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Sustainable Agriculture through Small-Scale Hydroponics and Enhanced Nutrient Management

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Abstract: This study recognises hydroponics as a valuable commercial technique for enhancing vegetable plant traits and tackles the problem of decreasing tomato yields in conventional agriculture caused by factors like adverse climate change, soil contamination, and lack of nutrients, which ultimately decreases plant growth as well as development. In this research tomato plants cultivated in a hydroponic system using three different nutrient methods (F-1, F-2, and F-3). The results showed that the F-2 nutrient solution significantly improved growth such as shoot length, root length, leaf count, stem girth, and the number of flowers and fruits compared to the other treatments. From the perspective of growing tomatoes, the research indicates that the F-2 nutrient formulation is the most effective for achieving better agronomic outcomes in hydroponic settings. Additionally, the study noted that excessively concentrated nutrient solutions caused stunted growth and reduced flowering and fruiting. In contrast, a properly balanced nutrient solution enhanced these traits, emphasizing the significance of electrical conductivity (EC), which represents the concentration of dissolved solids, as changes in EC affected the plants' agronomic characteristics.

Keywords: Hydroponics; Nutrients; Flowering; Sustainable Agriculture; Climate Change

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Introduction

The rising demand for fresh, nutritious food coupled with increasing concerns over environmental degradation and resource scarcity has brought sustainable agriculture to the forefront of global priorities. Traditional farming methods, while essential, often rely heavily on land, water, and chemical inputs, posing significant challenges in regions facing urbanization, climate change, and declining soil fertility. Hydroponic is the technique to plant development using nutrient solutions which may or may not include the use of an inert medium to provide mechanical support, such as rock wool, gravel, vermiculite, peat moss, sawdust, coir dust, coconut fibre, etc. (Sharma et al., 2018) Maharana and Koul (2011). The name hydroponics literally means "water work" and is derived from the Greek term's hydro, which means water and ponos, which means labour. Early in the 1930s, Professor William Gericke came up with the term "hydroponics" to refer to the practice of growing plants with their roots suspended in water that contains mineral nutrients. In 1940, Purdue University researchers established the Nutri culture system. Commercial hydroponic farms were established in several countries during the 1960s and 1970s, including the Russian Federation, Arizona, Abu Dhabi, Belgium, California, and Japan. According to needs of various plants, the majority of hydroponic systems automatically regulate the amount of water, nutrients and photoperiod (Resh,2013). Rapid industrialisation and urbanisation are reducing the amount of arable land as well as traditional farming methods, which have a variety of detrimental effects on the environment .Techniques for producing enough food must change in order to feed the world's expanding population in a sustainable manner (Sharma et al. 2018).While arable land decreases and conventional agriculture harms the environment, floriculture struggles globally with soil-borne diseases, limited land, weather constraints, and labour demands (Devi et al., 2011; Dinesh et al., 2014). An alternate strategy for sustainable production and the preservation of rapidly dwindling land and water resources is to modify the growing medium. In the current environment, soilless cultivation

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may be effectively started and taken into consideration as a substitute for growing crops, vegetables, or other healthful food plants (Butler and Oebker, 2006). Soilless agriculture encompasses hydroponics, aquaculture, and aerobic agriculture. According to Macwan et al. (2020), soilless hydroponic systems are suitable for cultivating a diverse group of plants, such as fruiting, flowering, medicinal, and ornamental varieties. It can be used to cultivate a wide range of special and commercial crops, such as leafy vegetables, tomatoes, cucumbers, peppers, strawberries, and many more. The United States of America and the Asia-Pacific region are the next two largest producers of hydroponics, with France, the Netherlands, and Spain leading the way in Europe (Prakash et al., 2020). Kamenetsky and Okivi (2012) noted the successful use of hydroponics for cut flower production in the Netherlands. Murumkar et al. (2012) define hydroponics as the art and science of soilless crop cultivation, a technique that mitigates soil-related challenges common in traditional agriculture. The benefits of hydroponics when there is no adequate soil for agricultural cultivation or when the soil is contaminated with certain illnesses, crops can still be cultivated. There is a significant reduction in labour for many intercultural tasks including watering, fumigating, cultivating, tilling, and other procedures. The technique is economically viable in high-density and costly land locations since the maximum yield can be achieved. Water and fertilizers can be used effectively with this strategy because there is less possibility of the beneficial chemicals being lost; it can therefore result in less pollution of the land and streams. By implementing this approach, soil-borne plant diseases can be effectively eliminated. Using the system (i.e., timely nutrient feeding, watering, and root environment) and various types of greenhouses allows for more thorough environmental control. By utilizing a water and nutrient solution, hydroponic systems facilitate soilless plant growth, providing superior control over factors such as plant nutrition, lighting, humidity, and temperature, which translates to efficient space utilization, reduced chemical inputs, water and fertilizer conservation, and accelerated, weather-independent yields, especially where traditional farming is challenging (Khater et al.,2021);(Masa et al.,2020);(Maucieri et al.,2019);(Sambo et al.,2019).Plants are cultivated on soil in traditional agriculture. However, plants do not require soil to flourish; rather, they require the nutrients found in the soil (Dubey & Nain, 2020).

In traditional soil-based farming and planting, plants must expend a lot of energy developing their extensive root system because the roots must sift through the soil for minerals and water. In summary, whether they are growing in soil or not, plants require water and nutrients. These macronutrients and micronutrients are supplied directly to the plants in hydroponics, which is recommended by soilless farming. Meric et al., (2011) highlighted that soilless cultivation is commonly used to better regulate the growing environment, reducing uncertainties related to soil water and nutrient availability. It also addresses issues such as the build-up of salinity, pests, and diseases (Fan et al., 2012), and reduces environmental pollution caused by fertigation runoff (Savvas, 2002; Rouphael et al., 2006). Additionally, this approach helps conserve water and fertilizers, significantly improving crop water use efficiency (Schwarz et al., 1996; Zekki et al., 1996)., (Zhang et al.,2016). Vegetables are vital cash crops, significantly improving farmer income and nutrition. To meet the rising demand, vegetable cultivation must expand to all possible locations and methods (Dass et al., 2002, 2008). Hydroponic systems facilitate the growth of numerous plants and vegetables, particularly leafy greens, which thrive in soilless media due to their short lifespan and these leafy vegetables have a tender texture and are abundant in antioxidants, fibre, vitamins, and minerals offering protection against various diseases (Park et al., 2013). Hydroponic cultivation has recently gained global popularity due to its efficient resource management and high-quality produce (Sharma et al., 2018). Traditional soil-based agriculture faces challenges like urbanization, natural disasters, climate change, and indiscriminate chemical and pesticide use, posing environmental threats. The tomato is a globally significant vegetable crop. In 2013, global production was estimated at 163.96 million metric tons, with China and India leading production (FAOSTAT, 2015). Tomatoes are consumed in various forms, including fresh, cooked, and processed. Canning transforms them into products such as juice, pulp, paste, and sauces (Cuartero and Fernandez, 1999). Tomatoes are a key vegetable crop in South Africa, with hydroponic production increasing due to higher market returns and limited agricultural resources. As a vital source of vitamins A and C, and minerals, tomatoes are essential to the human diet. South African growers face the challenge of meeting local demand for high-yield, quality tomatoes. This is often hindered by poor cultivation, inadequate nutrition, adverse weather, and pests/diseases. To mitigate unfavourable conditions like hail and summer heat, farmers are increasingly using soilless systems under shade nets to optimize yield and quality (Jones, 2008). Applying optimal nutrient concentrations in greenhouse hydroponics improves spinach growth and enables continuous, year-round production (Acharya et al., 2021). A nutritious leafy vegetable, spinach (Spinacia oleracea) can be consumed fresh, frozen, canned, sliced, or cooked. Being a rich source of vitamins A, C, K, magnesium, manganese, iron, and folate, as well as riboflavin, pyridoxine, vitamin E, calcium, and potassium, it has a high nutritional value, especially when fresh, frozen, steamed, or quickly boiled. Compared to soil-based methods, it offers several advantages, such as faster and uniform plant development, higher average yields, balanced growth, freedom from soil-borne diseases, the elimination of harmful chemical use, and superior produce quality. While hydroponic techniques are not yet widely commercialized in India, they are gaining significant popularity globally, and within India, various institutions and private firms are actively conducting experiments and training programs to promote efficient hydroponic system management. The United States and the Asia-Pacific area are the next most significant producers of hydroponics, with France, the Netherlands, and Spain leading the European market. Soil-based cultivation faces challenges due to industrialization, urbanization, climate change, natural disasters, and excessive chemical use, leading to soil degradation (Jensen & Collins, 1985). To address these issues, scientists have developed hydroponics, a soil-less cultivation method where plants grow in a nutrient-rich water solution. This technique allows for large-scale cultivation of crops and vegetables with higher yield quality, better taste, and superior nutritional value compared to traditional soil-based farming. Hydroponics is cost-effective, disease-free, and eco-friendly, making it increasingly popular worldwide in both developed and developing countries. It also has potential applications in space research and regions with limited arable land. As a sustainable method, hydroponics could help meet global food demands and support future advancements in agriculture. The global hydroponic market is projected to grow by 18.8% from 2017 to 2023, reaching USD 490.50 million by 2023 (Jensen & Collins, 1985). According to growers, continuous crop production is possible only through hydroponic systems, as they allow year-round cultivation, require less space, and enable plant growth in small areas with controlled environments (Hughes, 2017). Hydroponics ensures higher productivity and yields without being affected by climate or weather conditions (Sarah, 2017). The quality of hydroponic produce is superior because controlled environments ensure uniform production while conserving water and nutrients (Okemwa, 2015). Moreover, hydroponics is not seasonal, leading to consistent productivity throughout the year (Okemwa, 2015). Hydroponic farming is also easier, as it eliminates the need for ploughing, weeding, soil fertilization, and crop rotation, making it a clean and efficient method (Nguyen et al., 2016). (Acharya et al.,2021). Different methods for water movement in hydroponic setups- The hydroponic system can be of 2 types; Open system- In open hydroponic systems, the nutrient solution flows through the plant roots and is then discarded. This “single pass” method eliminates recirculation. This practice minimizes the chance of infections spreading among plants due to the frequent replacement of fresh nutrient solution. (Jones, 2005) Closed-system hydroponics is a soil-free growing technique that uses a recirculating nutrient solution. In this system, the same nutrient mix is continuously recovered, replenished, and recycled until fully utilized by the plants. This method reduces water and fertilizer use by up to 80%, making it an efficient and sustainable approach to food production. Types of hydroponic system and their operation -In hydroponic farming, the water tank is the core component, providing the necessary nutrient rich water for plant growth. These tanks generally share a common design, focused on holding and distributing the nutrient solution. To ensure optimal plant health, many systems include a reverse osmosis (RO) unit to eliminate water hardness, which can negatively impact growth. However, tank designs can vary slightly depending on the specific hydroponic system, such as the ebb and flow method. Hydroponic systems are often modified for resource reuse, with common types including wick, ebb -flow, drip, deep water culture, and nutrient film technique described below. (Dubey, N., & Nain, V. 2020)., (Jan et al.,2020). Wick system -The simplest hydroponic systems operate without electricity, relying on a basic setup where plants are rooted in a growing medium such as coco coir, vermiculite, perlite with a nylon wick (Shresta and Dunn,2013). Ebb-flow is the early commercial hydroponic system utilized a flood and drain principle, where a pump delivered nutrient solution from a reservoir to the grow bed, flooding it to a predetermined level for nutrient and moisture delivery. However, despite its versatility in supporting various crops, this design was susceptible to root rot, algae, and Mold (Nielsen et al., 2006). Consequently, modified systems incorporating filtration were developed. Drip-Drip hydroponics offers a highly efficient method for delivering water and nutrients directly to plant roots, making it a popular choice for both home and commercial cultivation (Rouphael and Colla, 2005). By utilizing a pump and a moderately absorbent growing medium, this system ensures controlled, slow dripping, minimizing water waste and supporting the consistent growth of various crops. Deep water culture (DWC) hydroponics suspends plant roots directly in a nutrient-rich solution, with an air stone providing essential oxygenation. A common example is the hydroponic bucket system. Plants are housed in net pots, allowing their roots to immerse and rapidly develop a substantial mass within the solution. Rigorous monitoring of oxygen and nutrient concentrations, salinity, and pH is crucial (Domingues et al., 2012) to prevent the rapid proliferation of algae and Molds within the reservoir. DWC systems are particularly effective for larger, fruit-bearing plants such as cucumbers and tomatoes, which thrive in this environment. Nutrient film technique- Dr. Allen Cooper invented the Nutrient Film Technique (NFT) in England in the mid-1960s. It was made to fix problems with older water-based growing systems (Sharma et al.2018). In NFT, water with plant food constantly flows through channels where plant roots hang. The channels are tilted so the water flows over the roots and back to a tank. This lets plants get food and water all the time. While this can sometimes lead to root problems, NFT works well for growing leafy greens, especially lettuce (Domingues et al., 2012). While hydroponic systems offer numerous advantages, their expense often limits adoption by small farmers. However, cost-effective solutions exist. Gumisiriza et al. developed A basic, easy hydroponic system for leafy greens, designed for economic viability. Another example is the Kratky method (Kratky.,2005), which eliminates the need for pumps and electricity. Plants in mesh pots are grown with a nutrient solution, relying on capillary action for root moisture, making it ideal for intensive leafy vegetable cultivation. Plant growth directly corresponds to the reduction of the nutrient solution, creating more air space for the roots. Leafy vegetables are harvested before the solution is exhausted. This method is practical for small farmers because it requires minimal maintenance, no pumps, absence of climate monitoring systems and no extra labour (Kratky,2009). A key disadvantage is the requirement for regular nutrient solution monitoring, making this method best suited for small-scale, non-automated vegetable production. Hydroponics uses growing material without soil- The following qualities are necessary for the growing media to be used in a hydroponics system: It must serve as a source of nutrients for healthy plant development and growth. It should be able to contain a lot of water. must concurrently provide the plant with gas and water. It needs to give the plant support. Growing media that is organic-(Cocopeat) It is a coconut husk byproduct. Numerous soilless crops, including tomatoes, eggplants, cucumbers, capsicums, spinach, water spinach, and others, can be produced with coconut peat without having a negative effect on the environment (Hussain et al., 2014). Hull of rice-A byproduct of milling rice is rice hulls. offer excellent drainage due to their lightweight nature. While similar in particle size and decomposition resistance to sawdust, rice hulls minimize nitrogen depletion in growing media. Availability permitting, rice hulls can be a valuable hydroponic substrate due to their slow decomposition, akin to coco coir. However, fresh rice hulls should be avoided due to potential contamination from rice, bacteria, fungal spores, weed seeds and decaying insects, Parboiled rice hulls (PRH), produced by drying after milling, are a preferred sterile option as they eliminate these contaminants (Shilpa et al.,2024). Inorganic growing media -Sand is a common hydroponic growing medium. Its fine particle size, smaller than gravel, slows drainage and enhances moisture retention. Sand is often combined with vermiculite, perlite, or coco coir to improve aeration for root development (Asao, 2012; Sharma et al., 2018). Vermiculite-Vermiculite, a heated and expanded hydrated magnesium aluminium silicate, is ideal for container media. Its unique, plate-like particles retain high amounts of water while promoting excellent aeration and drainage. This mineral also offers valuable cation exchange and buffering capacities and readily releases potassium and magnesium. Despite being less durable than sand or perlite, vermiculite's chemical and physical characteristics make it a superior choice for many containers gardening application (Gaikwad and Maitra.,2020). Rock wool-Rockwool is an effective medium for seed germination. This mineral Fiber, made from melted basalt rock and recycled slag, provides a lightweight and convenient growing environment, resulting in a high germination rate, low insect attack ratio, and excellent aeration and moisture retention (Putra and Yuliando, 2015). This study explores the potential of small-scale hydroponic systems enhanced with optimized nutrient management strategies as a sustainable model for local food production. It aims to assess plant growth performance, resource efficiency, and the broader implications for sustainable agricultural practices and community-based food systems. Additionally, check the impact of three distinct nutrient formulations on the agronomic performance and yield of vegetable growth in a nutrient solution. Parallel experiment using soil cultivation as a control was conducted to assess the relative effectiveness of the nutrient solution system and the tested formulations.

Material and Methods

Collection of Seed and Pretreatment

Some seeds were collected and treated with fungicide to prevent fungal infection as young seeds are very sensitive to fungus. The treated seeds were sown in a growing medium and ensuring adequate spacing for development. The sowing seeds were watered which facilitating seed imbibition and germination. The sowing seeds were placed under normal temperature. After some days, the seeds start to germinate. Then after 10-12 days, observation when the size of the plants when reach up to 1-2inch, with rapid growth with expansion of cotyledons selected for transplantation. These selected seedlings were placed in a water based growing medium.

Nutrient Composition for Hydroponic System

Hydroponic systems nourish plants by delivering a formulated water solution. The water containing essential elements for plant life. Plants require essential elements for growth and development. Since we grow plants in a hydroponic system, we must provide the nutrients they would normally get from soil. These include macronutrients like nitrogen (N) phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S). Additionally, we must supply micronutrients such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl). These macro and microelements are added to the water tank, allowing the plants to absorb them and grow. (Salisbury and Ross, 1992). The water medium consists of Calcium nitrate, Magnesium Nitrate, Potassium Nitrate, Magnesium Sulphate, Potassium Sulphate, Monopotassium Phosphate, Monoammonium Phosphate and micronutrients mixture. Standard hydroponic solution fertilizer and acids (Trejo-Téllez and Gómez-Merino, 2012 and Jain et al., 2019)

Table 1. Sources of nutrient elements and their usable form.

Fertilizers	Usable form
Calcium Nitrate $Ca(NO_3)_2.5H_2O$	Ca, N
Potassium Nitrate (KNO_3)	N, K

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Monopotassium (KH2PO4)	Phosphate	K, P
Monoammonium (NH4H2PO4)	Phosphate	P, N
Magnesium (MgSO4.7H2O)	Sulphate	S, Mg

Preparation of Nutrients for Hydroponic System

Hydroponic nutrient solution preparation for tomatoes, starts with high-quality water ideally reverse osmosis (RO) water or dechlorinated tap water. Otherwise, we can use tap water before using this water we can verify the pH and adjust it. The following nutrients are required at different growth stages.

To prepare a 500 mL stock solution, first measure the required amount of each fertilizer (as per the provided table) using a precise weighing scale. Each fertilizer should be dissolved separately in a small amount of distilled water to ensure complete dissolution. Stir each solution thoroughly until no solid particles remain. Once all fertilizers are fully dissolved, combine the individual solutions into a single container, except for calcium nitrate, which must be stored separately. After mixing, add more distilled water until the total volume reaches 500 ml since calcium nitrate reacts with certain other nutrients, it should be prepared and stored in a separate container to prevent precipitation or chemical imbalances. This results in two separate stock solutions: Stock A: Contains calcium nitrate ($Ca\ (NO_3)_2$).

Stock B: Contains all other fertilizers, including potassium nitrate (KNO_3), magnesium sulphate ($MgSO_4$), mono potassium phosphate (KH_2PO_4) Micronutrient Mix (Iron, Zinc, Manganese, Boron, Copper, Molybdenum, etc.) it can be added in the nutrients a very small amount.

Working Solution Preparation

Measure the required amount of stock solution based on volume of water reservoir. Then pour the measuring stock solution into a container with RO water. Stir or mix well to ensure proper mixing. Then after mixing measure the pH and EC of nutrient solution. And then adjust if it is necessary by adding more water (to low EC level) or more (to increase EC). The pH should be always maintained between 5.5-6.5.

Table 2. Macronutrients for hydroponics setup.

Nutrients	Formula	F- 1 (g/500mL)	F- 2 (g/500mL)	F- 3 (g/500mL)
Nitrogen	$(Ca\ (NO_3)_2)$	66.67	100	105
Phosphorous	KH_2PO_4	21.67	25	25.83
Potassium	KNO_3	75	100	110
Magnesium	$MgSO_4$	30	35	40

Table 3. Micronutrients for hydroponics setup.

Nutrients	Formula	F- 1(g/500mL)	F- 2 (g/500mL)	F- 3 (g/500mL)
Zinc	$ZnSO_4$	0.33	0.33	0.33
Molybdenum	Na_2MoO_4	0.06	0.06	0.06

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Manganese	$MnSO_4$	0.81	0.81	0.81
Copper	$CuSO_4$	0.23	0.23	0.23
Boron	$B_8H_8NO_2O_{17}$	0.5	0.5	0.5
Iron	Fe EDTA	3.33	3.33	3.33

Experimental Design for Hydroponic Technique

After transplantation, the seedlings were placed in three distinct nutrient compositions (Named F-1, F-2, and F-3) under room temperature. Approximately later seedlings of same size were placed in net pots and secured with deep water channels of a nutrient film system for each treatment. Aerators were used to maintain sufficient dissolved oxygen in the nutrient media, as aerator was not available we use an alternate Kratky method where, coco peat or foam sponge provided mechanical support for the growing seedlings in the nutrient system. Triplicate plants were grown in each three different nutrient solutions, each refreshed weekly soil grown triplicate plants served as the control. The pH and EC of the nutrient solution were maintained at specific levels during the early vegetative growth phase.

Application of Nutrient Formulation

The experiment followed a pre-established methodology outlined by Sahoo et al. (2024), ensuring consistency in nutrient formulation. Three distinct nutrient solutions (F-1, F-2, F-3) were used, each with progressively higher EC values. The EC was systematically increased from initial levels of 350,400and 450 µS/cm during seedling establishment, to 1500,2000,2500 µS/cm during vegetative growth stage, and finally 3000,3500and 4000 µS/cm during flowering and fruiting stage. The pH was consistently maintained at 6.5, a slightly acidic level optimal for nutrient uptake in many plants.

Analysis of Agronomic Traits

To assess the agronomic performance of plants under various treatments, a thorough analysis of essential growth characteristics was performed. Replicate plants from each treatment group selected for measurement. The following key parameters were evaluated: shoot length, providing a measure of above-ground growth; root length, indicative of root system expansion; leaf number, reflecting the rate of vegetative development; and leaf size, representing the photosynthetic area of the plant. The progression of plant development was continuously monitored and documented over a specified time frame. Precise numerical data for each measured parameter was recorded.

Statistical Analysis

In this experiment three replicates of each formulation were used to statistically assess and display the plant growth data (such as shoot length, root length, stem girth and leaf number) in the hydroponic system experiment as mean ± standard error of the mean (SEM), This data represented in graph format. In addition, to assess the variability of samples across every treatment group, the standard deviation (SD) was determined. To show the uniformity and dependability of plant responses in various nutritional or environmental circumstances, the mean provides a measure of central tendency, SEM illustrates the mean's reliability, and SD displays the variance in the data.

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Results

Agronomic Character Analysis

Table 4. Shoot length observed (in cm).

	CONTROL	F-1	F-2	F-3
Initial	5.4±0.1	5.33±0.11	5.33±0.57	5.3±0.1
Day 15	7.5±0.5	8.36±0.55	9.16±1.25	6.03±0.85
Day 30	11.33±2.08	12±1	15.4±1.63	7.73±1.10
Day 45	23.33±1.52	24±1	29±4.35	11.5±3.04
Day 60	32.33±4.93	28.66±1.15	38.33±10.40	18.83±7.07
Day 75	45.33±4.16	41.33±8.14	49.33±12.74	23.5±9.98

Table 5. Leaf number observed.

	CONTROL	F-1	F-2	F-3
Initial	2.66±0.57	3.66±0.57	2.66±0.57	2.66±0.57
Day 15	9.66±2.08	11±2	13.12±2.64	6.66±2.08
Day 30	14.66±2.51	18±1	21.33±2.08	10±3.60
Day 45	22.33±2.51	23.33±1.52	27±7	14.33±3.21
Day 60	35.66±4.04	35±5	49±17.34	24±5.29
Day 75	45.33±3.51	49.33±9.50	72±21.93	29±6.55

Table 6. Root length observed (in cm).

	CONTROL	F-1	F-2	F-3
Initial	1.5±0.2	1.4±0.1	1.36±0.20	1.36±0.15
Day 15	3.23±0.25	3±0.5	4.4±0.65	2±0.2
Day 30	4.46±0.47	4.7±0.43	6.5±1.80	2.76±0.41

Day 45	9±0.8	8.33±1.52	14.06±0.90	5.7±1.58
Day 60	12.1±1.1	13.58±1.41	19.83±2.36	8.9±1.38
Day 75	16.93±2.45	17.6±1.83	26.33±3.21	12.5±2.343

Table 7. Stem girth (in cm).

	CONTROL	F-1	F-2	F-3
Initial	1.23±0.20	1.2±0.1	1.13±0.05	1.16±0.20
Day 15	1.43±0.15	1.6±0.1	1.63±0.20	1.46±0.11
Day 30	1.8±0.1	1.83±0.05	2.1±0.2	1.66±0.15
Day 45	2.2±0.1	2.3±0.1	2.7±0.2	1.9±0.2
Day 60	2.6±0.1	2.7±0.2	3±0.26	2.13±0.25

Table 8. Final Changes in morphological features of different nutrient treated vegetable plants grown under hydroponic system.

Agronomic traits	Control	F-1	F-2	F-3
Shoot length(cm)	45.33±4.16	41.33±8.14	49.33±12.74	23.5±9.98
Leaf number	45.33±3.51	49.33±9.50	72±29.93	29±6.55
Root length(cm)	16.93±2.45	17.6±1.83	26.33±3.21	12.5±2.343
Flower number per plant	7±0.57	5.34±0.33	9±0.57	4.66±0.65
Fruit number per plant	4.33±2.08	5.33±1.52	6.66±1.52	2.33±0.57

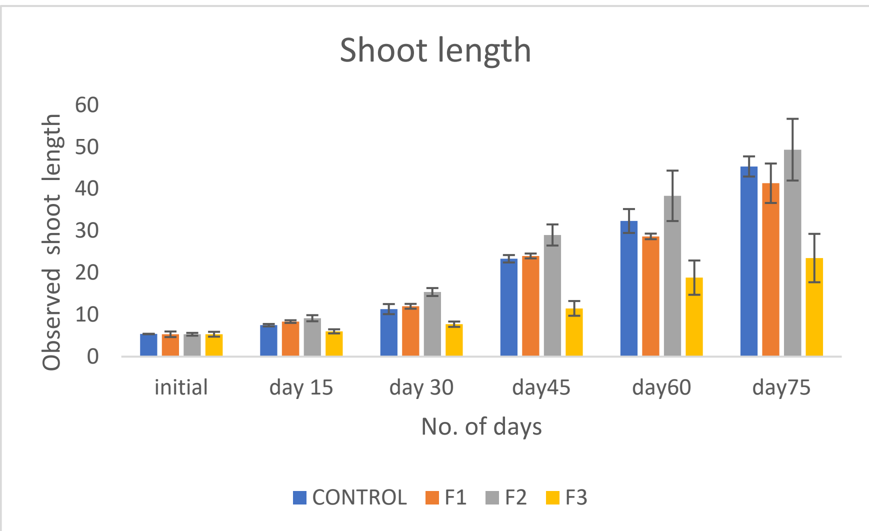

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Figure 1. The graph illustrates the observed shoot lengths of different treated plants. Such as F-1, F-2, F-3 and control group over different time intervals. Each treatment shows how the shoot length changes with time compared to control.

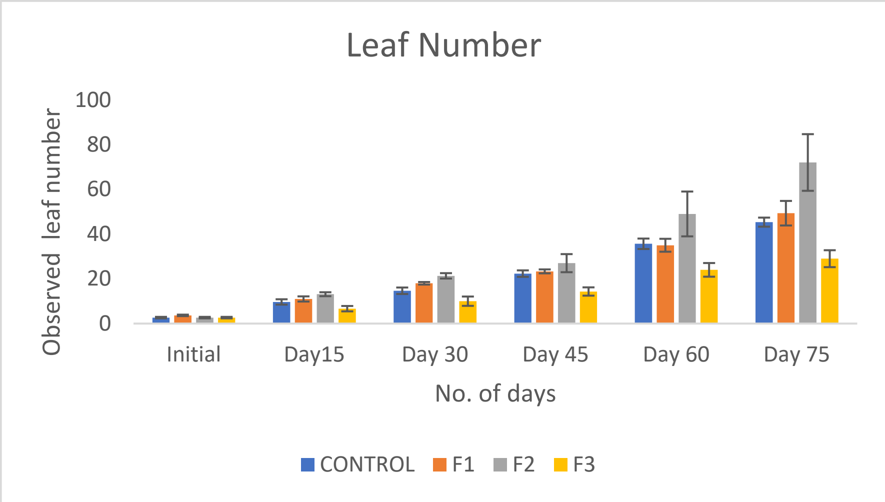

Figure 2. The graph shows the observed leaf number of different treated plants F-1, F-2, F-3 and control group over different days.

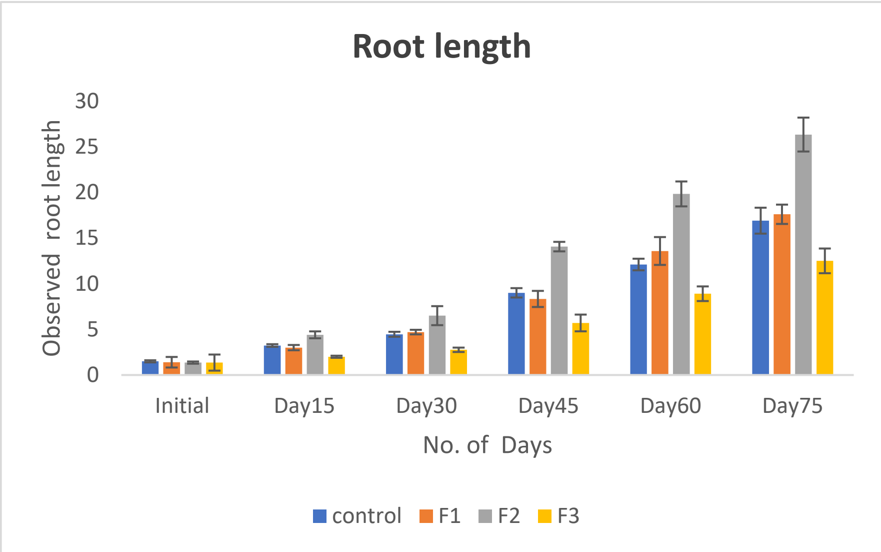

Figure 3. The graph represents the observed root length of different treated (F-1, F-2, F-3) plants with compared to control group over different days. .

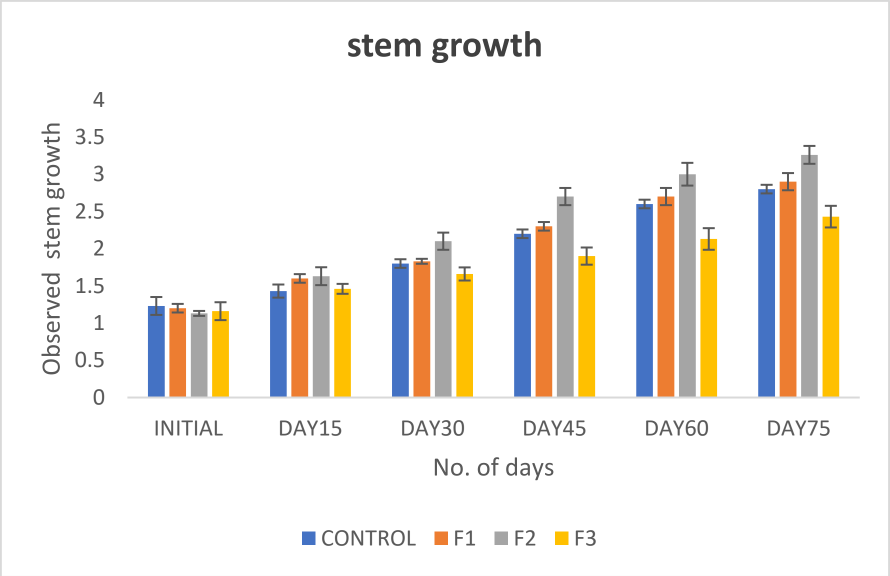

Figure 4. The graph shows the observed stem girth of different treated (F1, F-2, F-3) plants with compared to control over different time interval.

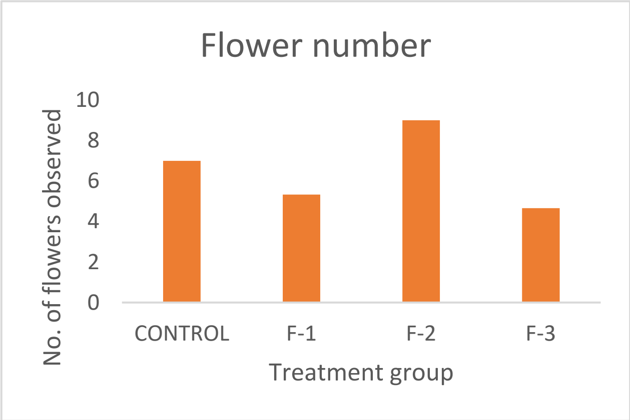

Figure 5. Showing the no. of flower per plant of each treatment group i.e. Control, F-1, F-2, and F-3.

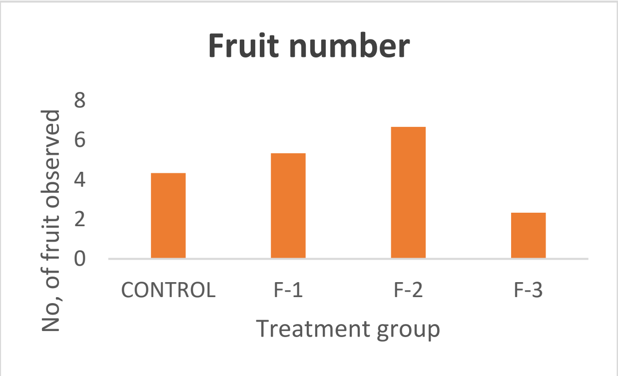

Figure 6. Showing the no. of fruits per plant of each treatment group i.e. Control, F-1, F-2, and F-3.

Three different fertilizer formulations (F-1, F-2, and F-3) were applied to experimental plants grown in nutrient systems, while soil-grown plants were used as a control. Over the course of 60 days, vegetative growth indicators were tracked. The F-2 formulation had the greatest vegetative growth response at 30 days after treatment, as evidenced by increased shoot length, leaf number, stem girth and root length. F-1, the control, and F-3 came next. Bud initiation in tomato plants started

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after 60 days and continued through 75 days. At the 75-day observation point, tomato plants treated with F-2 within the nutrient system exhibited superior performance in key agronomic traits. The F-2 supplemented plant having shoot length (49.33±12.74), root length (26.33±3.21), leaf number (72±21.93) as compared to others. For parameter study triplicate plant were taken.

Nutrient optimization – pH and Electrical conductivity (EC)are critical factors for plant growth and development. Supplementation with the F-2 nutrient formulation during fruit formation resulted in a higher growth, fruit yield compared to the control and other nutrient treatments. The highest flower and fruit yield was observed in F-2 supplemented plants at pH 6.5 and EC 3500 µS/cm. Conversely, high EC levels at pH 6.5 decreased flower and fruit yield in F-3 supplemented plants.

Tomato Flower and Fruit Yield Assessment

The 60-day cultivation period, as depicted in figure [figure 1],highlighted a significant trend :hydroponic plants treated with F-2 produced a notably higher number of flowers .This pattern persisted through the 90-day observation period ,where increased flower development culminated in robust fruit formation .By 90th day ,F-2 supplemented by hydroponic plants demonstrated significantly elevated flower and fruit counts per plant, far surpassing those of soil-grown plants. Conversely, both F-1 and F-3 supplemented plants exhibited a decline in flower and fruit production per plant when compared to control.

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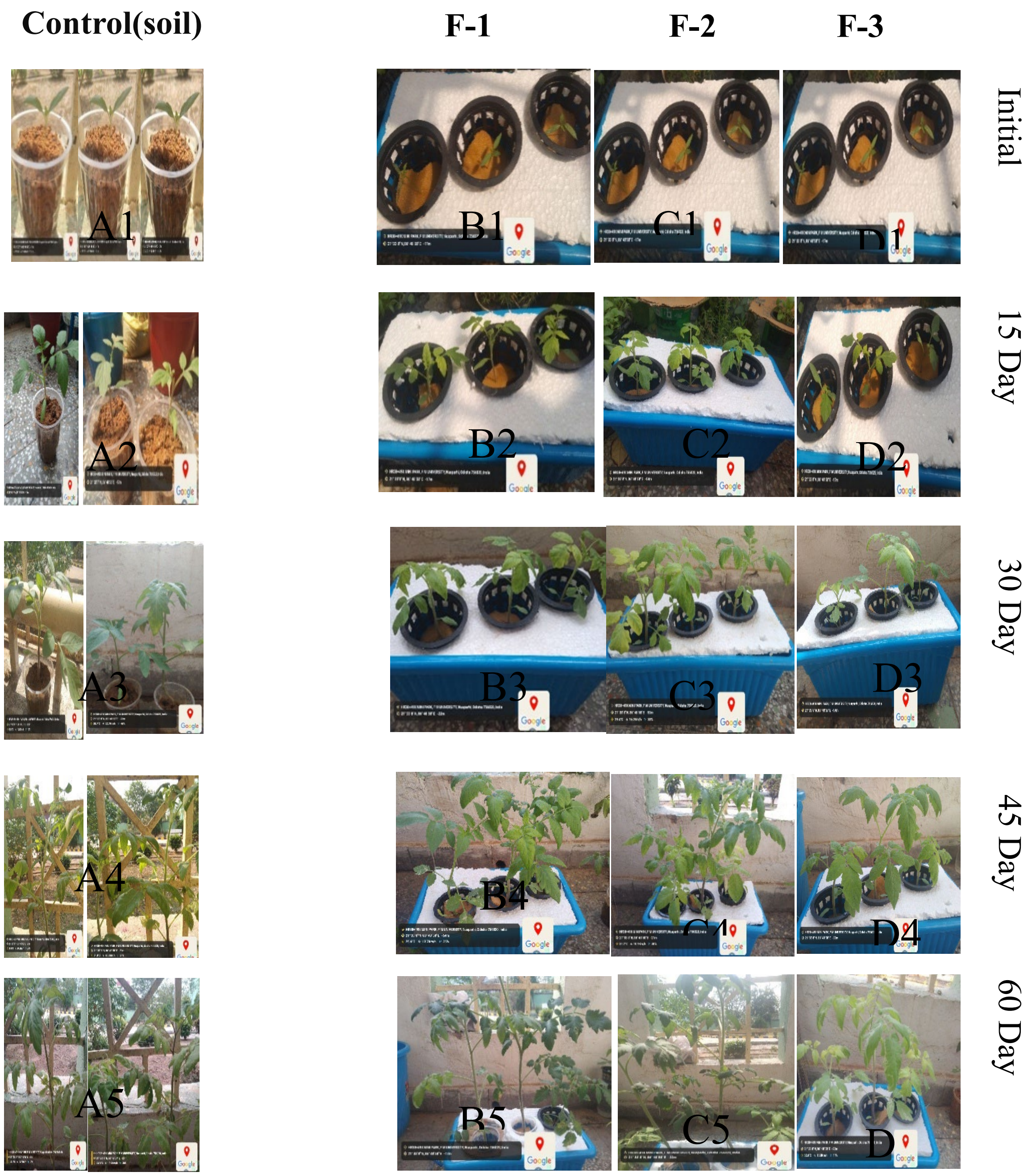

Figure 7. Figure showing various developmental stages of tomato plant grown in different under hydroponic condition .A1,B1,C1,D1;The initial stage of the plants grown in control and 3 different nutrient treatment.A2,B2,C2,D2 is the vegetative stage of the plant after 15 day,A3,B3,C3,D3 is showing the growth of the plant near 30 day,A4,B4,C4,D4 showing the development of the plant on 45 day and finally A5,B5,C5,D5 showing the growth and development of the plant on day 60.

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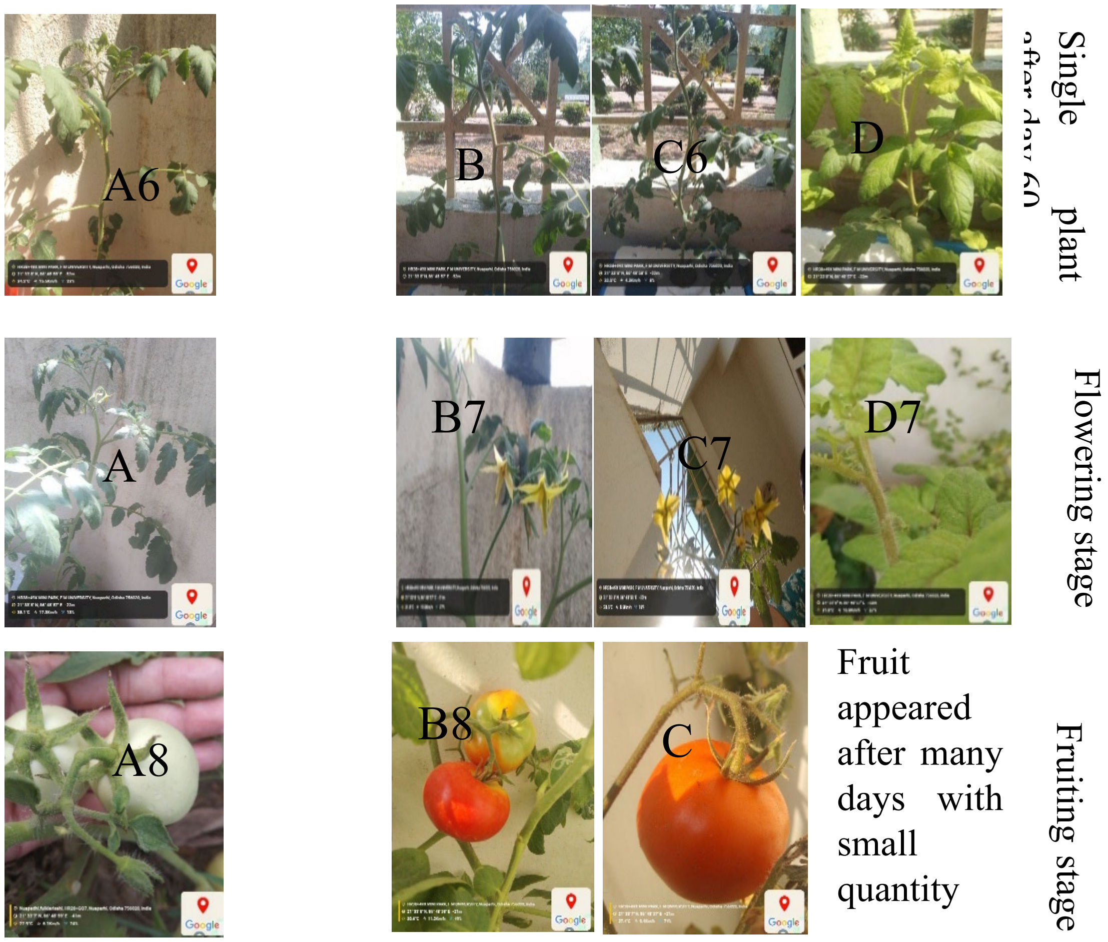

Figure 8. A6, B6, C6, D6 showing the growth of the single plants after 60 days that is nearly 75 day, and the A7, B7, C7, D7 shows the flowering stage of the plant. Finally, A8, B8, C8 shows the fruiting stage of this plant.

Figure 9. Root growth of samples.

Discussion

According to the research's findings, hydroponic crop yields may be significantly impacted by nutrient optimization. The results of the research demonstrate that plant growth, yield, and overall system efficiency are all affected directly by regulating the nutrient solution, including the optimal ratio of macro and micronutrients. The findings will be compared to previous studies, analysed in the context of hydroponic farming, and their broader implications for future agricultural methods will be explored. The need to adjust nutrient concentrations to the requirements of the crop is further supported by the fact that plants that receive the optimal nutrient solution grow more. Plants in F-2 group exhibited increase in height, increase in root length, increase in stem girth and increase in leaf number as compared to the F-1, F-3 and control group. Vegetable plants treated with F-2 formulation in hydroponic system shows better agronomic character as compared to soil grown plant due to

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continuous water solution recycling and availability of nutrients at actual time. According to Chen *et al*. (2021) balanced nutrient application in plants helps the productivity. The result of this experiment aligned with earlier report by Sahoo *et al*. (2024), Nardi *et al*. (2022), Razan *et al*. (2023) the plants under hydroponic condition with balanced nutrients formulation shows better result compared to control group. Here the EC plays vital role in plant growth and development. The nutrient with higher EC shows higher concentration of salts and fertilizers present in nutrient solution. At the time of seedling stage EC was lower, in vegetative stage its increased, but in reproductive or flowering stage it was higher. The experiment shows that the nutrient solution of F-1, F-2 and F-3 shows variation in EC value that means the amount of concentration varies among them. The F-3 solution having higher EC so that the growth of the plant was decreased (stunted)as compared to other. The F-2 treated plants shows better growth, whereas the F-1and F-2 plants shows slightly difference among them. This experiment also clarifies that the growth of the plant depends on the concentration of solids dissolve in the water, the higher the amount of solid is directly related to higher EC but the lower the number of solids show lower EC this plays vital role in plant growth and development. The yielding of fruits also depends on the concentration of nutrients, as seen in category F-1, F-2, and F-3 compared to control group.

Conclusions

Three nutrient formulas were used to assess tomato plant growth, develop yield, and fruit production in hydroponic settings, and the results were compared to those of traditional soil-grown plants. The results show that a modified nutrient formulation, F-2 (EC 400,2000 and 3500 µS/cm), significantly enhanced fruit yield, flower production, vegetative growth, and seedling development. The results of the study show that the F-2 nutrient formulation attains a healthy morphological status, which is required to increase flower and fruit yield. According to Kane et al. (2006), these results indicate that the ideal EC level for tomato plant flower and fruit development is 3500 µS/cm. According to Santos Junior et al. (2013), the EC of the F-2 nutrient formulation was progressively increased to this optimal level throughout the growth cycle, from seedling to fruiting. According to Sahoo et al. (2024), strawberry plants exposed to high nutrient concentrations similarly exhibit decreased growth and productivity when their EC level is exceeded. When compared to plants cultivated in soil or treated with conventional nutrient formulations, the agronomic characteristics of plants supplemented with the F-2 nutrient formulation were much greater. According to this, the improved F-2 This implies that the enhanced F-2 formulation led to a superior growth and production status. To further improve commercial tomato growing, future research should focus on developing automated nutrient delivery and hydroponic systems, based on the established optimal EC level of 3500 µS/cm.

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