>5 dS m^{-1}) in the rhizosphere can severely hinder water and nutrient absorption, ultimately resulting in reduced crop yields (Bustomi *et al*., 2014; Santos and Torres, 2018). Understanding the influence of EC on plant growth is crucial for optimizing tomato cultivation.

2.4.2 Improved systems of cultivation- Hydroponics

The Nutrient Film Technique (NFT) is a widely used hydroponic system where plants are cultivated in narrow, sloping channels with a continuous flow of nutrient solution over the roots. This setup creates a highly oxygenated environment that enhances nutrient absorption and promotes fast plant growth. According to Li *et al*. (2019), NFT systems are especially well-suited for leafy greens and herbs, but also fruit vegetables like tomato, as these plants have shallow root systems and high-water demands.

Floating hydroponics, or deep-water culture (DWC), involves suspending plants in a nutrient-rich solution with their roots submerged. The plants are supported by floating rafts, typically made of expanded plastic, which allow the roots to access the solution while providing stability for the plant. According to Singh *et al*. (2020), this method is particularly suitable for crops with longer growth cycles, such as tomatoes and peppers, as it offers a stable environment for root development.

Aeroponics is an advanced hydroponic system in which plant roots are suspended in the air and misted with a nutrient solution. This method delivers nutrients directly to the roots in the form of mist, fostering rapid growth and efficient nutrient absorption. According to Guller (2017), aeroponics is particularly well-suited for plants with delicate root systems, such as strawberries and orchids, as it reduces root damage and enhances nutrient uptake.

Aggregate systems referred to as substrate culture, utilize a solid medium to support plant roots and ensure stability. Common growing media include rockwool, perlite, and vermiculite.

According to Bugbee (2016), aggregate systems are highly versatile and can be used to grow a variety of crops, such as tomatoes, cucumbers, and peppers. They are especially ideal for larger plants with extensive root systems, as the solid medium offers both support and proper aeration.

Many crops have been successfully grown using substrate culture, with conventional systems like the Dutch bucket being based on this method. However, the demand for more cost-effective agriculture has led to the development of low-cost substrate volume cultures. The goal of this approach is to reduce production costs associated with the substrates used.

2.5.0 Plant Growth Response to Varying Electrical Conductivity

2.5.1 Morphological performance

Plant height is a fundamental indicator of overall growth, often reflecting the plant's response to nutrient availability and environmental conditions. Studies have shown that the electrical conductivity of the nutrient solution significantly affects plant height. Lower EC levels can lead to stunted growth due to insufficient nutrient availability, while excessively high EC levels can cause salt stress, also limiting growth (Wortman, 2015; De Freitas *et al*., 2017). However, optimal EC levels promote balanced nutrient uptake, contributing to greater plant height and overall vigour.

Leaf production is closely tied to a plant's ability to photosynthesize and grow, with enough leaves being an indicator of healthy growth and productivity. Studies show that moderate EC levels, typically between 1.25 and 1.50 dS m^{-1}, promote the highest leaf production in tomato plants. Both lower and higher EC levels can reduce leaf number, either due to nutrient deficiencies or salt stress, respectively (Ding *et al*., 2018).

Plant girth, or stem diameter, is a key indicator of a plant's strength and resilience. Thicker stems are typically linked to better structural support and enhanced ability to withstand environmental stress. Research has shown that maintaining optimal EC levels can promote increased stem girth, which is essential for supporting the plant as it matures and produces fruit (Acosta *et al*., 2008; Beyl and Trigiano, 2016).

2.5.2 Plant growth as affected by nutrient solution electrical conductivity

Ozalkan *et al*. (2010) identified a correlation between leaf area and increased dry matter accumulation in plants. They also noted that leaf area decreased during grain filling, while the average above-ground weight increased most significantly during the linear vegetative growth stage. An increase in leaf area provides a larger surface for light interception, leading to greater production and accumulation of photosynthates in the plant. As the plant matures, more leaves undergo senescence, causing a reduction in leaf area and, consequently, a decrease in dry matter accumulation. Li and Stanghellini (2001) indicated that high EC levels reduced tomato leaf area by inhibiting leaf expansion.

The plant's affinity for photosynthetic processes decreases at this point because ageing leaves have little to no chlorophyll. Poorter and Remkes (1990) observed that species that are closer to more favourable environments grow quicker when plants grow under similar conditions. According to Poorter (1989), the observation was explained by variations in the distribution of biomass, chemical composition, and formation of leaf area.

Relative growth rate is a measurement of the total plant dry weight gain over a period relative to the starting weight. This also shows how efficiently the plant is growing. McCall and Brazaityte (1997) reported that high EC levels led to a reduction in the relative growth rate of tomatoes. Heinen *et al*. (2001) showed that both low and high EC levels reduced tomato growth. The response of tomato growth to variations in EC may differ depending on the cultivation system, influencing plant development.

Net assimilation rates (NAR) is the plant's dry matter increment per unit leaf area per unit time. This can alternatively be described as the photosynthetic or biomass-generating efficiency of the leaves. Schwarz and Kuchenbuch (1997) demonstrated that an increase in EC negatively affected the NAR of tomato plants. Specifically, they found that elevated EC levels resulted in reduced NAR.

2.6. Physiological Characteristics of Tomato in Varying Nutrient Solution Strength

2.6.1 Chlorophyll content

Chlorophyll content is directly related to the plant's ability to perform photosynthesis, which is essential for growth and development. Electrical conductivity influences chlorophyll concentration by affecting nutrient uptake, particularly nitrogen, which is a key component of chlorophyll. Research shows that moderate EC levels promote higher chlorophyll content, enhancing photosynthetic efficiency and, consequently, plant growth (Usman *et al.,* 2023). On the other hand, extreme EC levels either too low or too high can impair chlorophyll synthesis, leading to reduced photosynthetic activity and stunted growth.

2.6.2 Photosynthesis efficiency (chlorophyll fluorescence)

Photosynthetic efficiency, as measured by chlorophyll fluorescence, is a critical indicator of a plant's photosynthetic performance, reflecting its capacity to capture and convert light energy into chemical energy. This metric provides insight into whether the plant is operating at optimal efficiency or experiencing physiological stress due to environmental factors.

Under favourable growing conditions, photosynthesis proceeds efficiently, whereas suboptimal growing conditions can induce stress, resulting in a decline in photosynthetic activity. Prolonged or severe environmental stress can further impair the plant's photosynthetic machinery, leading to reduced growth and overall physiological function. Shin *et al*. (2020)

proposed that an increase in EC is associated with a reduction in photosynthetic efficiency, serving as a potential indicator of plant stress.

2.7 Influence of Electrical Conductivity Modulation on Yield

Electrical Conductivity (EC) measures the total concentration of soluble salts, including those from fertilizers, in a growing medium Van *et al* (2020). Since most fertilizer salts are macronutrients, EC serves as a useful indicator of macronutrient levels. However, it does not provide information about micronutrient content. For optimal plant growth, most crops thrive in a growing medium with an EC range of **2.0 to 3.5 mS/cm** (where 1 mS/cm = 1 mmho/cm = 1 dS/m = 1000 µS/cm) Van *et al* (2020).

The impact of EC on tomato fruit yield is complex, with both fruit size and number being affected. Buck *et al*. (2008) also found that specific tomato varieties can sustain a consistent fruit number across a range of EC levels. Moderate EC levels can reduce fruit size due to a decrease in water flow into the fruit, while excessively high EC levels can reduce both fruit number and size.

The yield reductions under high EC conditions are often proportional to plant growth reductions (Munns and tester 2008). A higher nutrient solution EC reduces the fresh fruit yield of tomato with an equal balance of macronutrients (Ehret *et al*., 2013). The findings of Méndez-Cifuentes *et al*. (2023) declared that increasing EC levels can enhance yield. Similarly, Hernández-Pérez *et al*. (2020) reported that certain tomato varieties exhibit relative insensitivity to fluctuations in EC, maintaining stable yields despite variations. Effective irrigation management, maintaining an EC range of 1 to 4 mS/cm, can support plant growth, and increase fruit yield (Carballo-Méndez *et al*., 2023).

In soilless culture, various growing media, such as rockwool, coir, peat, tuff, perlite, and sawdust, are employed, each demonstrating distinct responses to fluctuations in nutrient solution EC levels. Lower EC, coupled with increased irrigation during periods of high solar radiation, enhances water and mineral absorption, which can improve yield; however, this may also lead to a decline in fruit quality (Carballo-Méndez *et al*., 2023).

2.8 Fruit Quality of Tomato in Varied Electrical Conductivity

Electrical conductivity levels can affect various aspects of tomato fruit quality, including the occurrence of physiological disorders, organoleptic properties, and postharvest shelf life. Elevated EC levels have been shown to reduce the susceptibility of tomatoes to physiological disorders such as blossom-end rot and fruit cracking.

2.8.1 Sugar content (%Brix)

Sugar content in tomatoes is an important quality attribute, influencing taste and market value. The electrical conductivity of the nutrient solution can affect the accumulation of sugars in tomato fruits. Furthermore, increased EC can enhance the concentrations of dry matter, soluble solids, sugars, acids, minerals, and vitamins in the fruit, thereby improving its flavour and nutritional profile. The work of Moya *et al*. (2017), proved that high EC increases the sugar content (%Brix) of tomatoes. However, excessively high EC levels may lead to a decline in fruit sugar and acid content, negatively impacting flavour (Dorai *et al*., 2008). Additionally, the timing and precision of irrigation practices are critical factors that influence both the yield and quality of tomato crops (Sezen *et al*., 2010).

2.8.2 Fruit pH

The pH of a fruit is a measure of its acidity or alkalinity, which is determined by the concentration of hydrogen ions (H^+) present in the fruit's juice or pulp. This parameter is crucial in influencing the fruit's taste, ripening process, and shelf life. Solis-Toapanta *et al*. (2020)

demonstrated that EC levels significantly affect the pH of tomatoes. Conversely, Moya *et al*. (2017) and Bautista *et al*., (2020) reported that the pH of tomato fruit was not significantly influenced by variations in the EC of the nutrient solution.

2.8.3 Vitamin C Content

Vitamin C is an essential micronutrient and a key antioxidant in tomatoes. The EC of nutrient solution plays a significant role in modulating vitamin C content.

Optimal EC levels enhance the uptake of essential nutrients, including nitrogen, which is critical for the biosynthesis of vitamin C (Wang *et al*., 2015). Research by Zafra *et al*. (2018) found that tomatoes grown at moderate EC levels (1.0 to 1.5 dS m^{-1}) exhibited higher vitamin C content compared to those cultivated at either higher or lower EC levels. Elevated EC levels can induce osmotic stress, which impairs the plant's capacity to synthesize vitamin C, while low EC levels may limit nutrient availability, hindering optimal growth and metabolic processes.

Rico *et al.* (2016) and Moya *et al*. (2017) conducted studies that demonstrated an 8.8% increase in vitamin C content in fruit samples from plants grown under high EC conditions, compared to those cultivated at low EC levels.

2.8.4 Lycopene Content

Lycopene, a carotenoid responsible for the red colour of tomatoes and linked to various health benefits, is also influenced by EC levels. Research indicates that the EC of the nutrient solution plays a significant role in lycopene synthesis and accumulation.

Dumas *et al*. (2003) found that tomatoes grown under optimal EC conditions (1.2 to 1.8 dS m^{-1}) exhibited higher lycopene content compared to those cultivated at lower or higher EC levels. Elevated EC levels can induce stress, thereby reducing lycopene production, while excessively low EC levels may compromise plant health and productivity, negatively impacting lycopene accumulation (Hanson *et al*., 2018). Additionally, the findings of Bahrami *et al*. (2020) emphasise that balanced EC levels create favourable conditions for optimal lycopene biosynthesis and accumulation.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Site

The experiment was conducted at the Forest and Horticultural Crops Research Centre (FOHCREC), Kade, in the Denkyembour district of the Eastern Region of Ghana. The first experiment was conducted from October 2023 to January 2024 while the second was carried out from February to May 2024. This site is situated at latitudes 6° 09' and 6° 06' N and longitudes 0° 55' and 0° 49' W, at an altitude of 135.9 m above sea level. FOHCREC is positioned within the semi-deciduous forest agroecological zone of Ghana.

3.2 Greenhouse Ambient Climatic Conditions

Daily temperature and humidity readings in the greenhouse were recorded hourly throughout the experimental period using a TR72A2 thermorecorder obtained from TANDD Corporation, Japan.

3.3 Experimental Materials and Treatments

3.3.1 Tomato Varieties

The study evaluated two tomato varieties: the Anna F1 hybrid from Seminis Vegetable Seed Company (St. Louis, Missouri, U.S.), known for its suitability for greenhouse cultivation, and the Jaguar F1 hybrid from Technisem (Longué-Jumelles, France), a variety that performs well in both open field and greenhouse settings (Ambang *et al.*, 2016; Ayarna *et al.*, 2020).

These varieties are first-generation hybrid tomatoes selected for their hybrid vigour, which includes higher yield, better disease resistance, and enhanced growth compared to non-hybrid varieties. These varieties are specifically bred for resistance to common tomato diseases, ensuring healthy plants and high productivity. They provide uniformity in plant characteristics, beneficial for experimental consistency and reliable results. Additionally, their adaptability to various growing conditions makes them suitable for testing under different electrical conductivity (EC) levels.

3.3.2 Electrical Conductivity Management Levels

Four levels of electrical conductivity (EC) modulation-High (H), High-Low (HL), Low (L), and Low-High (LH)were implemented to evaluate the effects of varying nutrient solution strengths on tomato growth, yield, fruit quality, and water use efficiency while minimizing stress and preventing nutrient imbalances. These treatments are shown below:

Electrical Conductivity Management Levels

EC of nutrient solution (dS m^{-1})	EC modulation during plant growth
1.2 (Low)	Low EC was applied from the vegetative phase through the reproductive phase
1.2/2.4 (Low-High)	Low EC was applied at the vegetative and changed to High EC at the reproductive phase
2.4 (High)	High EC was applied from the vegetative phase through the reproductive phase
2.4/1.2 (High-Low)	High EC was applied at the vegetative and changed to Low at the reproductive phase

3.3.3 Nutrient Solution formulation

The Enshi Nutrient Solution recipe (Hori, 1966) was adopted for this experiment as a recommended formulation for growing a variety of vegetable crops. This recipe as shown in Table 1 offers a balanced mix of essential nutrients specifically designed for the hydroponic industry. Nutrient solutions were prepared based on the treatments, with the pH adjusted to 5.5-6.5 using 70% nitric acid. Plants were supplied with the nutrient solution through a recirculating system that utilized submersible pumps and a drip irrigation system. The nutrient solution was provided to the plants for 15 minutes each day in split irrigations, particularly, beginning two weeks after transplanting. Based on the treatment implemented, each nutrient solution sample was renewed every three to four days. The pH and EC of the nutrient solution were monitored and measured using a Hanna pH/EC meter. Electrical conductivity modulation was implemented following flower set to adjust the EC of the nutrient solution in response to the evolving physiological requirements of the plants.

Table 1. Enshi Nutrient solution recipe

Major ELEMENT	NH_4-N	NO_3-N	PO_4-P	K	Ca	Mg	S
(ppm)	23.4	992	126.7	312.8	160.4	48.6	192.2

Minor ELEMENT	Fe	B	Mn	Zn	Cu	Mo
(ppm)	3.0	0.5	0.5	0.05	0.02	0.01

3.4 Cultivation Method

Plants were cultivated using Low Node order pinching at High-Density planting (LN&HD) system. In this system, the plants were pinched after the second truss was fully developed to halt further growth. A low substrate volume of 1.0 L per plant was utilized, consisting of cocopeat (coconut husk fibre) sourced from FibreWealth Ghana Limited. A total of 25 plants per treatment were cultivated, spaced 0.2 m within rows and 1.2 m between rows. Each plant was securely trellised with twines to support growth, ensure optimal light interception, prevent overcrowding, reduce the risk of disease, and facilitate easier management throughout their growth cycle. At the flower set stage, the flowers were treated with a solution of 1.0 mL/L of 4-chlorophenoxyacetic acid (4-CPA) to enhance fruit set.

3.5 Experimental Design and Statistical Analyses

The experiment was designed as a 2 x 4 factorial (variety x EC levels) in a Randomized Complete Block Design (RCBD) with three replications. The factors were two varieties of tomato and four EC modifications with 25 plants per treatment. Data were analysed using GenStat (Rothamsted Research, Harpenden, UK), and Tukey's $HSD_{(0.05)}$ was used to separate significant differences among the means that differed significantly as described by Gomez and Gomez (1984).

3.6 Data Collection

Data were collected at regular intervals throughout the growth cycle, focusing on the following parameters:

- Morphological characteristics (plant height, stem diameter, leaf number, biomass dry weight)
- Physiological characteristics (photosynthetic efficiency, chlorophyll content)
- Yield components (fruit number per plant, yield per unit area)
- Fruit quality (total soluble solids, pH, vitamin C content, and lycopene content)

3.6.1 Morphological Characteristics

The height of each plant was measured using a meter rule, taken from the base to the tip of the apical leaf. The stem diameter, or girth, was measured at the base of the plant using a pair of vernier callipers 5.0 cm above the ground during the vegetative stage and at the base of the first truss during the reproductive stage. The total number of leaves per plant was determined by counting all fully opened leaves at the vegetative and reproductive stages.

3.7 Physiological Characteristics

The photosynthetic efficiency (chlorophyll fluorescence) is a key tool for understanding photosynthesis and how plants respond to environmental changes (change in EC of nutrient solutions). Using a Plant Efficiency Analyzer (Pocket PEA, Hansatech Ltd., King's Lynn, UK), the photosynthetic efficiency of the plants was measured from the vegetative stage to the reproductive stage, with assessments conducted at 14, 50, and 75 days after transplanting. Measurements were taken successively at the third leaf below the first truss, the last leaf below the first truss, and the last leaf below the second truss.

The chlorophyll content of the leaves was measured and expressed as the Chlorophyll Concentration Index (CCI) following the method described by Bajracharya (1999). Measurements were taken using an Apogee chlorophyll meter (Apogee Instruments Inc., Logan, UT, USA) during the vegetative and reproductive growth phases. Chlorophyll content was measured using the same methodology employed to determine +photosynthetic efficiency.

3.8 Yield Component

The number of fruits per plant was determined by dividing the total harvested fruits by the number of tagged plants, while fruit yield was assessed by weighing the harvested fruits on a scale. The yield per unit area was determined using the formula provided in Equation 1, which calculates the total weight of harvested fruits divided by the greenhouse's cultivation area.

$$\text{Yield per unit area} = \frac{\text{Total yield(kg)}}{\text{Area (m}^2\text{)}} \; \ldots\ldots\ldots\ldots Equation\ 1$$

3.9 Fruit Quality

The fruit quality was assessed by measuring some components, including total soluble solids (TSS) in Brix%, fruit pH, lycopene content, and vitamin C content.

The Brix percentage was determined using an Atago digital hand-held pocket refractometer (Atago Co. Ltd, Tokyo, Japan). The TSS in the fruit juice was determined by placing a few drops of juice on the refractometer's prism.

The vitamin C (ascorbic acid) content was estimated following the procedure outlined by Igwemmar *et al*. (2013). An aliquot of 5.0 mL of pooled tomato juice was diluted with 45.0 mL of 0.1% oxalic acid and then titrated with a dye solution until a noticeable colour change occurred. The results were expressed as milligrams of ascorbic acid per gram of fresh weight.

Lycopene content was measured using the method described by Fish *et al*. (2012). To extract the lycopene, 100 mL of a n-hexane solution (2:1:1) was applied to one gram of homogenate, which was then incubated for a full day. Following incubation, the extract was mixed with 15 mL of distilled water to separate the polar phase (bottom) from the non-polar phase (top). The absorbance of the non-polar phase was measured at wavelengths 451 nm and 503 nm, using n-hexane as a blank.

3.10 Growth Parameters

To evaluate plant growth performance in response to EC modulation, some growth parameters, including leaf area, relative growth rate, and net assimilation rate were evaluated. Some plants were destructively sampled, with both shoot and root sections oven-dried at 70 °C for 72 hours.

Leaf area, as an indicator of the photosynthetic surface, was measured during both the vegetative and reproductive phases to evaluate the plant's response to EC modulation. In this process, the leaves were carefully harvested and spread evenly on a white platform, where a scanned image was captured. This image was then analyzed using LIA32 software (https://www.agr.nagoya-u.ac.jp/-shinkan/LIA32, accessed September 10, 2024).

Relative Growth Rate (RGR) is a key metric in plant physiology that quantifies the rate at which a plant's dry mass increases in relation to its existing mass over a defined period. The Relative Growth Rate (RGR) was calculated using Equation 2.

$(RGR = \frac{\ln W2 - \ln W1}{t2 - t1})$…Equation 2

- **W_1**: Initial weight
- **W_2**: Final weight
- **t_1**: Initial time
- **t_2**: Final time.
- **ln**: Natural logarithm.

Net Assimilation Rate (NAR) measures the rate at which a plant accumulates dry matter (biomass) per unit of leaf area over a specified period, as calculated using Equation 3.

$$\text{NAR} = \frac{(W_2 - W_1) \cdot (\ln\ L_2 - \ln\ L_1)}{(t_2 - t_1) \cdot (L_2 - L_1)} \text{ ………} Equation\ 3$$

Where:

- **W_1**: Initial dry weights of the plant
- **W_2**: Final dry weights of the plant
- **L_1:** Initial leaf area
- **L_2**: Final leaf area
- **t_1**: Initial time
- **t_2**: Final time
- **ln**: Natural logarithm.

3.11 Water Uptake and Water Use Efficiency (WUE)

Plant resource use characteristics, specifically regarding water use, were evaluated from the day of transplanting to the 75th day after transplanting. To determine the daily water uptake, periodic measurements of the volume of water absorbed by the plants were conducted by subtracting the unabsorbed nutrient solution from the initial volume supplied, as described by Ayarna *et al*. (2020). This measurement was conducted periodically whenever the volume of the nutrient solution had significantly decreased.

The total water uptake was determined by carefully measuring the cumulative volumes of nutrient solution absorbed by the plant throughout its growth period.

The efficiency of water use was assessed by calculating the ratio of the total weight of fresh fruit produced by each plant to the total volume of water that the plant utilized during its growth. This measurement provides insight into how effectively the plant converts water into fruit yield.

3.12 Quality Control Measures Implemented During Data Collection:

1. Instrument Calibration: Accurate data collection was ensured by routinely calibrating instruments to assess their precision, bias, and scale of measurement.
2. Standardized Procedures: Standardizing data collection techniques using comprehensive procedure manuals, consistency among various data collectors and locations was preserved.
3. Multiple Measurements: More accurate data was achieved by identifying and fixing mistakes using several measurements, observations, or samples.
4. Data Cleaning: The general accuracy of the data was applied for routinely cleaning the data to resolve errors, inconsistencies, and missing values.
5. Data was analysed using the proper tools and shown in tables or graphs.

CHAPTER FOUR

4.0 Results

4.1. Greenhouse Ambient Temperature and Humidity During the Cropping Cycle

The environmental conditions (temperature and humidity) recorded over the growing period for both experiments are shown in Figure 1 (a-d).

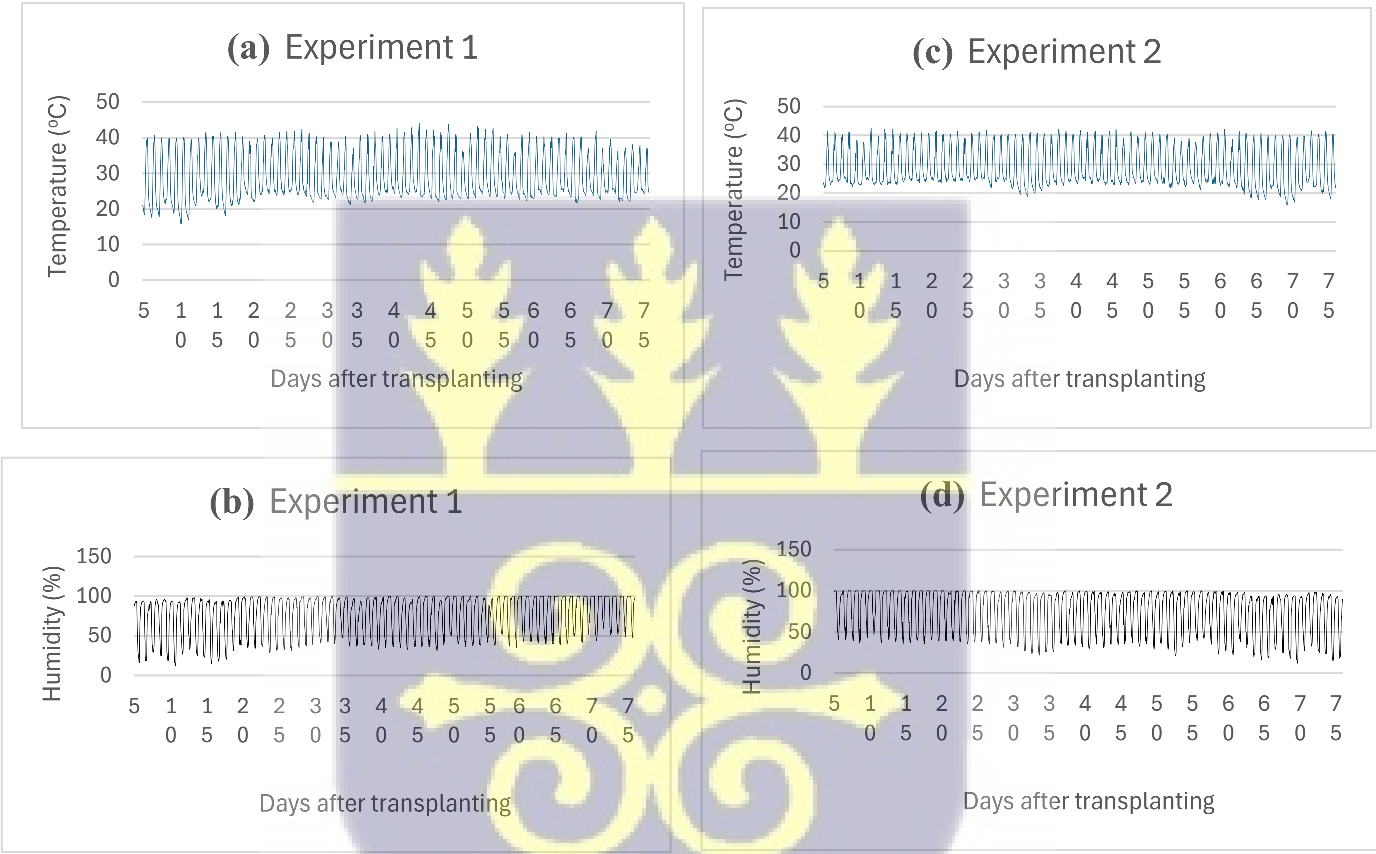

Figure 1. Greenhouse ambient temperature and humidity over the experimental period.

4.2 Morphological responses of Anna and Jaguar varieties to EC modulation

The study examined the impact of different levels of electrical conductivity modulation (H, HL, L, and LH) levels on the morphological growth of Anna and Jaguar tomato varieties.

4.2.1. Plant height

The EC modulation levels (H, HL, L, and LH) had a significant effect ($p < 0.05$) on plant height in both tomato varieties (Table 2). At the reproductive stage, the Anna variety produced taller plants than the Jaguar variety across all EC modulation levels. The different levels of EC modulation had a significant impact on the height of each tomato variety during both the vegetative and reproductive stages.

Table 2. Influence of EC modulation on plant height of two tomato varieties

		Experiment 1		Experiment 2	
EC modulation	Variety	**Vegetative stage** (cm)	**Reproductive stage** (cm)	**Vegetative stage** (cm)	**Reproductive stage** (cm)
H	**Anna**	44.31 ± 0.57^{aC}	153.11 ± 1.22^{aB}	47.54 ± 0.63^{aB}	157.92 ± 0.53^{aA}
HL		48.07 ± 0.92^{aB}	166.77 ± 1.59^{aA}	44.58 ± 0.45^{aC}	144.38 ± 0.64^{aB}
L		58.62 ± 0.83^{aA}	145.87 ± 0.97^{aC}	49.08 ± 0.30^{aA}	128.96 ± 0.77^{aD}
LH		39.64 ± 0.39^{aD}	166.81 ± 1.69^{aA}	43.42 ± 0.71^{aC}	134.73 ± 1.03^{aC}
H	**Jaguar**	44.52 ± 0.51^{aB}	98.15 ± 0.57^{bA}	34.83 ± 0.46^{bA}	87.99 ± 0.96^{bC}
HL		45.75 ± 1.04^{bB}	98.38 ± 0.53^{bA}	33.92 ± 0.73^{bA}	97.53 ± 0.75^{bA}
L		47.46 ± 0.51^{bA}	99.14 ± 0.58^{bA}	34.88 ± 0.07^{bA}	98.08 ± 0.91^{bA}
LH		39.37 ± 0.69^{aC}	95.91 ± 1.02^{bA}	35 ± 0.14^{bA}	94.48 ± 1.30^{bB}
P-values					
EC		<.001	<.001	<.001	<.001
V		<.001	<.001	<.001	<.001
EC × V		<.001	<.001	<.001	<.001
CV%		2.6	1.3	2.2	1.3

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$).
CV%= Coefficient of variation.

4.2.2. Leaf number

The leaf numbers of the two varieties were affected significantly ($p<0.05$) by EC modulation (Figures 2 a and 2b). Across all treatments, the Anna variety consistently produced a higher number of leaves (17–19) compared to the Jaguar variety (12–15). Treatment H resulted in a higher leaf count compared to the other treatments in the Anna variety during both the vegetative growth phase (Figure 2a) and the reproductive growth phase (Figure 2b). In the Jaguar variety, treatments H and LH exhibited a higher leaf count than the other treatments (Figure 2a), while treatments H and L produced more leaves than the others during the vegetative growth stage (Figure 2b).

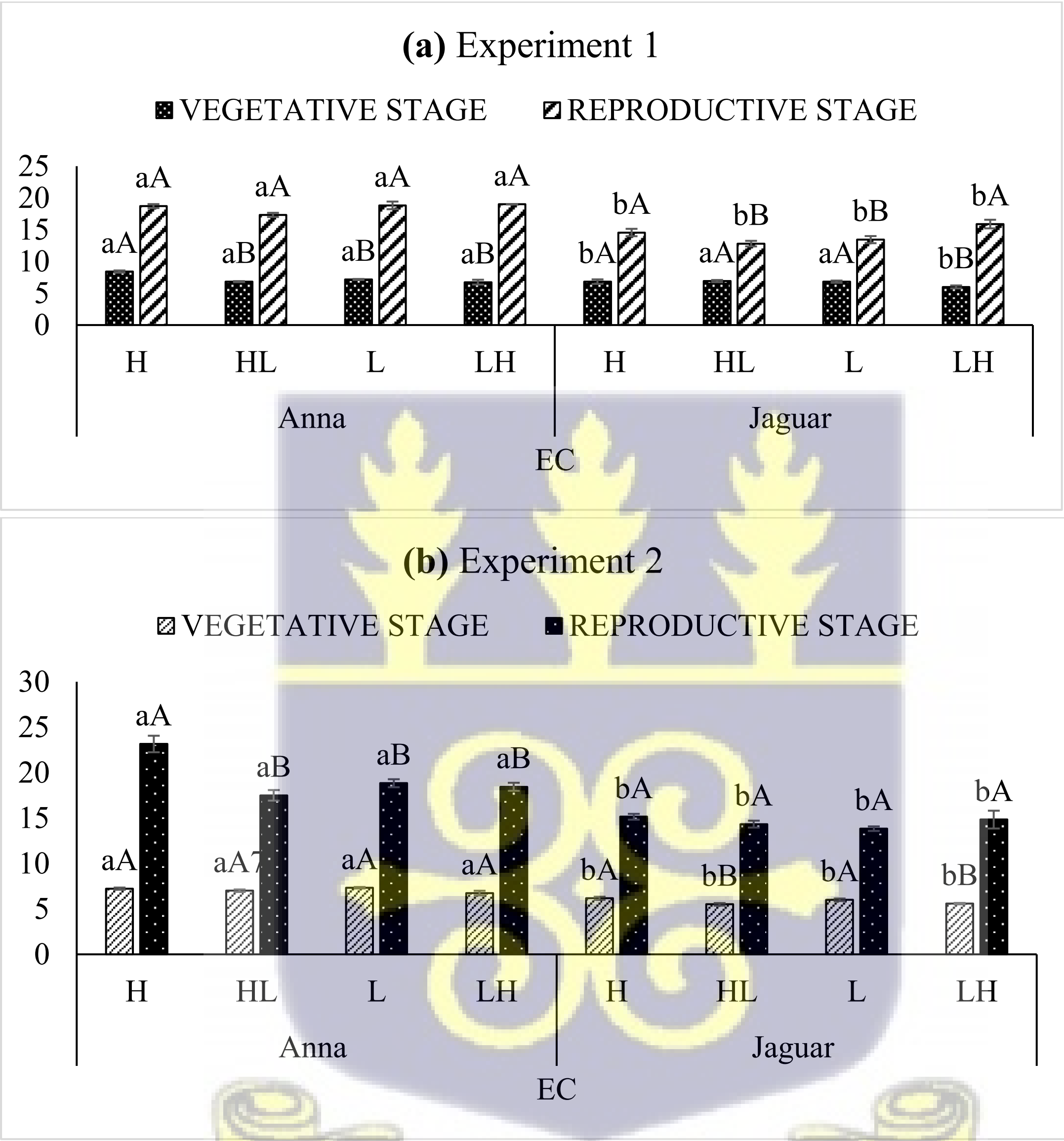

Figure 2. Leaf Number of two tomato varieties as influenced by EC modulation.
Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD (p<0.05).

4.2.3. Stem girth

In the reproductive stage, the girth of both varieties was significantly ($p < 0.05$) influenced by EC modulation (Table 3). The H and HL treatments increased plant girth for both varieties compared to the other treatments during the reproductive stage. EC varied significantly throughout the entire plant growth period in both experiments. However, there was no significant variation in girth between the two varieties, except in the reproductive stage of Experiment 2.

Table 3. Influence of EC modulation on the stem girth of two tomato varieties

Treatment		Experiment 1		Experiment 2	
EC modulation	**Variety**	**Vegetative stage** (mm)	**Reproductive stage** (mm)	**Vegetative stage** (mm)	**Reproductive stage** (mm)
H	Anna	0.53±0.03^{aA}	0.74±0.01^{aA}	0.41±0.01^{aB}	0.76±0.01^{aA}
HL		0.47±0.02^{aA}	0.74±0.01^{bA}	0.42±0.05^{aB}	0.76±0.01^{aA}
L		0.48±0.01^{aA}	0.55±0.03^{bB}	0.48±0.02^{aA}	0.72±0.01^{aB}
LH		0.44±0.04^{aA}	0.55±0.02^{aB}	0.48±0.02^{aA}	0.61±0.01^{aC}
H	Jaguar	0.50±0.00^{aA}	0.77±0.00^{aA}	0.41±0.01^{aA}	0.65±0.02^{bA}
HL		0.48±0.02^{aA}	0.82±0.02^{aA}	0.44±0.02^{aA}	0.68±0.01^{bA}
L		0.50±0.03^{aA}	0.55±0.01^{bB}	0.48±0.01^{aA}	0.56±0.01^{bB}
LH		0.44±0.03^{aA}	0.55±0.01^{aB}	0.45±0.02^{aA}	0.54±0.01^{bB}
P-values					
EC		0.035	<.001	0.017	<.001
V		0.958	0.975	0.83	<.001
EC × V		0.793	<.001	0.717	<.001
CV%		7.9	6.6	8.3	2.6

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$). EC=electrical conductivity.

4.3. Growth and Physiological responses of two tomato varieties to EC modulation

4.3.1 Leaf area

The leaf area of the two varieties was significantly ($p<0.05$) influenced by EC modulation. From the two experiments, Table 3 shows that leaf area was highest in the HL (3290.9 to 3808 cm^2) treatment for both varieties compared to the other treatments. Conversely, the leaf area decreased (ranging from 1,442.2 to 2,284.8 cm^2) in both varieties under the L treatment.

Treatment		Experiment 1		Experiment 2	
EC	**Variety**	**Vegetative Stage (cm^2)**	**Reproductive Stage (cm^2)**	**Vegetative Stage (cm^2)**	**Reproductive Stage (cm^2)**
H	Anna	543.3 ± 80.6^{bB}	3537.6 ± 51.8^{aB}	553.7 ± 20.9^{aC}	3732.9 ± 97.4^{aA}
HL		640.1 ± 74.8^{aB}	3810.6 ± 17.5^{aA}	874.3 ± 21.5^{aA}	3808.2 ± 18.4^{aA}
L		1054 ± 101^{aA}	2260.7 ± 21.3^{aC}	774 ± 150^{aB}	2284.8 ± 33.7^{aC}
LH		827.6 ± 35.6^{aA}	3509.9 ± 76.7^{aB}	1066 ± 47.7^{aA}	3097.3 ± 38^{aB}
H	Jaguar	790.9 ± 60.5^{aA}	1377 ± 23.4^{bC}	627.1 ± 40^{aA}	1442.2 ± 10.6^{bD}
HL		653 ± 91.6^{aA}	3290.9 ± 85^{bA}	641.4 ± 15.1^{bA}	3077.5 ± 28.3^{bA}
L		572.4 ± 96.1^{bA}	2076 ± 38.4^{bB}	684.4 ± 51^{aA}	2141.4 ± 30^{bB}
LH		606 ± 40.7^{aA}	1533.3 ± 55.8^{bC}	842.2 ± 56.7^{bA}	1852.8 ± 41.3^{bC}
P-values					
EC		0.208	<.001	<.001	<.001
V		0.071	<.001	0.027	<.001
EC × V		0.003	<.001	0.128	<.001
CV%		2.7	3.2	5.3	2.9

Table 4. Leaf area of two tomato varieties as influenced by EC modulation

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$). EC= electrical conductivity.

4.3.2. Relative growth rate (RGR)

Electrical conductivity modulation significantly affected the RGR of both varieties ($p < 0.05$), as shown in Table 5. In Experiment 1, treatments H and HL increased the RGR of the Anna variety (0.021 $g.g^{-1}d^{-1}$), while the same treatments decreased the RGR for the Jaguar variety (0.016 to 0.017 $g.g^{-1}d^{-1}$). In Experiment 2, treatment HL increased the relative growth rate (RGR) of the Anna variety to 0.018 $g.g^{-1}d^{-1}$, while the Jaguar variety experienced a reduced RGR of 0.015 $g.g^{-1}d^{-1}$. In the Anna variety, the relative growth rate (RGR) was significantly reduced under treatment L compared to the other treatments in Experiment 1. In contrast, the Jaguar variety exhibited a decrease in RGR with the HL treatment relative to the other treatments in Experiment 2.

4.3.3 Net assimilation rate (NAR)

Electrical conductivity modulation significantly ($p < 0.05$) affected the NAR of both varieties in both experiments, as shown in Table 5. The NAR in the Jaguar variety under treatments L and LH was significantly higher (0.336 and 0.353 mg cm-2 day-1, respectively) compared to the Anna variety, which recorded NAR values of 0.243 and 0.229 mg cm-2 day-1 under the same treatment conditions. In Experiment 2, the net assimilation rate (NAR) for the Jaguar variety decreased to 0.218 mg cm-2 day-1 under the HL treatment, while NAR values for the other treatments ranged from 0.370 to 0.520 mg cm-2 day-1.

Table 5. Effect of EC modulation on relative growth rate and net assimilation rate of two tomato varieties

		Experiment 1		Experiment 2	
EC modulation	**Variety**	**Relative growth rate ($g\ g^{-1} day^{-1}$)**	**Net assimilation rate ($mg\ cm^{-2}\ day^{-1}$)**	**Relative growth rate ($g\ g^{-1}\ day^{-1}$)**	**Net assimilation rate ($mg\ cm^{-2}\ day^{-1}$)**
H	**Anna**	0.021 ± 0.001^{aA}	0.348 ± 0.035^{aA}	0.020 ± 0.002^{aA}	0.269 ± 0.031^{bA}
HL		0.021 ± 0.000^{aA}	0.280 ± 0.004^{aAB}	0.019 ± 0.001^{aA}	0.239 ± 0.014^{aA}
L		0.016 ± 0.000^{aB}	0.243 ± 0.011^{bB}	0.018 ± 0.000^{aA}	0.317 ± 0.036^{aA}
LH		0.019 ± 0.001^{aA}	0.229 ± 0.015^{bB}	0.019 ± 0.000^{aA}	0.264 ± 0.007^{bA}
H	**Jaguar**	0.016 ± 0.000^{bA}	0.339 ± 0.012^{aA}	0.020 ± 0.000^{aB}	0.521 ± 0.029^{aA}
HL		0.017 ± 0.002^{bA}	0.238 ± 0.042^{aA}	0.015 ± 0.000^{bC}	0.218 ± 0.012^{aC}
L		0.018 ± 0.000^{aA}	0.336 ± 0.02^{aA}	0.019 ± 0.000^{aB}	0.370 ± 0.007^{aB}
LH		0.023 ± 0.001^{aA}	0.353 ± 0.057^{aA}	0.023 ± 0.001^{aA}	0.489 ± 0.026^{aA}
P-values					
EC		0.266	0.095	0.001	<.001
V		0.004	0.077	0.329	<.001
EC × V		0.008	0.049	0.002	<.001
CV%		2.3	5	5.03	5.03

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$). EC= electrical conductivity.

4.3.4. Chlorophyll fluorescence (photosynthetic efficiency)

In Experiments 1 and 2, as shown in Figures 3a and 3b, the Anna variety subjected to LH treatment recorded the maximum photosynthetic efficiency (0.77) at 50 days after transplanting (DAT). Following this, there was a notable decrease in photosynthetic efficiency, which dropped to 0.68. Treatments H and L showed comparable patterns in photosynthetic efficiency, whereas the HL treatment consistently showed the lowest photosynthetic efficiency throughout the experiment. In the same way, Figures 3c and 3d illustrate that Jaguar recorded the maximum photosynthetic efficiency (0.78) when exposed to treatment LH. Subsequently, this efficiency declined as it approached 75 DAT. As the plants approached 75 DAT, there was a noticeable decrease in photosynthetic efficiency across all treatments in both the Anna and Jaguar varieties.

Figure 3. Effect of EC modulation on Chlorophyll fluorescence of two tomato varieties: Experiments 1 and 2, Anna (a, b) and Jaguar (c, d).

4.3.5 Chlorophyll content

Electrical conductivity modulation significantly (p<0.05) affected the chlorophyll content of the two tomato varieties at both stages of growth in the two experiments (Table 6). In the reproductive phase of both experiments, the Jaguar variety showed a decrease in chlorophyll content, with levels between 37.4 and 45.26 µmol m^{-2} across all EC modulation treatments. In contrast, the Anna variety maintained higher chlorophyll levels, ranging from 45.03 to 49.13 µmol m^{-2}. The L treatment lowered chlorophyll levels in the Jaguar cultivar. In contrast, the Anna variety saw an increase in chlorophyll levels.

Table 6. Effect of electrical conductivity modulation on chlorophyll Content of two tomato varieties

Treatment		Experiment 1 (µmol m^{-2})		Experiment 2 (µmol m^{-2})	
EC modulation	Variety	Vegetative stage	Reproductive stage	Vegetative Stage	Reproductive stage
H	Anna	44.55 ± 0.78^{aA}	46.071 ± 1.71^{aA}	44.02 ± 0.57^{bA}	49.13 ± 0.87^{aA}
HL		41.96 ± 0.54^{bB}	45.43 ± 0.35^{aA}	43.93 ± 1.58^{aA}	44.33 ± 0.58^{aB}
L		44.11 ± 0.31^{aA}	45.03 ± 0.87^{aA}	44.84 ± 0.43^{bA}	48.58 ± 0.26^{aA}
LH		40.17 ± 0.42^{bB}	45.32 ± 0.98^{aA}	44.96 ± 1.13^{aA}	47.83 ± 0.85^{aA}
H	Jaguar	46.36 ± 0.82^{aA}	44.77 ± 0.26^{aA}	47.55 ± 0.66^{aA}	45.26 ± 0.79^{bA}
HL		45.62 ± 0.35^{aA}	43.27 ± 0.46^{aA}	45.48 ± 0.48^{aC}	44.44 ± 0.12^{aA}
L		44.29 ± 0.96^{aA}	37.40 ± 2.92^{bB}	47.82 ± 0.36^{aA}	45.64 ± 0.44^{bA}
LH		44.67 ± 0.46^{aA}	45.18 ± 2.03^{aA}	46.34 ± 0.56^{aB}	44.77 ± 1.29^{bA}
P-values					
EC		0.001	0.017	0.019	<.001
V		<.001	0.007	<.001	<.001
EC × V		0.011	0.046	0.038	0.029
CV%		2.3	5	2.7	2.3

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD (p<0.05). EC= electrical conductivity.

4.3.6 Water use efficiency (WUE), total water uptake (TWU), and trends in water uptake

Total water use uptake was significantly (p<0.05) influenced by EC modulation in the two tomato varieties as shown in Table 7, in experiments 1 and 2. The total water uptake in the Anna variety ranged from 5.9 to 6.39 L/plant, higher than the Jaguar variety. Both varieties exhibited the highest water uptake in the H modulation compared to the other modulations.

WUE significantly varied (p<0.05) in the Anna and Jaguar varieties under EC modulation

(Table 7). Notably, the WUE was higher in Jaguar across all treatments than in Anna. The Jaguar variety recorded 0.093 L kg^{-1} higher water use efficiency WUE than the Anna variety under the LH treatment. In Anna, the LH treatment demonstrated the highest WUE (0.041 L kg^{-1}) compared to the H and HL treatments, which showed the lowest WUE (0.026 and 0.030 L kg^{-1}, respectively).

The trends in water uptake among the two varieties were comparable for the EC modulations (Figure 4). The low (L) treatment exhibited the least uptake characteristics relative to the other treatments. In the Jaguar variety, a gradual divergence in uptake characteristics was noted among the treatments within 23 DAT, while a similar trend was observed in the Anna variety within 15 DAT. Among the treatments, the highest water uptake trend was consistently observed in the H modulation for both varieties. In experiment 2, the two varieties showed a notable increase in water uptake across the treatments between 32 and 40 DAT.

Table 7. effect of EC modulation on water us efficiency and total water uptake of two tomato varieties

		Experiment 1		**Experiment 2**	
EC modulation	**Variety**	**WUE (kg L^{-1})**	**TWU (L)**	**WUE (kg L^{-1})**	**TWU (L)**
H	**Anna**	$0.023±0.0005^{bA}$	$27.78±0.12^{aA}$	$0.026±0.001^{bC}$	$28.25±0.05^{aA}$
HL		$0.028±0.0002^{aA}$	$22.70±0.18^{aB}$	$0.030±0.0005^{bC}$	$23.24±0.17^{aB}$
L		$0.032±0.0007^{bA}$	$19.06±0.08^{aC}$	$0.035±0.0004^{bB}$	$19.78±0.12^{aC}$
LH		$0.024±0.001^{bA}$	$22.64±0.07^{aB}$	$0.041±0.0005^{bA}$	$17.70±0.17^{bD}$
H	**Jaguar**	$0.073±0.0069^{aB}$	$21.39±0.29^{bA}$	$0.075±0.001^{aA}$	$21.36±0.33^{bA}$
HL		$0.030±0.0017^{aC}$	$19.56±0.29^{bB}$	$0.038±0.003^{aC}$	$17.12±0.23^{bC}$
L		$0.066±0.0016^{aB}$	$13.14±0.03^{bC}$	$0.064±0.001^{aB}$	$15.67±0.32^{bD}$
LH		$0.117±0.0048^{aA}$	$13.14±0.09^{bC}$	$0.064±0.003^{aB}$	$19.44±0.31^{aB}$
P-values					
EC		<.001	<.001	<.001	<.001
V		<.001	<.001	<.001	<.001
EC × V		<.001	<.001	<.001	<.001
CV%		5.9	1.5	5.8	1.9

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$). EC= electrical conductivity. WUE= water use efficiency. TWU= total water use.

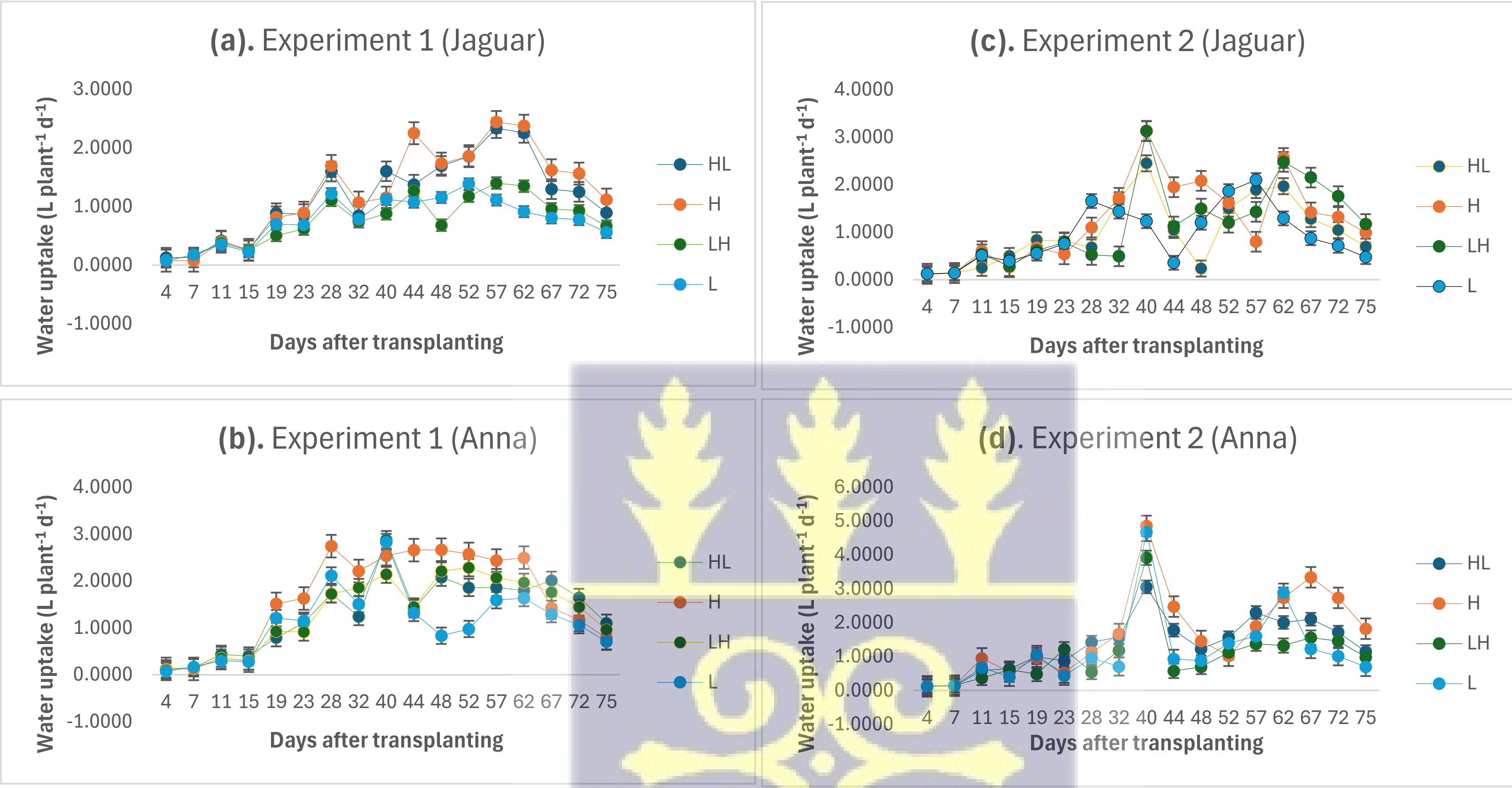

Figure 4. Influence of EC modulation on water uptake in Jaguar (a, c) and Anna (b, d) tomato varieties in two experiments

4.4 Yield and Yield Components

As shown in Table 8, electrical conductivity modulation significantly ($p < 0.05$) influenced both the number of fruits per plant and the yield of the two tomato varieties in Experiments 1 and 2. The Jaguar variety recorded the lowest number of fruits per plant (6.3) when subjected to LH modulation, while other treatments within the same variety, including the Anna, recorded between 7.3 and10 fruits per plant in experiment one and two respectively. Modulation of EC did not affect fruit number per plant in the Anna variety. In the Jaguar variety, LH modulation significantly reduced the number of fruits per plant by 18.2% compared to other treatments, which recorded between 9.7 and 7.3 fruits per plant in L modulation in both experiments.

The yield of the two varieties varied significantly ($p < 0.05$) with EC modulation in both experiments. In the Jaguar variety, higher yields ranging from 3602.2 to 6706.0 kg m^{-2} were achieved with the H, HL, and L treatments, significantly surpassing the 2275.8 to 3083 kg m^{-2} obtained from the same treatments in the Anna variety. The highest yield, consistently ranging from 6110 to 6706 kg m^{-2}, was achieved with the H treatment in the Jaguar variety, outperforming the other treatments. The highest yield, consistently ranging from 6110 to 6706 kg m^{-2}, was achieved with the H treatment in the Jaguar variety, while the yield of the Anna variety showed no variation with EC modulation.

Table 8. Effect of EC modulation on fruit number and yield of two tomato varieties

		Experiment 1		
EC modulation	**Variety**	**Fruit number $plant^{-1}$**	**Yield (g $plant^{-1}$)**	**Yield (g m^{-2})**
H	**Anna**	8.3±0.33^{aA}	648.30±13.8^{bA}	2679.9±57.5^{bA}
HL		8.0±0.00^{aA}	644.03±5.18^{bA}	2683±5.18^{bA}
L		7.3±0.33^{aA}	546.30±23.3^{bA}	2275.8±97^{bA}
LH		8.0±0.00^{aA}	607.50±13.3^{aA}	2530.7±55.2^{aA}
H	**Jaguar**	8.0±0.58^{aA}	1547.00±127^{aA}	6110±200^{aA}
HL		8.0±0.00^{aA}	1539.70±54.1^{aA}	6415±225^{aA}
L		7.3±0.33^{aA}	864.70±16.6^{aB}	3602.2±69.1^{aB}
LH		6.3±0.33^{bB}	592.40±38^{aC}	2468±158^{aC}
P-values				
EC		0.001	<.001	<.001
V		0.007	<.001	<.001
EC × V		0.006	<.001	<.001
CV%		7	6.3	6.3

Experiment 2

EC modulation	Variety	Fruit nuer/plant	Yield (g/plant)	Yield (g/m^2)
H		10.0±0.00^{aA}	740.00±28.1^{bA}	3083.0±117^{bA}
HL		9.3±0.33^{aA}	687.20±5.99^{bA}	2862.9±25^{bA}
L	**Anna**	8.7±0.33^{aA}	722.20±12.9^{bA}	3008.5±53.5^{bA}
LH		9.3±0.33^{aA}	695.87±9.48^{aA}	2899.0±39.5^{aA}
H		8.7±0.33^{bB}	1609.80±49.9^{aA}	6706.0±208^{aA}
HL		8.0±0.58^{bB}	1240.20±61.5^{aB}	5167.0±256^{aB}
L	**Jaguar**	9.7±0.33^{aA}	997.00±13.3^{aC}	4153.6±55.3^{aC}
LH		7.7±0.33^{bB}	651.00±49.4^{aD}	2712±206^{aD}
P-values				
EC		0.086	<.001	<.001
V		0.004	<.001	<.001
EC × V		0.006	<.001	<.001
CV%		6.8	6.6	6.6

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$). EC= electrical conductivity modulation.

4.5 Fruit Quality

4.5.1 Lycopene content

Electrical conductivity modulation significantly ($p<0.05$) influenced lycopene content in both tomato varieties, as shown in Figures 5a and 5b. Treatments H and HL resulted in higher lycopene content of 34.53 to 35.57 mg kg^{-1} in the Anna variety, compared to 30.57 to 31.23 mg kg^{-1} in the Jaguar variety. Lycopene content did not vary markedly in the Jaguar variety; however, the H, HL, and LH treatments significantly increased lycopene content in the Anna variety during Experiment 1. In Experiment 2, the HL treatment yielded the highest lycopene content of 35.5 mg kg^{-1} in the Anna variety, while the same treatment resulted in a lower content of 31.98 mg kg^{-1} in the Jaguar variety. The L treatment consistently recorded the lowest lycopene content in both varieties.

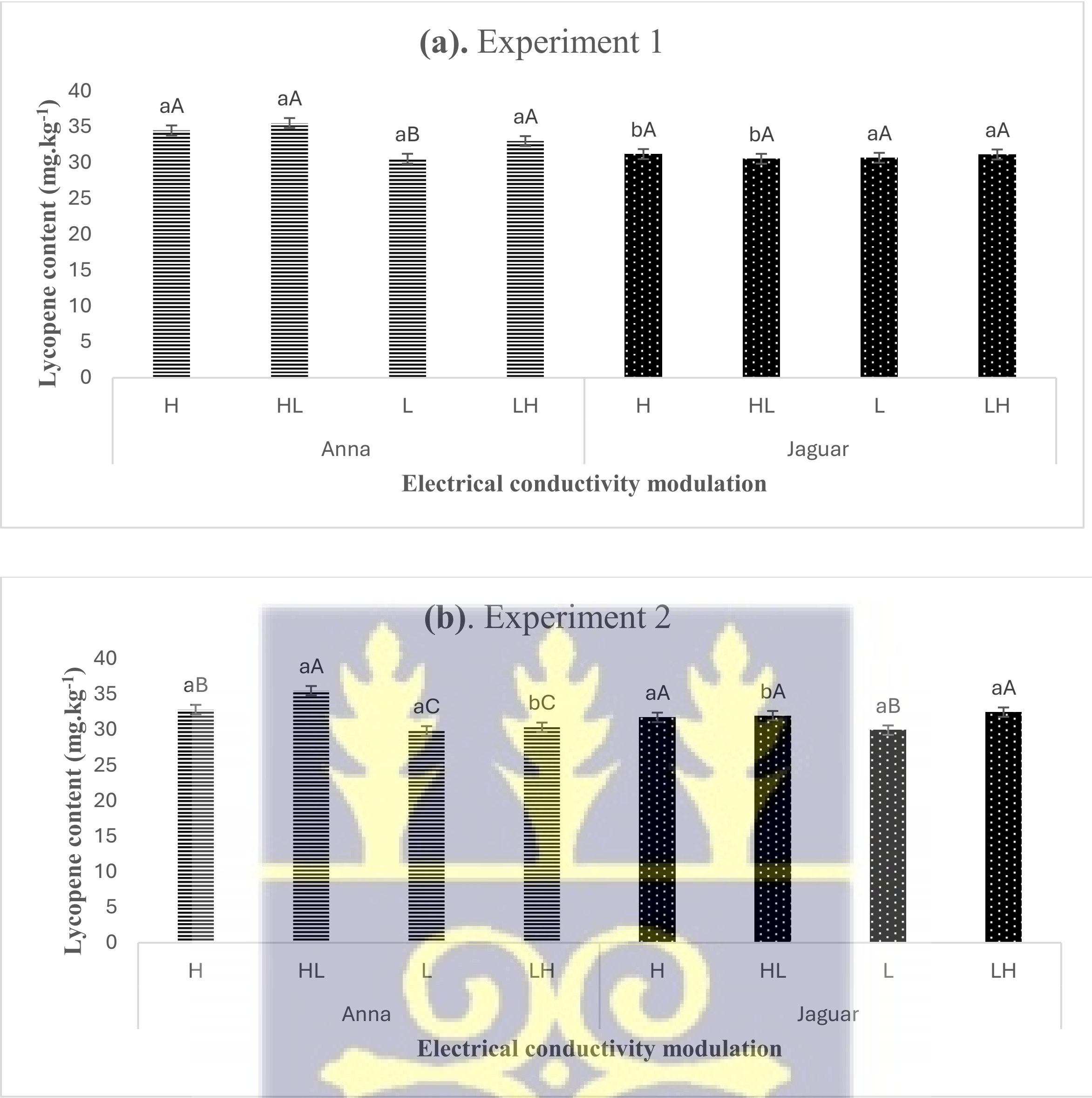

Figure 5: Effect of electrical conductivity modulation on lycopene content of two tomato varieties

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$).

4.5.2 Vitamin C

As shown in Figure 6, electrical conductivity modulation significantly ($p < 0.05$) influenced vitamin C content, with the Anna variety achieving the highest levels of 23.78 and 23.97 mg/100g in both experiments under the HL treatment. In contrast, the Jaguar variety showed lower vitamin C content, measuring 18.36 and 15.84 mg/100g under the same treatment conditions. Both varieties demonstrated a consistent reduction in vitamin C content when subjected to the H treatment in comparison to the other treatments.

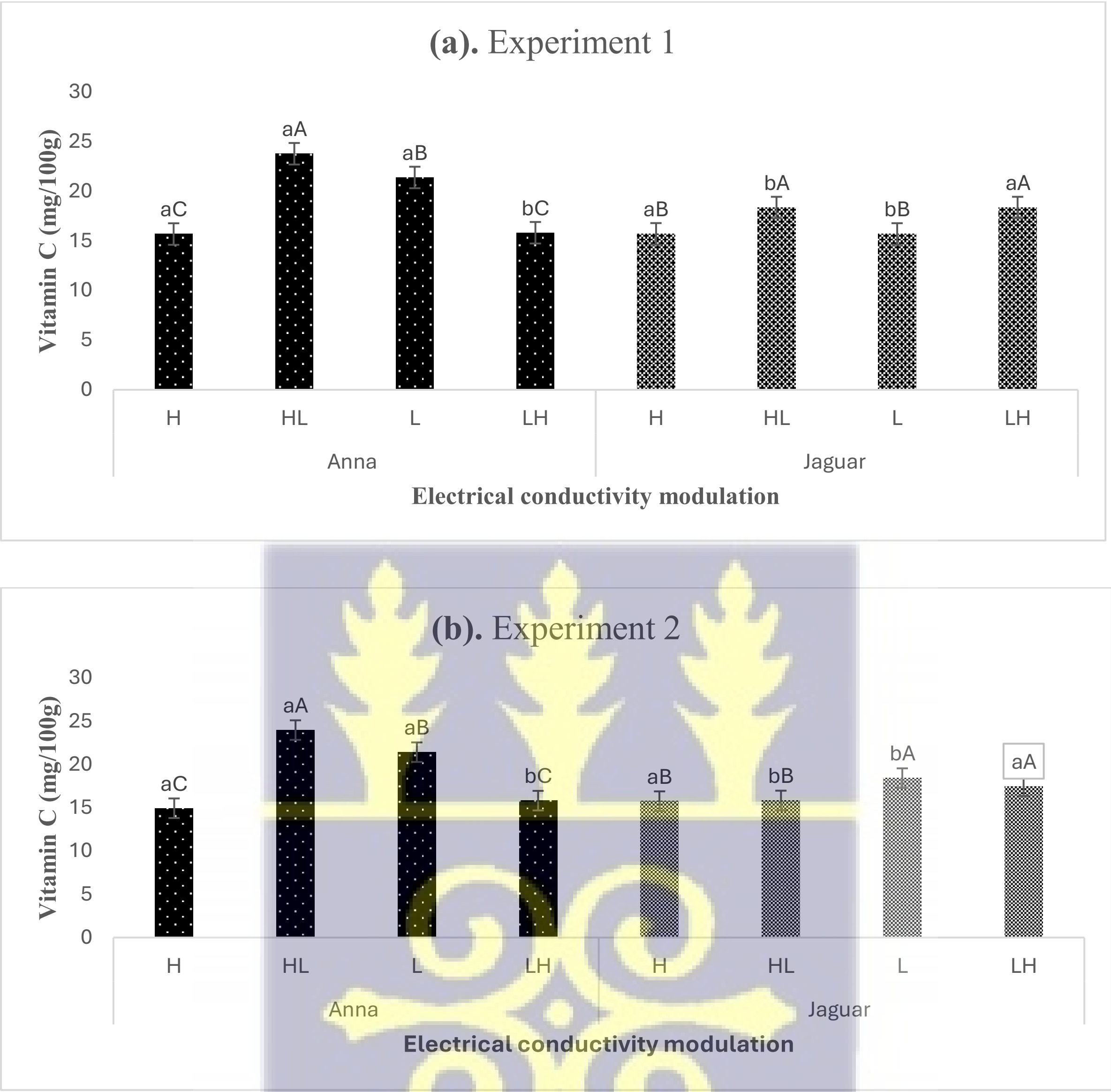

Figure 6: Impact of electrical conductivity modulation on vitamin C content in tomato varieties
Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$)

4.5.3 Total soluble solids/sugar content (%Brix)

In the two experiments, EC modulation significantly affected the sugar content of both varieties ($p < 0.05$). The LH treatment notably increased the sugar content in the Anna variety, which significantly, was higher than that observed in the Jaguar variety under the same treatment. (Table 9). In Experiments 1 and 2, the Anna variety exhibited a reduced sugar content under the L treatment compared to the other EC levels. In the Jaguar variety, sugar content was highest in the H treatment, ranging from 6.19 to 6.24 %Brix, while the L treatment recorded the lowest levels, between 3.78 and 3.81 %Brix.

Table 9. Effect of electrical conductivity modulation on %Brix of two tomato varieties

EC modulation	Variety	Experiment 1	Experiment 2
H	**Anna**	6.94 ± 0.03^{aB}	7.22 ± 0.05^{aB}
HL		6.94 ± 0.04^{aB}	6.28 ± 0.06^{aC}
L		4.74 ± 0.03^{aC}	6.14 ± 0.03^{aD}
LH		7.72 ± 0.01^{aA}	7.69 ± 0.01^{aA}
H	**Jaguar**	6.19 ± 0.02^{bA}	6.24 ± 0.01^{bA}
HL		5.93 ± 0.04^{bB}	4.11 ± 0.02^{bC}
L		3.81 ± 0.04^{bD}	3.78 ± 0.06^{bD}
LH		5.71 ± 0.03^{bC}	5.46 ± 0.03^{bB}
P-values			
EC		<.001	<.001
V		<.001	<.001
EC × V		<.001	<.001
CV%		1.5	1.7

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$).

4.5.4 Fruit pH

Electrical conductivity modulation significantly ($p<0.05$) impacted the pH of the two tomato varieties (Table 10). In the Anna cultivar, treatment H resulted in a higher pH of 4.77, compared to 4.6 in the Jaguar. Conversely, in the Jaguar variety, treatment LH produced a higher pH of 4.47 than the 4.33 recorded for the Anna variety (Experiment 1). Treatment H in the Anna variety showed the highest pH compared to the other treatments. Additionally, in the Jaguar variety, treatment H again exhibited the highest pH compared to the other treatments. In Experiment 2, the two tomato varieties exhibited no significant ($p<0.05$) variation with EC modulation.

Table 10: Influence of electrical conductivity modulation on pH of two tomato varieties

		Experiment 1	Experiment 2
EC modulation	Variety	pH	pH
H	**Anna**	4.77 ± 0.07^{aA}	4.33 ± 0.03^{aA}
HL		4.33 ± 0.03^{aB}	4.30 ± 0.0^{aA}
L		4.30 ± 0.0^{aB}	4.27 ± 0.09^{aA}
LH		4.33 ± 0.03^{bB}	4.30 ± 0.0^{aA}
H	**Jaguar**	4.60 ± 0.06^{bA}	4.37 ± 0.03^{aA}
HL		4.43 ± 0.03^{aB}	4.23 ± 0.03^{aA}
L		4.33 ± 0.03^{aB}	4.30 ± 0.0^{aA}
LH		4.47 ± 0.03^{aB}	4.33 ± 0.09^{aA}
P-values			
EC		<.001	0.414
V		0.362	0.823
EC × V		0.006	0.710
CV%		1.5	2.1

Lowercase letters Compare EC between varieties. Uppercase letters compare EC within a Variety. Means followed by the same alphabet are not significantly different according to Tukey HSD ($p<0.05$).

CHAPTER FIVE

DISCUSSION

5.0 Effect of electrical conductivity modulation on the morphological characteristics of tomato varieties

5.1.1 Plant height

The modulation of electrical conductivity significantly influenced the plant height of the Anna variety, leading to an increase of 30.3% to 38.1% compared to the Jaguar variety. This finding suggests that different tomato varieties respond distinctly to changes in electrical conductivity due to inherent varietal attributes, as also reported by Wortman *et al*. (2015) and De Freitas *et al.* (2017). The Anna variety exhibited a longer internode length, resulting in a taller plant height. Optimal EC levels promote resource use efficiency for enhanced growth and vigour. Sonneveld and Voogt (2009) reported similar findings, indicating that adjusting EC levels can enhance plant growth.

Notably, maintaining EC at high levels or modulating it from high to low significantly increased plant height in the Anna variety compared to other EC levels. Wu *et al*. (2008) found that higher EC levels during the reproductive period can enhance plant growth. Additionally, Heinen *et al*. (2001) confirmed that low EC levels may restrict nutrient availability, potentially hindering crop growth.

5.1.2 Leaf number

EC modulation had a significant impact on leaf production in both tomato varieties. The findings of Rosadi *et al*. (2014)a confirm that EC significantly influences the growth and development of hydroponically grown tomatoes. The Anna variety produced a significantly higher number of leaves compared to the Jaguar variety. The differential responses observed between the varieties suggest that the Anna variety possesses more efficient physiological mechanisms for the uptake and assimilation of water and nutrients under high EC conditions than the Jaguar variety.

Although the responses to EC modulation were inconsistent between the two varieties, a higher leaf number production in either variety was significantly influenced by maintaining EC at high strength. In contrast, Rosadi *et al.* (2014) reported that high EC reduced leaf number. This contrast may be attributed to the differences in cultivation systems and the EC levels used in the respective studies. Also, Ding *et al.* (2018) reported that both low and high EC levels had a negative impact on fresh leaf yield, which contradicts the findings of this study. Matsuda *et al*. (2012), in another vein, reported that high EC treatment was relatively mild and had no impact on the growth and development of the whole plant and its leaf characteristics. However, the results of this study indicate that high EC markedly increased leaf production in tomatoes.

5.1.3 Stem girth

The nutrient solutions provided in this cultivation system, whether maintained at a high electrical conductivity (EC) or modulated from high to low EC, led to a consistent increase in stem girth of 25.7% to 30.8% compared to other EC levels in both varieties. This implies that plants in this cultivation system benefit from a nutrient-rich environment, particularly during the vegetative stage, when they require abundant nutrients from high EC to develop thicker stems. This observation is supported by the findings of Lu *et al*. (2022), which indicates that High usually increase plant growth. High or fluctuating EC levels are effective for promoting increased plant girth growth, as noted by Beyl and Trigiano (2016), who reported that optimal EC levels enhance this aspect of growth.

5.2 Effect of electrical conductivity modulation on plant physiological growth indices of tomato varieties

5.2.1 Leaf area (LA)

Research has clearly pointed out to the importance of electric conductivity (EC) in nutrient solutions on plant growth, as well leaf area. Wu *et al*. (2008). A higher EC level can improve nutrient uptake, however if it is too high, then salt stress will occur. Anna had the maximum leaf area followed by Jaguar, which was partly due to more leaves in Anna (Table 4). The results show that, EC significantly affected the leaf area of the tomato varieties. Plants exposed to high to low EC conditions exhibited the largest leaf area in both varieties. This phenomenon can be attributed to the interplay of nutrient availability and adaptive growth responses. Initially, the high EC environment offers a rich supply of essential nutrients, which stimulates robust plant growth. As the EC conditions transition from high to low, the plants may respond by optimizing nutrient uptake and adjusting their growth strategies. A reduction in electrical conductivity (EC) may prompt plants to optimize their leaf expansion as a strategic adaptation to changing environmental conditions. This is consistent with the findings of Li and

Stanghellini (2001), which demonstrated that lower EC levels can result in an 8% increase in leaf area. Such adaptations not only enhance photosynthetic capacity but also improve the plant's ability to capture light and resources in a dynamic environment.

In the Anna variety, plants exposed to fluctuating EC conditions displayed maintained photosynthetic efficiency, indicating a downregulation of activity as a protective response to nutrient stress. This mechanism enables the Anna variety to balance energy production with resource allocation, ensuring survival in varying conditions. In contrast, the Jaguar variety exhibited an increase in photosynthetic efficiency between the vegetative and reproductive growth stages. These contrasting responses illustrate how different plant varieties can adapt to the same EC conditions based on their genetic and physiological characteristics.

5.2.2 Relative growth rate (RGR)

The Anna variety showed a 21.4% higher relative growth rate compared to the Jaguar variety, highlighting distinct varietal responses to EC modulation. This enhanced growth rate may be linked to the Anna variety's higher total water uptake, which is crucial for facilitating nutrient transport and supporting metabolic processes essential for growth. Higher EC levels, particularly those with high EC modulation, resulted in increased RGR compared to lower EC levels. All treatments with high EC demonstrated significantly higher total water uptake than the low EC treatment, thus accounting for the increased RGR. In the Anna variety, observations revealed that a decreased leaf area, coupled with a narrower stem girth, pointed to a diminished sink strength when subjected to low EC conditions. This reduction in both leaf and stem dimensions ultimately also accounts for the notable decline in the RGR.

The findings of this study are consistent with those of Signore *et al*. (2016) and Watanabe *et al*. (2022), who reported that high EC in the nutrient solution raises osmotic pressure surrounding plant roots. This raised osmotic pressure facilitates enhanced nutrient uptake, ultimately promoting better growth and an increased RGR. Excessively high EC levels can induce osmotic stress, adversely affecting both water absorption and nutrient uptake. Conversely, Méndez-Cifuentes *et al*. (2023) observed that lower EC levels can mitigate osmotic pressure, promoting more effective nutrient assimilation.

The Jaguar variety displayed a distinct response pattern, exhibiting a high RGR under low-high EC. This increase in RGR indicates the variety's ability to adapt to nutrient fluctuations.

5.2.3 Net assimilation rate (NAR)

In the Anna variety, the net assimilation rate (NAR) showed a notable increase under high EC conditions in comparison to both low and low-high EC levels. On the other hand, both the high EC and low-high EC modulation treatments reliably improved NAR when compared to other treated conditions in the Jaguar variety. When exposed to low-high or high EC conditions, the Jaguar variety exhibited a 45.9% to 48.4% greater increase in NAR compared to the Anna variety. The observed difference can be explained by the fact that the Anna variety underwent significantly higher physiological stress when exposed to both high and low-high EC conditions. In contrast, the Jaguar variety appears to be more able to adapt to these fluctuating EC environments. This suggests that the Anna variety may have a lower tolerance to changes in EC, leading to increased physiological stress compared to the more adaptable Jaguar variety.

5.3 Effect of electrical conductivity modulation on the physiological characteristics of tomato varieties

5.3.1 Photosynthetic efficiency

Maximum photosynthetic efficiency was observed with low-high EC modulation at 50 days after transplanting (DAT) in both varieties, followed by a sharp decline in efficiency thereafter. This initial peak can be explained by the low water and nutrient uptake during early plant growth, which supported adequate development. As growth progressed, the demand for water and nutrients increased. Modulating EC from low to high likely enhanced nutrient availability for plant utilization. However, the subsequent decline in photosynthetic efficiency may be linked to a physiological downregulation of photosynthetic activities due to the cessation of growth resulting from the pinching of the apical portion.

Tomato varieties exhibit differing levels of susceptibility to stress, as evidenced by the findings of Murchie *et al*. (2013) and Roșca *et al*. (2023). These studies highlight that genetic and phenotypic variations between varieties can significantly influence their responses to environmental stressors, such as high EC or nutrient availability. This variability underscores the importance of selecting appropriate varieties for specific growing conditions to optimize yield and overall plant health.

Although Shin *et al*. (2020) proposed that increasing EC correlates with a decrease in photosynthetic efficiency as an indicator of stress, it is important to recognize that reductions in photosynthetic efficiency may also reflect phenological growth attributes. As plants develop, their physiological and morphological characteristics change, which can influence their photosynthetic capacity.

5.3.2 Chlorophyll content

In the Jaguar variety, chlorophyll content decreased by 3.0-5.0% from the vegetative to reproductive growth stages, indicating a potential stress response and a shift in resource allocation as the plant transitions to reproduction. In contrast, the Anna variety exhibited a 6.0% increase in chlorophyll content during the same period, suggesting an enhanced capacity for photosynthesis and a more robust adaptation to reproductive demands. This divergence highlights the different physiological strategies employed by these varieties in response to developmental changes. In the Anna variety, chlorophyll production remained high under both high and low EC levels. Ding *et al.* (2018), established a divergent view that both very low and high EC depressed chlorophyll content and photosynthesis in tomatoes.

This finding contrasts with the study by Al-Gaadi *et al*. (2024), which demonstrated that high EC levels led to reductions in chlorophyll content, photosynthesis, and yield in hydroponically grown tomatoes. However, this perspective is supported by Lu *et al*. (2022), whose research indicated that increased EC levels during the reproductive stage enhanced chlorophyll content and improved fruit quality. This discrepancy highlights the complexity of plant responses to EC levels, suggesting that varietal differences and growth conditions may significantly influence outcomes.

5.3.3 Water use efficiency and total water uptake

The Anna variety exhibited a significantly greater water consumption than the Jaguar variety throughout the entire growth period. Specifically, the Anna variety utilised 17.3 - 27.1% more water than the Jaguar variety. This difference in water usage highlights the Anna variety's higher demand for water. However, the Jaguar variety demonstrated a remarkable ability to utilize water efficiently for fruit biomass production, significantly better than the Anna variety. This study found that the Jaguar variety is 45.2% to 62.6% more water-use efficient than the Anna variety. A larger portion of the water in the Anna variety may have been allocated to the production of non-harvestable biomass, such as larger stems and more leaves. According to the study by Dorais *et al*. (2001), it was demonstrated that EC modulation induces different responses in various tomato varieties.

High EC resulted in increased water uptake in the two varieties compared to other EC levels; however, the Anna variety was not water-use efficient under these conditions. The findings of this current study align with Méndez-Cifuentes *et al*. (2023), who reported that low EC decreased water uptake. However, EC modulation from high to low in the Jaguar reduced WUE significantly compared to the other treatments. This is partially in line with Heinen *et al*. (2002) who observed that low EC affected positively WUE in rockwool-grown tomatoes. Al Meselmani *et al*. (2022) also indicated that regulation of EC is important to enhance water uptake and reduce stress.

The water uptake trend displayed similarity between the two varieties throughout their phenological growth stages. Water uptake was low during the first 7 days after planting because the plants were still very small and young. Since smaller and younger plants have less biomass and fewer leaves, they require less water. After 19 days, the plants began to undergo important developmental changes, such as flower set. This stage marked a shift in the plant's water needs, increasing water uptake. The water uptake continued to rise during the fruit set and fruit development phases (from 28 DAT), as these stages require more resources, including water, for the growth and development of fruits.

5.4 Effect of electrical conductivity modulation on the yield of tomato varieties

5.4.1 Number of fruits and yield

In the Anna variety, the number of fruits per plant was 8% higher compared to the Jaguar variety, highlighting its potential for fruit production. However, the Jaguar variety demonstrated a significant yield advantage, producing between 36.7% and 45.3% higher yields than the Anna variety. This difference can be attributed to the larger fruit size in the Jaguar variety.

In the Anna variety, EC modulation did not affect fruit number or yield. This observation is consistent with the findings of Buck *et al*. (2008), who stated that specific varieties maintain a consistent number of fruits across different EC levels. However, in the Jaguar variety, fruit number decreased with low-to-high EC modulation, while the highest yield was obtained with high and high-to-low EC modulation. Results follow similar trends reported by Méndez-Cifuentes *et al.* (2023), who observed that increasing EC levels can enhance tomato yield.

The Anna variety exhibited notable stability in its tolerance to varying EC levels, which contributed to consistent yields. This observation agrees with Hernández-Pérez *et al*. (2020), who noted that certain tomato varieties are relatively insensitive to fluctuations in EC levels, maintaining steady yields across these variations.

5.5 Effect of electrical conductivity on the fruit quality of tomato varieties

5.5.1 Lycopene content

The lycopene content in the fruits from the Anna variety was 7.5% higher than that found in the Jaguar variety, indicating a significant nutritional superiority. When Anna plants were exposed to the high-low EC treatment, their fruits contained 14% more lycopene than those from Jaguar plants treated similarly. Under the high EC treatment, the lycopene content in Anna fruits was 9.6% higher than in Jaguar fruits, highlighting the impact of EC modulation on the nutritional composition of the fruit. In line with the findings of this study, Moya *et al*. (2017) demonstrated that higher EC enhanced lycopene content, resulting in an increase of 6.3% compared to lower EC conditions

Plants subjected to low EC conditions exhibited a decrease in fruit lycopene content in both the Anna and Jaguar varieties. This suggests that lower levels of EC may limit the availability of essential nutrients or affect metabolic processes involved in lycopene synthesis, leading to a reduction in its accumulation. The decrease in lycopene content under low EC conditions could be due to reduced nutrient uptake.

5.5.2 Vitamin C

Fruits harvested from Anna plants demonstrated a notable increase in vitamin C content, being 11.3% higher than those from Jaguar plants. This difference could stem from inherent genetic variations between the two varieties, as noted by Kwabena *et al*. (2019).

Furthermore, under high-low EC modulation conditions, the cultivation of Anna resulted in vitamin C levels in the fruits that were between 22.8% and 33.9% greater than those from Jaguar plants. Moya *et al*. (2017), conducted a study that revealed a notable increase of 8.8% in vitamin C levels when comparing fruit samples from plants grown in high EC to those in low EC.

5.5.3 Total soluble solids (TSS)- %Brix

Anna variety consistently had 17.8-28.4% higher sugar content in its fruits than the Jaguar variety, and this difference holds across all the EC levels. Anna's sugar content increased by 17.2% with low-high EC modulation, higher than recorded in the other EC levels. In contrast, the fruits produced by the Jaguar plants exhibited a significant increase in sugar content, showing a significant 22.8% higher when grown under high EC conditions than fruits harvested from the other EC levels. The work of Moya *et al*. (2017) further supports the findings of this study that high EC increases the sugar content (%Brix) of tomatoes. It is worth noting that the increases in the sugar content were more associated with high EC whereas, low EC significantly reduced sugar content in the two varieties.

5.5.4 fruit pH

The fruit pH increased significantly under high EC compared to the other treatments in both varieties. However, the Anna variety showed a slightly greater increase in pH, with a 3.6% higher pH than the Jagua variety. The findings of Solis-Toapanta *et al*. (2020) prove that EC levels have a significant impact on the pH of tomatoes.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

The two varieties, Anna and Jaguar did not respond in the same way to changes in EC, indicating that the two varieties have distinct tolerances and adaptations to varying EC conditions. These diverse responses of Anna and Jaguar to EC modulation highlight how different tomato varieties can exhibit unique adaptations, suggesting that other varieties may also show similar variations in EC modulation.

1. The study found that maintaining a high electrical conductivity or modulating EC from high to low significantly enhanced the growth of tomato plants.
2. Modulating electrical conductivity from low to high significantly enhanced the photosynthetic activity of tomato plants, while chlorophyll content increased at both high and low EC levels.
3. The Jaguar variety achieved the highest tomato yield with both high and high-to-low EC modulation. On the other hand, tomato yield in the Anna variety remained consistent across all EC levels.
4. The Jaguar variety exhibited increased water use efficiency when grown in low-to-high EC conditions. This improved efficiency may contribute to the sustainability of hydroponic systems, particularly in areas where water conservation is a critical consideration.

5. High-to-low EC modulation significantly enhanced the lycopene and vitamin C content in tomato fruits, whereas low-to-high EC modulation increased sugar content (% Brix).

This study demonstrates that the Anna variety exhibited greater stability under variable EC conditions and exhibited superior nutritional content. In contrast, the Jaguar variety demonstrated impressive water-use efficiency with considerable yield potential, under high EC conditions.

6.2 RECOMMENDATION

If the goal is to maximize nutritional value in terms of high levels of lycopene, vitamin C, and total soluble solids, Anna is recommended, as it showed improved fruit quality under higher EC conditions.

On the other hand, if the focus is on overall yield and WUE, where a stable and more efficient water management system is desired, Jaguar might be more suitable, as it demonstrated better WUE. Additionally, this variety is recommended for cultivation under low substrate volume conditions with a recirculating hydroponic system in regions with water scarcity.

It is recommended that this study be repeated to assess the performance of a broader range of tomato varieties and further explore their responses to EC modulation.

The work should also be repeated using a containerized root restricted condition.

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APPENDIX

Appendix 1: ANOVA of Plant Height at Vegetative Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	4.242	2.121	1.46	
Electrical Conductivity	3	570.798	190.266	131.32	<.001
Variety	1	68.851	68.851	47.52	<.001
Electrical Conductivity*Variety	3	126.329	42.110	29.06	<.001
Residual	14	20.285	1.449		
Total	23	790.505			

Appendix 2: ANOVA of Plant Height at Reproductive Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	23.235	11.617	4.02	
Electrical Conductivity	3	268.398	89.466	30.99	<.001
Variety	1	17607.417	17607.417	6098.55	<.001
Electrical Conductivity*Variety	3	2234.379	744.793	257.97	<.001
Residual	14	40.420	2.887		
Total	23	20173.849			

Appendix 3: ANOVA of Plant Height at Vegetative Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.2198	0.1099	0.13	
Electrical Conductivity	3	35.1922	11.7307	14.26	<.001
Variety	1	793.1550	793.1550	964.32	<.001
Electrical Conductivity*Variety	3	28.4919	9.4973	11.55	<.001
Residual	14	11.5150	0.8225		
Total	23	868.5740			

Appendix 4: ANOVA of Plant Height at Reproductive Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	4.981	2.490	1.06	
Electrical Conductivity	3	268.398	89.466	30.99	<.001
Variety	1	13241.313	13241.313	5611.44	<.001
Electrical Conductivity*Variety	3	1246.833	415.611	176.13	<.001
Residual	14	33.036	2.360		
Total	23	14915.716			

Appendix 5: ANOVA of Number of Leave at Vegetative Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	1.0806	0.5403	5.08	
Electrical Conductivity	3	4.7578	1.5859	14.91	<.001
Variety	1	2.5026	2.5026	23.52	<.001
Electrical Conductivity*Variety	3	2.2786	0.7595	7.14	0.004
Residual	14	1.4894	0.1064		
Total	23	12.1091			

Appendix 6: ANOVA of Number of Leaves at Reproductive Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	1.3493	0.6747	0.96	
Electrical Conductivity	3	17.7746	5.9249	8.45	0.002
Variety	1	110.8110	110.8110	158.03	<.001
Electrical Conductivity*Variety	3	4.0113	1.3371	1.91	0.175
Residual	14	9.8170	0.7012		
Total	23	143.7633			

Appendix 7: ANOVA of Number of Leave at Vegetative Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.06396	0.03198	0.44	
Electrical Conductivity	3	1.37792	0.45931	6.29	0.006
Variety	1	9.62667	9.62667	131.78	<.001
Electrical Conductivity*Variety	3	0.16333	0.05444	0.75	0.543
Residual	14	1.02271	0.07305		
Total	23	12.25458			

Appendix 8: ANOVA of Number of Leaves at Reproductive Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	2.787	1.394	1.38	
Electrical Conductivity	3	38.055	12.685	12.56	<.001
Variety	1	146.768	146.768	145.30	<.001
Electrical Conductivity*Variety	3	21.482	7.161	7.09	0.004
Residual	14	14.141	1.010		
Total	23	223.233			

Appendix 9: ANOVA of Stem Girth at Vegetative Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.007708	0.003854	2.69	
Electrical Conductivity	3	0.016279	0.005426	3.79	0.035
Variety	1	0.000004	0.000004	0.00	0.958
Electrical Conductivity*Variety	3	0.001479	0.000493	0.34	0.793
Residual	14	0.020025	0.001430		
Total	23	0.045496			

Appendix 10: ANOVA of Stem Girth at Reproductive Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.005854	0.002927	1.47	
Electrical Conductivity	3	0.169769	0.056590	28.37	<.001
Variety	1	0.000002	0.000002	0.00	0.975
Electrical Conductivity*Variety	3	0.174436	0.058145	29.15	<.001
Residual	14	0.027925	0.001995		
Total	23	0.377987			

Appendix 11: ANOVA of Stem Girth at Vegetative Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.003508	0.001754	1.26	
Electrical Conductivity	3	0.020033	0.006678	4.81	0.017
Variety	1	0.000067	0.000067	0.05	0.830
Electrical Conductivity*Variety	3	0.001900	0.000633	0.46	0.717
Residual	14	0.019425	0.001387		
Total	23	0.044933			

Appendix 12: ANOVA of Stem Girth at Reproductive Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.0002333	0.0001167	0.37	
Electrical Conductivity	3	0.1366458	0.0455486	146.03	<.001
Variety	1	0.1276042	0.1276042	409.11	<.001
Electrical Conductivity*Variety	3	0.0643458	0.0214486	68.77	<.001
Residual	14	0.0043667	0.0003119		
Total	23	0.3331958			

Appendix 13: ANOVA of Leaf Area at Vegetative Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	9591.	4796.	0.25	
Electrical Conductivity	3	99644.	33215.	1.72	0.208
Variety	1	73643.	73643.	3.82	0.071
Electrical Conductivity*Variety	3	440840.	146947.	7.62	0.003
Residual	14	269878.	19277.		
Total	23	893597.			

Appendix 14: ANOVA of Leaf Area at Reproductive Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	26318.	13159.	1.77	
Electrical Conductivity	1	8790671.	8790671.	1185.58	<.001
Variety	3	6567141.	2189047.	295.23	<.001
Electrical Conductivity*Variety	3	4528497.	1509499.	203.58	<.001
Residual	14	103805.	7415.		
Total	23	20016432.			

Appendix 15: ANOVA of Leaf Area at Vegetative Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	7769.	3885.	0.28	
Electrical Conductivity	3	404299.	134766.	9.78	<.001
Variety	1	83861.	83861.	6.09	0.027
Electrical Conductivity*Variety	3	92715.	30905.	2.24	0.128
Residual	14	192874.	13777.		
Total	23	781518.			

Appendix 16: ANOVA of Leaf Area at Reproductive Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	8405.	4202.	0.68	
Electrical Conductivity	1	7290525.	7290525.	1171.70	<.001
Variety	3	5102629.	1700876.	273.36	<.001
Electrical Conductivity*Variety	3	3735055.	1245018.	200.09	<.001
Residual	14	87111.	6222.		
Total	23	16223725.			

Appendix 17: ANOVA of Relative Growth Rate (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	2.932E-06	1.466E-06	0.58	
Electrical Conductivity	3	1.108E-05	3.694E-06	1.47	0.266
Variety	1	2.991E-05	2.991E-05	11.89	0.004
Electrical Conductivity*Variety	3	4.446E-05	1.482E-05	5.89	0.008
Residual	14	3.523E-05	2.516E-06		
Total	23	1.236E-04			

Appendix 18: ANOVA of Relative Growth Rate (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	4.194E-06	2.097E-06	1.09	
Electrical Conductivity	3	5.289E-05	1.763E-05	9.19	0.001
Variety	1	1.961E-06	1.961E-06	1.02	0.329
Electrical Conductivity*Variety	3	4.786E-05	1.595E-05	8.32	0.002
Residual	14	2.686E-05	1.918E-06		
Total	23	1.338E-04			

Appendix 19: ANOVA of Net Assimilation Rate (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.003118	0.001559	0.55	
Electrical Conductivity	3	0.022048	0.007349	2.58	0.095
Variety	1	0.010361	0.010361	3.64	0.077
Electrical Conductivity*Variety	3	0.028719	0.009573	3.36	0.049
Residual	14	0.039904	0.002850		
Total	23	0.104150			

Appendix 20: ANOVA of Net Assimilation Rate (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.005108	0.002554	1.78	
Electrical Conductivity	3	0.099753	0.033251	23.23	<.001
Variety	1	0.097360	0.097360	68.01	<.001
Electrical Conductivity*Variety	3	0.078604	0.026201	18.30	<.001
Residual	14	0.020043	0.001432		
Total	23	0.300867			

Appendix 21: ANOVA of Chlorophyll Fluorescence at 14 Days After Transplanting (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.00020833	0.00010417	2.22	
Electrical Conductivity	3	0.00010000	0.00003333	0.71	0.563
Variety	1	0.00001667	0.00001667	0.35	0.561
Electrical Conductivity*Variety	3	0.00015000	0.00005000	1.06	0.396
Residual	14	0.00065833	0.00004702		
Total	23	0.00113333			

Appendix 22: ANOVA of Chlorophyll Fluorescence at 14 Days After Transplanting (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.00005833	0.00002917	0.51	
Electrical Conductivity	3	0.00050000	0.00016667	2.89	0.073
Variety	1	0.00006667	0.00006667	1.15	0.301
Electrical Conductivity*Variety	3	0.00050000	0.00016667	2.89	0.073
Residual	14	0.00080833	0.00005774		
Total	23	0.00193333			

Appendix 21: ANOVA of Chlorophyll Fluorescence at 50 Days After Transplanting (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.00010433	0.00005217	3.05	
Electrical Conductivity	3	0.00221936	0.00073979	43.21	<.001
Variety	1	0.00243997	0.00243997	142.53	<.001
Electrical Conductivity*Variety	3	0.00111861	0.00037287	21.78	<.001
Residual	14	0.00023967	0.00001712		
Total	23	0.00612194			

Appendix 22: ANOVA of Chlorophyll Fluorescence at 50 Days After Transplanting (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.00011858	0.00005929	3.38	
Electrical Conductivity	3	0.00222732	0.00074244	42.30	<.001
Variety	1	0.00245795	0.00245795	140.02	<.001
Electrical Conductivity*Variety	3	0.00111856	0.00037285	21.24	<.001
Residual	14	0.00024575	0.00001755		
Total	23	0.00616816			

Appendix 21: ANOVA of Chlorophyll Fluorescence at 75 Days After Transplanting (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.0003583	0.0001792	1.31	
Electrical Conductivity	3	0.0059458	0.0019819	14.54	<.001
Variety	1	0.0009375	0.0009375	6.88	0.020
Electrical Conductivity*Variety	3	0.0078458	0.0026153	19.19	<.001
Residual	14	0.0019083	0.0001363		
Total	23	0.0169958			

Appendix 22: ANOVA of Chlorophyll Fluorescence at 75 Days After Transplanting (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.0004083	0.0002042	1.27	
Electrical Conductivity	3	0.0004792	0.0001597	0.99	0.426
Variety	1	0.0009375	0.0009375	5.81	0.030
Electrical Conductivity*Variety	3	0.0063125	0.0021042	13.04	<.001
Residual	14	0.0022583	0.0001613		
Total	23	0.0103958			

Appendix 23: ANOVA of Chlorophyll Content at Vegetative Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	4.164	2.082	2.03	
Electrical Conductivity	3	28.161	9.387	9.15	0.001
Variety	1	38.608	38.608	37.64	<.001
Electrical Conductivity*Variety	3	16.848	5.616	5.48	0.011
Residual	14	14.359	1.026		
Total	23	102.141			

Appendix 24: ANOVA of Chlorophyll Content at Reproductive Stage (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	38.943	19.472	4.06	
Electrical Conductivity	3	68.606	22.869	4.76	0.017
Variety	1	47.377	47.377	9.87	0.007
Electrical Conductivity*Variety	3	49.654	16.551	3.45	0.046
Residual	14	67.220	4.801		
Total	23	271.800			

Appendix 25: ANOVA of Chlorophyll Content at Vegetative Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	11.196	5.598	3.72	
Electrical Conductivity	3	8.216	2.739	1.82	0.019
Variety	1	33.915	33.915	22.52	<.001
Electrical Conductivity*Variety	3	4.885	1.628	1.08	0.038
Residual	14	21.081	1.506		
Total	23	79.293			

Appendix 26: ANOVA of Chlorophyll Content at Reproductive Stage (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.085	0.042	0.04	
Electrical Conductivity	3	35.266	11.755	10.00	<.001
Variety	1	23.399	23.399	19.91	<.001
Electrical Conductivity*Variety	3	14.256	4.752	4.04	0.029
Residual	14	16.452	1.175		
Total	23	89.457			

Appendix 27: ANOVA of Water Use Efficiency (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.002217	0.001109	0.35	
Electrical Conductivity	3	0.514819	0.171606	54.02	<.001
Variety	1	1.192111	1.192111	375.25	<.001
Electrical Conductivity*Variety	3	0.646611	0.215537	67.85	<.001
Residual	14	0.044476	0.003177		
Total	23	2.400235			

Appendix 28: ANOVA of Water Use Efficiency (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.0007697	0.0003849	0.48	
Electrical Conductivity	3	0.1326587	0.0442196	55.51	<.001
Variety	1	0.4459415	0.4459415	559.80	<.001
Electrical Conductivity*Variety	3	0.1278328	0.0426109	53.49	<.001
Residual	14	0.0111525	0.0007966		
Total	23	0.7183552			

Appendix 29: ANOVA of Total Water Uptake (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.0163	0.0082	0.08	
Electrical Conductivity	3	251.4459	83.8153	803.45	<.001
Variety	1	233.5191	233.5191	2238.52	<.001
Electrical Conductivity*Variety	3	30.5032	10.1677	97.47	<.001
Residual	14	1.4605	0.1043		
Total	23	516.9450			

Appendix 30: ANOVA of Total Water Uptake (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.1591	0.0795	0.45	
Electrical Conductivity	3	179.6269	59.8756	340.47	<.001
Variety	1	88.7695	88.7695	504.76	<.001
Electrical Conductivity*Variety	3	68.6743	22.8914	130.17	<.001
Residual	14	2.4621	0.1759		
Total	23	339.6919			

Appendix 31: ANOVA of Number of Fruits per Plant (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	2.5833	1.2917	8.68	
Electrical Conductivity	3	4.3333	1.4444	9.71	0.001
Variety	1	1.5000	1.5000	10.08	0.007
Electrical Conductivity*Variety	3	2.8333	0.9444	6.35	0.006
Residual	14	2.0833	0.1488		
Total	23	13.3333			

Appendix 32: ANOVA of Number of Fruits per Plant (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	1.0833	0.5417	1.54	
Electrical Conductivity	3	2.8333	0.9444	2.69	0.086
Variety	1	4.1667	4.1667	11.86	0.004
Electrical Conductivity*Variety	3	6.8333	2.2778	6.49	0.006
Residual	14	4.9167	0.3512		
Total	23	19.8333			

Appendix 33: ANOVA of Fruits Weight per Plant (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	14688.	7344.	0.89	
Electrical Conductivity	3	1198894.	399631.	48.31	<.001
Variety	1	1657567.	1657567.	200.37	<.001
Electrical Conductivity*Variety	3	922418.	307473.	37.17	<.001
Residual	14	115818.	8273.		
Total	23	3909384.			

Appendix 34: ANOVA of Fruits Weight per Plant (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	7154.	3577.	0.95	
Electrical Conductivity	3	787747.	262582.	69.84	<.001
Variety	1	1024364.	1024364.	272.44	<.001
Electrical Conductivity*Variety	3	685378.	228459.	60.76	<.001
Residual	14	52639.	3760.		
Total	23	2557282.			

Appendix 35: ANOVA of Yield per Square Meter (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	49631.	24815.	0.45	
Electrical Conductivity	3	19083508.	6361169.	115.47	<.001
Variety	1	26619986.	26619986.	483.21	<.001
Electrical Conductivity*Variety	3	14560259.	4853420.	88.10	<.001
Residual	14	771259.	55090.		
Total	23	61084643.			

Appendix 36: ANOVA of Yield per Square Meter (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	124155.	62078.	0.95	
Electrical Conductivity	3	13671795.	4557265.	69.84	<.001
Variety	1	17778409.	17778409.	272.44	<.001
Electrical Conductivity*Variety	3	11895112.	3965037.	60.76	<.001
Residual	14	913583.	65256.		
Total	23	44383053.			

Appendix 37: ANOVA of Lycopene Content (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.691	0.345	0.16	
Electrical Conductivity	3	186.700	62.233	27.96	<.001
Variety	1	2.491	2.491	1.12	0.308
Electrical Conductivity*Variety	3	225.616	75.205	33.79	<.001
Residual	14	31.156	2.225		
Total	23	446.654			

Appendix 38: ANOVA of Lycopene Content (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	7.6480	3.8240	5.09	
Electrical Conductivity	3	57.2777	19.0926	25.43	<.001
Variety	1	1.7395	1.7395	2.32	0.150
Electrical Conductivity*Variety	3	41.3064	13.7688	18.34	<.001
Residual	14	10.5128	0.7509		
Total	23	118.4844			

Appendix 39: ANOVA of Vitamin C (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.5722	0.2861	0.39	
Electrical Conductivity	3	385.5354	128.5118	174.95	<.001
Variety	1	271.0218	271.0218	368.95	<.001
Electrical Conductivity*Variety	3	294.6048	98.2016	133.68	<.001
Residual	14	10.2842	0.7346		
Total	23	962.0183			

Appendix 40: ANOVA of Vitamin C (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	2.7650	1.3825	1.61	
Electrical Conductivity	3	30.7387	10.2462	11.95	<.001
Variety	1	34.0077	34.0077	39.65	<.001
Electrical Conductivity*Variety	3	10.0582	3.3527	3.91	0.032
Residual	14	12.0079	0.8577		
Total	23	89.5775			

Appendix 41: ANOVA of Total Soluble Solids/Square Content (%Brix) (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.011944	0.005972	2.22	
Electrical Conductivity	3	6.987037	2.329012	865.23	<.001
Variety	1	8.322963	8.322963	3091.97	<.001
Electrical Conductivity*Variety	3	18.413704	6.137901	2280.22	<.001
Residual	14	0.037685	0.002692		
Total	23	33.773333			

Appendix 42: ANOVA of Total Soluble Solids/Square Content (%Brix) (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.002500	0.001250	0.28	
Electrical Conductivity	3	179.6269	59.8756	340.47	<.001
Variety	1	22.555741	22.555741	4978.73	<.001
Electrical Conductivity*Variety	3	7.522407	2.507469	553.47	<.001
Residual	14	0.063426	0.004530		
Total	23	39.577778			

Appendix 43: ANOVA of Fruit pH (Experiment 1)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.020833	0.010417	2.46	
Electrical Conductivity	3	0.474583	0.158194	37.43	<.001
Variety	1	0.003750	0.003750	0.89	0.362
Electrical Conductivity*Variety	3	0.081250	0.027083	6.41	0.006
Residual	14	0.059167	0.004226		
Total	23	0.639583			

Appendix 44: ANOVA of Fruit pH (Experiment 2)

Source of variation	Degree of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Replication	2	0.000833	0.000417	0.05	
Electrical Conductivity	3	0.024583	0.008194	1.02	0.414
Variety	1	0.000417	0.000417	0.05	0.823
Electrical Conductivity*Variety	3	0.011250	0.003750	0.47	0.710
Residual	14	0.112500	0.008036		
Total	23	0.149583			