WATER CULTURE: HYDROPONICS

Impacts of Hydroponic Stratagem on Growth and Yield Performance Factors in Tomatoes (Lycopersicon esculentum)

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Abstract

Food insecurity in Nigeria is exacerbated by seasonal shifts, high labor demands, and environmental degradation. To address these challenges and close the supply-demand gap for tomato (Solanum lycopersicum), this study evaluated a robust, easy-to-operate hydroponic system for year-round cultivation. Two tomato varieties (UC and Ruma) were grown using two systems: a soilless hydroponic setup and a traditional soil-filled potted control under identical environmental conditions. Morphological and reproductive parameters were evaluated using ANOVA and Bonferroni post-hoc tests ($p < 0.05$). Results revealed that while soil-grown plants achieved significantly taller plant heights (Ruma Soil: 35.90 ± 0.13 cm), the hydroponic system dramatically enhanced vegetative and reproductive outcomes. The UC Hydroponic treatment yielded the highest mean number of leaves (32.65 ± 1.10), branches (11.09 ± 0.35), leaf size (13.89 ± 0.28 cm^2), and stem girth (1.56 ± 0.03 cm), significantly outperforming all other groups ($p < 0.001$). Crucially, UC Hydroponics also recorded the highest reproductive metrics, including flower count (8.62 ± 1.08), fruit yield (12.78 ± 2.19), and fruit size (5.41 ± 0.49 cm). Both hydroponic treatments produced larger fruit sizes than their soil-based counterparts. These findings demonstrate that managed soilless cultivation optimizes vegetative growth and significantly enhances fruit traits. Consequently, this system offers a viable path toward year-round agricultural production, economic diversification, and food security in ecologically compromised regions.

Keywords: hydroponics; tomato cultivation; soilless agriculture; food security

1 Introduction

Food insecurity remains one of the most pressing challenges facing Nigeria, a country with a rapidly growing population exceeding 220 million. Despite its vast agricultural potential, Nigeria relies heavily on food imports, spending billions of naira annually on commodities such as rice, wheat, and tomatoes (Adewumi and Bello, 2024). The agricultural sector is constrained by a multitude of factors, including overdependence on rain-fed farming, limited mechanization, inadequate post-harvest infrastructure, and persistent conflicts between farmers and herders (Ogunleye et al., 2025). These constraints are exacerbated by climate change, which has introduced greater variability in rainfall patterns and increased the frequency of extreme weather events, further destabilizing food production systems (Food and Agriculture Organization [FAO], 2026).

Tomato (*Lycopersicon esculentum* Mill.), a member of the Solanaceae family, is one of the most economically important vegetable crops globally and holds significant dietary and commercial value in Nigeria. It is a key ingredient in local cuisine and serves as a primary source of essential vitamins A and C, minerals, and bioactive compounds—such as lycopene—which are crucial for human health (Okoro and Nwachukwu, 2024). However, domestic tomato production is highly seasonal, with most

harvests occurring during the rainy season. This seasonality leads to pronounced supply-demand mismatches: during the dry season (November–March), tomato prices skyrocket, and the country resorts to importing large quantities of tomato paste and fresh tomatoes, primarily from China and European nations, to meet local demand (Makka et al., 2024). This structural deficit is further compounded by post-harvest losses that can eliminate up to 40% of the total harvest due to deficient storage and transportation facilities (Umar and Adebayo, 2025).

According to recent estimates, global tomato production exceeds 180 million tonnes annually; however, post-harvest losses and seasonal supply gaps remain substantial challenges in developing nations (FAO, 2026).

Beyond seasonal limitations, soil degradation poses a critical threat to sustainable agriculture in Nigeria. In the Niger Delta region, decades of oil exploration have caused extensive hydrocarbon contamination, rendering vast areas of farmland unproductive and endangering the livelihoods of local communities (Umar and Adebayo, 2025). Furthermore, soil-borne diseases, nematode infestations, and nutrient depletion continue to reduce the productivity of conventional farming systems (Dauda et al., 2022). These concurrent challenges necessitate innovative agricultural practices that can decouple food production from the structural constraints of soil and season.

Hydroponics, a method of cultivating plants without soil by supplying essential mineral nutrients directly through a water solution, has emerged as a promising alternative to address these limitations (Velazquez-Gonzalez et al., 2022). Modern hydroponics was pioneered in the 1920s and 1930s by researchers such as William Gericke at the University of California, who demonstrated that plants could be successfully grown to maturity using only water and precise nutrient solutions (Caputo, 2022). Since its inception, hydroponic systems have evolved into diverse technical configurations—including deep-water culture, nutrient film technique (NFT), drip systems, and aeroponics—each offering distinct operational requirements and performance advantages (Balliu et al., 2021).

One of the most significant benefits of hydroponics is its capacity for year-round production within controlled environments such as greenhouses. By decoupling crop growth from external weather conditions, these systems ensure a stable supply of fresh produce regardless of the season (Chen et al., 2025). Moreover, because water and nutrients are recirculated, hydroponics consumes up to 90% less water than conventional soil-based agriculture, making it particularly viable for arid and semi-arid regions (Janssen et al., 2025). This controlled environment also minimizes pesticide reliance by eliminating many soil-borne pests and diseases, thereby reducing chemical inputs and enhancing food safety (Halbert-Howard et al., 2021).

Globally, the adoption of hydroponics has accelerated in recent years, driven by rapid urbanization, arable land scarcity, and rising consumer demand for locally grown, pesticide-free produce. In Europe and North America, hydroponic facilities range from small-scale urban installations to large commercial operations that supply supermarkets year-round (Velazquez-Gonzalez et al., 2022). In Asia, countries such as Japan, South Korea, and Singapore have invested heavily in controlled-environment agriculture to bolster food self-sufficiency (Sharma and Gupta, 2025). Conversely, adoption across Africa remains in its infancy, hindered by high initial capital costs, limited technical expertise, and inadequate policy support (Adewumi and Bello, 2024). Nigeria—with its abundant sunlight, regional water resources, and expanding urban middle class—stands to benefit significantly from the implementation of locally adapted hydroponic technologies.

Given these institutional and environmental advantages, *Solanum lycopersicum* (tomato) serves as an ideal candidate for hydroponic cultivation due to its relatively short growth cycle, strong responsive-

ness to nutrient management, and high market value. Hydroponically grown tomatoes frequently exhibit superior fruit quality, including higher sugar content, firmer texture, and an extended shelf life compared to their soil-grown counterparts (Okoro and Nwachukwu, 2024). Furthermore, the ability to precisely control nutrient composition allows for the enrichment of tomatoes with specific micronutrients, offering potential health benefits (Gonzali and Perata, 2020).

Despite these advantages, there is a dearth of empirical research on hydroponic tomato production in Nigeria. Most existing studies focus on soil-based agronomy or have been conducted in other countries with different climatic and socio-economic contexts. Consequently, locally generated evidence is required to guide the design, implementation, and scaling of hydroponic systems in Nigeria. This study aims to fill this gap by constructing and evaluating a closed-loop hydroponic system for tomato production in northeastern Nigeria. By comparing the growth and yield performance of hydroponically grown tomatoes with those cultivated in conventional soil, this research will provide critical insights into the feasibility and potential benefits of soilless agriculture in the region.

1.1 Taxonomy and botanical description of tomato

The tomato (*Solanum lycopersicum* L., formerly *Lycopersicon esculentum* Mill.) belongs to the family Solanaceae, which includes other economically important crops such as pepper (*Capsicum* spp.), eggplant (*Solanum melongena*), and potato (*Solanum tuberosum*). The genus *Lycopersicon* was originally separated from *Solanum* based on morphological characteristics, particularly anther structure and fruit morphology. However, modern molecular phylogenetic studies have led to the reclassification of *Lycopersicon* as a section within the genus *Solanum*, resulting in the accepted botanical name *Solanum lycopersicum* L. (Oladipo et al., 2025). Despite this taxonomic revision, the synonym *Lycopersicon esculentum* remains widely used in horticultural and agricultural literature.

The taxonomic hierarchy for the tomato plant is as follows (Oladipo et al., 2025; USDA Plants Database, 2025):

- **Kingdom:** Plantae
- **Clade:** Angiosperms
- **Clade:** Eudicots
- **Clade:** Asterids
- **Order:** Solanales
- **Family:** Solanaceae
- **Genus:** *Solanum L.*
- **Species:** *Solanum lycopersicum L.* (syn. *Lycopersicon esculentum* Mill.)

In tropical regions, tomato plants typically grow as annual or short-lived perennial herbs. They possess a taproot system characterized by extensive lateral branching, which facilitates efficient water and nutrient uptake—a feature that makes them highly suited for hydroponic cultivation (Okoro and Nwachukwu, 2024). The stem is pubescent and exhibits either a determinate (bush-type) or indeterminate (vine-type) growth habit, which determines the specific pruning requirements. The compound leaves are alternately arranged, each consisting of five to nine leaflets with serrated margins. The hermaphroditic, yellow flowers are borne in racemes; while predominantly self-pollinating, they are also subject to insect-mediated cross-pollination. The fruit is a botanical berry that varies widely in size, shape, and color, ranging from small cherry types to large beefsteak varieties, and spanning a color palette that includes red, yellow, orange, and purple (Gonzali and Perata, 2020).

1.2 Problem statement and justification

- **Seasonality and Food Scarcity:** Globally, and particularly in Nigeria, traditional open-field agriculture is heavily constrained by seasonal variations. This dependency results in severe food scarcity, reduced crop yields, and market volatility during the dry season.
- **The Tomato Supply-Demand Gap:** Tomato is a critical staple crop consumed by over 200 million Nigerians. However, the domestic sector suffers from a massive supply-demand deficit where local production consistently fails to meet national consumption needs, leading to high import bills and periodic, extreme scarcity (Okoro and Nwachukwu, 2024).
- **Underfunding and High Commodity Costs:** Insufficient funding and inadequate investment in modern agricultural infrastructure limit production capacities. This undercapitalization drives up the cost of agricultural commodities, making essential food items increasingly unaffordable for the populace.
- **Environmental Degradation:** In specific regions, such as the oil-polluted ecosystems of the Niger Delta, extensive soil contamination from oil spills has rendered traditional arable land unproductive, highly toxic, and difficult to cultivate.
- **Labor and Time Constraints:** Conventional soil-based agriculture demands high physical labor inputs and lengthy cultivation cycles. These inefficiencies lower profit margins and discourage youth and prospective investors from entering the agricultural sector.

1.3 Objectives of the study

1.3.1 Aim

The primary aim of this study is to develop a scientifically sound, robust, and user-friendly hydroponic farming system to facilitate the year-round cultivation of tomatoes, thereby mitigating seasonal scarcity and establishing a viable framework for economic diversification.

1.3.2 Specific objectives

To achieve this aim, the study will seek to:

1. Design and construct a scientifically optimized, robust hydroponic system tailored for tomato cultivation and adaptable for other herbaceous crops.
2. Monitor and evaluate the growth, physiological development, and yield of hydroponically grown tomato crops from the seedling stage through to full physiological maturity, fruiting, and harvest.
3. Assess and establish the economic viability of the developed hydroponic system as a scalable framework for national economic diversification.
4. Deploy and validate the hydroponic system as a soil-less agricultural alternative specifically optimized for food production in the oil-degraded environments of the Niger Delta.

2 Literature review

2.1 Soil-based agriculture: Limitations and challenges

Soil has long been the traditional medium for plant cultivation, providing physical support, water retention, and an essential reservoir of mineral nutrients (Kumar et al., 2018). However, the productivity of soil-based systems is increasingly constrained by an array of environmental and anthropogenic factors. Soil degradation—driven by erosion, salinization, nutrient depletion, and

chemical contamination—has become a critical global concern, affecting approximately one-third of the world's agricultural land (FAO, 2026). In Nigeria, this degradation is particularly acute. The northern regions suffer from severe desertification and topsoil loss due to overgrazing and unsustainable farming practices, while the oil-producing southern regions face extensive hydrocarbon pollution that has disrupted soil structure and eliminated fertility (Umar and Adebayo, 2025).

In addition to physical degradation, soil-borne pathogens—including fungi (such as *Fusarium* and *Pythium*), bacteria, and nematodes—pose a persistent threat to crop yields. These organisms can survive in the soil matrix for years and are notoriously difficult to eradicate without intensive crop rotations or synthetic fumigants (Dauda et al., 2022). Managing soil-borne diseases incurs substantial economic costs, and the subsequent reliance on chemical pesticides raises severe environmental and public health concerns.

Furthermore, conventional soil-based agriculture remains heavily labor-intensive. In many rural parts of Nigeria, the agricultural workforce is aging rapidly as younger demographics migrate to urban centers in search of alternative livelihoods, creating a severe shortage of skilled farmworkers (Chen et al., 2025). This labor deficit, combined with the grueling physical demands of manual weeding, irrigation, and harvesting, diminishes the economic appeal of farming and strictly limits the scalability of traditional agricultural operations.

2.2 Hydroponic systems: Principles and types

Hydroponics, derived from the Greek words *hydro* (water) and *ponos* (labor), is a method of cultivating plants without soil by utilizing mineral nutrient solutions dissolved in water. The modern concept of hydroponics is widely credited to William Gericke of the University of California, Berkeley, who in 1929 demonstrated that crops could be successfully grown to maturity without a soil substrate. By delivering essential elements directly to the root zone, hydroponic cultivation bypasses the traditional limitations of soil, optimizing resource efficiency and enhancing growth rates.

Hydroponics is a method of cultivating plants without soil, where roots are supplied with a nutrient solution containing all essential macro- and micronutrients. This solution is typically aerated to ensure an adequate oxygen supply to the roots, which is critical for cellular respiration and efficient nutrient uptake (Balliu et al., 2021).

Several types of hydroponic systems have been developed, each with distinct operational characteristics:

- **Deep-Water Culture (DWC):** Plants are suspended with their roots submerged in a continuously aerated nutrient solution. While simple and cost-effective, this system can be prone to root diseases if not properly managed.
- **Nutrient Film Technique (NFT):** A thin stream of nutrient solution flows continuously over the roots through sloping channels. This method is widely used for cultivating leafy greens and herbs.
- **Drip Systems:** The nutrient solution is delivered directly to the base of each plant via drip emitters, and the excess solution is collected and recirculated. This highly versatile system is well-suited for larger plants such as tomatoes and peppers.
- **Aeroponics:** Roots are suspended in the air and misted with a nutrient solution at regular intervals. This configuration provides excellent oxygenation but requires precise control to prevent the roots from drying out (Tunio et al., 2021).

The advantages of hydroponic systems are well-documented. They enable precise control over nutrient delivery, optimize water-use efficiency through recirculation, and eliminate the risk of soil-borne diseases. Moreover, hydroponics facilitates year-round production in controlled environments, independent of seasonal climate variability (Velazquez-Gonzalez et al., 2022). This capability is particularly relevant amid climate change, where unpredictable weather patterns increasingly disrupt traditional farming cycles. Recent advancements in automation and sensor technology have further enhanced the precision and scalability of these systems, making them viable for both small-scale urban farms and large commercial operations (Janssen et al., 2025).

Aeroponics, a related soilless cultivation technique, involves suspending plant roots in the air and intermittently misting them with a nutrient solution. Research indicates that aeroponic systems can enhance root oxygenation and nutrient uptake, leading to accelerated growth rates compared to traditional hydroponics (Tunio et al., 2021). However, these systems generally demand more sophisticated infrastructure and intensive maintenance.

To mitigate these challenges, recent engineering breakthroughs have led to the development of hybrid systems that integrate automation, sensors, and data analytics to dynamically optimize nutrient delivery and environmental conditions (Janssen et al., 2025). Ultimately, selecting the ideal system depends on crop type, operational scale, available resources, and technical expertise.

2.3 Global adoption and technological advances

Hydroponic agriculture has experienced remarkable growth over the past two decades. In North America and Europe, commercial hydroponic farms produce a significant portion of greenhouse vegetables, including tomatoes, cucumbers, and lettuce (Velazquez-Gonzalez et al., 2022). In the Netherlands, one of the world's leading agricultural exporters, advanced hydroponic systems enable year-round production with minimal water and pesticide use. Similarly, in the Middle East, countries like the United Arab Emirates have invested heavily in hydroponics to overcome water scarcity and reduce dependence on food imports (Griebel et al., 2022).

Technological innovations have been key drivers of this expansion. The use of light-emitting diode (LED) technology allows for efficient supplemental lighting in greenhouses, enabling year-round production even in northern latitudes. Sensor networks and Internet of Things (IoT) platforms provide real-time monitoring of pH, electrical conductivity, temperature, and humidity, allowing for precise adjustments to optimize plant growth (Janssen et al., 2025). Furthermore, machine learning algorithms are increasingly being applied to predict crop yields, detect nutrient deficiencies, and automate fertigation schedules, reducing labor requirements and improving resource efficiency.

Despite these advances, the adoption of such technologies in sub-Saharan Africa remains limited due to high capital costs and a lack of local technical support. However, recent initiatives by development organizations and private companies have begun introducing simplified, low-cost hydroponic systems suitable for smallholder farmers (Adewumi and Bello, 2024). These systems often leverage locally available materials and solar-powered pumps to lower operational costs.

2.4 Hydroponic tomato production

Tomato (*Solanum lycopersicum*) is one of the most widely grown crops in hydroponic systems globally. It is exceptionally well-suited to soilless culture due to its vigorous root system and high responsiveness to precision nutrient management. Studies show that hydroponically grown tomatoes frequently achieve higher yields than their soil-grown counterparts, alongside superior fruit quality

attributes such as elevated sugar content, firmer texture, and extended shelf life (Okoro and Nwachukwu, 2024). Tailoring nutrient solutions to specific growth stages also optimizes both vegetative growth and fruit development.

Beyond being a dietary staple, tomatoes are a rich source of bioactive compounds—including carotenoids (such as lycopene), ascorbic acid (vitamin C), and diverse polyphenols—which contribute strong antioxidant and health-promoting properties (Gonzali and Perata, 2020). The nutritional profile of tomatoes is closely tied to growing conditions; research suggests hydroponic systems can yield comparable or superior phytochemical concentrations relative to traditional soil cultivation, depending on proper nutrient management (Okoro and Nwachukwu, 2024). Furthermore, because controlled environment hydroponics is typically enclosed, pesticide applications can be sharply reduced, yielding produce with lower chemical residues.

2.5 The Nigerian agricultural sector and research gaps

In Nigeria, the adoption of hydroponics remains in its infancy despite its recognized potential. The country's agricultural sector continues to rely heavily on traditional open-field methods, leading to low productivity, high post-harvest losses, and a growing dependence on food imports (Tajudeen and Taiwo, 2018). The escalating cost of food items—including tomatoes—places a severe strain on household budgets and national foreign exchange reserves. Recent studies emphasize the capacity of hydroponic farming to address these vulnerabilities, particularly in urban and peri-urban centers where where arable land availability is increasingly scarce.

Globally, hydroponic farming has expanded significantly over the past decade. In India, for example, commercial hydroponic operations have grown substantially since the early 2000s, driven by rapid urbanization and worsening water scarcity (Sharma and Gupta, 2025). Similarly, nations in the Middle East, where arable land is severely limited, have invested heavily in controlled-environment agriculture. By contrast, Nigeria's hydroponic sector remains underdeveloped, constrained by high initial capital costs, limited technical expertise, and insufficient policy support. Although several pilot projects have been initiated by universities, non-governmental organizations, and private firms, there is still a lack of systematic, peer-reviewed research evaluating the performance of these systems under local conditions (Ogunleye et al., 2025).

Existing literature in Nigeria focuses primarily on hydroponic fodder production for livestock, leaving a critical gap in research regarding vegetable crops. A notable exception is the work of Tajudeen and Taiwo (2018), who advocated for the adoption of soilless farming to help achieve the Sustainable Development Goals. More recently, Makka et al. (2024) analyzed the economics of irrigated tomato production in Gombe State; while they highlighted the profitability of dry-season farming, they also underscored its heavy reliance on irrigation and the severe challenges posed by regional water scarcity.

The present study addresses these gaps by designing, developing, and testing a closed-loop hydroponic system tailored for tomato cultivation in northeastern Nigeria. By generating empirical data on plant growth, crop yield, and resource efficiency, this research aims to deliver a locally adaptable, cost-effective, and highly efficient soilless farming solution.

3 Materials and methods

3.1 Study area

The study was conducted at the Biological Sciences research farm, Federal University of Kashere, Gombe State, Nigeria. Gombe State is located in the northeastern region of the country, lying between latitudes 9°30' and 12°30' N and longitudes 8°05' and 11°45' E. Its topography is characterized by mountainous terrain in the southeast and flat, open plains in the central and northern areas. The state covers approximately 20,265 km^2 and has a population exceeding 2.5 million. The climate is tropical, featuring a distinct dry season (November–March) and a wet season (April–October), with an average annual rainfall of approximately 850 mm. The experimental site was equipped with a controlled environment to minimize external climatic interference.

3.2 Construction and set-up of the hydroponic devices

A galvanized greenhouse is essential for establishing an effective hydroponic farming system. A galvanized structure facilitates the control of temperature, humidity, and solar intensity, thereby creating the necessary environmental conditions for optimal plant growth and development (Al-lakhverdiev, 2020). The hydroponic components were assembled inside this greenhouse.

A customized, elongated plastic trough was developed to accommodate the net pots. These net pots were placed into pre-drilled holes along the troughs at intervals of 30 to 40 cm to ensure adequate space for plant growth and proper aeration. Foam cubes were cut to uniform dimensions of 4 to 5 cm using a sharp scalpel. A small cavity was hollowed out in the center of each cube, and the foam was moistened with water. Tomato (*Solanum lycopersicum*) seeds were placed within these cavities and allowed to germinate for two weeks. Following the two-week germination period, the foam cubes containing the seedlings were transferred into the net pots at a density of one cube per pot.

3.3 Hydroponic system configuration and operation

The customized plastic troughs were arranged horizontally and connected sequentially using elbow joints to ensure seamless fluid continuity. The trough assembly featured two primary plumbing lines: (i) an inlet pipe for introducing the nutrient solution, and (ii) an outlet pipe to manage overflow at designated water levels. The inlet pipe delivered a blended water and essential nutrient solution from the mixing chamber into the interconnected troughs, while the outlet pipe recycled the overflow back into the chamber. Consequently, the system operated as a closed-loop recycling mechanism (Halbert-Howard et al., 2021).

To optimize nutrient uptake, the solution was regulated to flow slowly through the troughs. This allowed the roots, extending from the foam cubes inside the net pots, to absorb the surrounding water and nutrients. The net pots provided structural anchorage, while the continuous availability of the nutrient solution facilitated root absorption and xylem conduction, ultimately promoting plant growth and development. Liquid mobility throughout the troughs was driven by a 2-horsepower submersible pump connected to a power source via a timer switch. This pump propelled the solution from the mixing chamber into the primary inlet pipe to initiate system circulation.

3.4 Structural support and water supply

The entire apparatus was suspended on a custom-fabricated iron frame designed as a stationary platform. A 3,000-liter water reservoir tank was positioned adjacent to the system and linked to the

nutrient mixing chamber via a medium-diameter plastic hose to maintain a continuous water supply. The primary water source was a functional borehole or a standard well (Griebel et al., 2022).

3.5 Ancillary components and plant materials

Additional materials utilized for the hydroponic setup included fabricated plastic seedling trays for germination, various diameters of connection tubing for advanced plumbing configurations, and specialized scarification mixtures for seed pretreatment to enhance germination speed and success rates.

3.6 Potted plants as experimental control

Viable tomato seedlings were randomly transferred into 150 pots filled with rich loamy soil. These pots, purchased from the Dadin Kowa Horticultural Center in Gombe, were prepared concurrently with the loading of viable seedlings into the hydroponic device. Each experimental setup was split into three groups and subjected to identical environmental conditions.

3.7 Tools for environmental factor evaluation

A pH meter was used to determine the acidity or alkalinity of both the water/nutrient solution (Capodaglio et al., 2016) and the soil used in the control experiment. The gathered data were documented in a physical logbook and a digital backup was created. Furthermore, an environmental data logger was utilized to monitor environmental parameters, including temperature, light intensity, humidity, carbon dioxide, and dissolved oxygen (Fat et al., 2023). These data were similarly recorded in a logbook and saved digitally.

3.8 Data collection and analysis

3.8.1 Morphological parameters

Morphological data were collected over a seven-week period. Following the methodology of Abdullateef et al. (2023), the recorded parameters included plant height, leaf size (calculated as leaf length multiplied by breadth, by constant k), stem girth, number of leaves, and number of branches. Plant height, leaf length, and leaf breadth were measured using a standard meter rule, while stem girth was determined using a Titan 23175 electronic digital caliper.

3.8.2 Reproductive parameters

The following reproductive characteristics were recorded after anthesis (flower emergence):

- Number of flowers/buds
- Number of fruits
- Fruit size (Abdullateef et al., 2023)

Collected data were analyzed using SPSS (Version 20). An Analysis of Variance (ANOVA) test was utilized to evaluate the relationships between the dependent and independent variables. Finally, the two experimental setups were compared to elucidate the results.

4 Results and discussion

The growth and morphological parameters of tomato plants cultivated under hydroponic and soil-based systems are presented in Table 1. The study evaluated four treatment combinations: UC Hydro-

ponics, Ruma Hydroponics, UC Soil, and Ruma Soil. The assessed variables included plant height, leaf and branch numbers, leaf size, stem girth, as well as bud and fruit counts.

Table 1. Mean values of morphological and reproductive parameters.

Morphological/Reproductive Parameters	UC Hydroponics	Ruma Hydroponics	UC Soil	Ruma Soil
	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Plant height (cm)	29.94 ± 1.00	30.73 ± 1.23	34.49 ± 0.14	35.90 ± 0.13
Number of leaves	32.65 ± 1.10	20.98 ± 0.60	26.13 ± 0.61	22.97 ± 0.58
Number of branches	11.09 ± 0.35	7.07 ± 0.20	7.41 ± 0.16	6.84 ± 0.18
Leaf size (cm^2)	13.89 ± 0.28	11.62 ± 0.23	6.92 ± 0.14	6.83 ± 0.13
Stem girth (cm)	1.56 ± 0.03	1.37 ± 0.04	0.96 ± 0.01	0.92 ± 0.01
Number of flowers	20.62 ± 1.08	17.65 ± 0.67	11.32 ± 0.81	19.95 ± 0.70
Number of fruits	16.78 ± 2.19	15.44 ± 1.29	10.19 ± 1.37	16.47 ± 1.53
Fruit size (cm)	5.41 ± 0.49	5.15 ± 0.54	3.89 ± 0.83	4.72 ± 0.43

Note: Values are mean ± standard error.

4.1 Plant height

The analysis of plant height revealed a significant difference among the four treatment groups ($p < 0.001$). Ruma Soil recorded the highest mean plant height (35.90 ± 0.13 cm), followed by UC Soil (34.49 ± 0.14 cm), while Ruma Hydroponics and UC Hydroponics exhibited lower values at 30.73 ± 1.23 cm and 29.94 ± 1.00 cm, respectively. Bonferroni post-hoc comparisons indicated that plants in UC Hydroponics were significantly shorter than those in UC Soil ($p = 0.015$) and Ruma Soil ($p = 0.001$). Similarly, plants in Ruma Hydroponics were significantly shorter than those in Ruma Soil ($p = 0.004$). Conversely, no significant differences in plant height were observed between UC Hydroponics and Ruma Hydroponics ($p = 1.000$), nor between UC Soil and Ruma Soil ($p = 1.000$).

These findings demonstrate that soil-grown plants achieved greater heights than their hydroponically grown counterparts. This outcome contrasts with the findings of Kaushal et al. (2023), who reported significantly greater plant height in tomato varieties cultivated under a circulated nutrient film technique (NFT) hydroponic system compared to traditional soil cultivation. Their study, which evaluated Roma, Tolstoi, and Russian Yellow tomato varieties, demonstrated enhanced plant height, leaf number, fruit number, and overall yield within the NFT hydroponic system. Similarly, Olubanjo and Alade (2018) observed superior plant heights in tomatoes grown using rice-husk and sawdust substrates than in soil. Specifically, rice husk yielded the maximum plant height of 42.74 cm compared to 27.80 cm in soil. The authors attributed these variations to the distinct physicochemical properties of the growing media and the respective planting methods.

Although the plant height findings in this study deviate from previous literature, these discrepancies may stem from variations in hydroponic system design, nutrient formulation, plant genotype, and environmental conditions. Hydroponic cultivation does not inherently guarantee greater plant height; rather, vegetative performance depends heavily on the precise conditions maintained within the root zone. For instance, Nasir and Sato (2023) demonstrated that nutrient solution concentration significantly influences tomato growth, yield, and fruit quality in hydroponic systems. Therefore, the relatively greater height of the soil-grown plants in this study does not necessarily indicate the

overall superiority of soil cultivation, as other critical growth and reproductive parameters favored the hydroponic treatments.

4.2 Number of leaves

Regarding the number of leaves, a significant difference was observed among the four treatments ($p < 0.001$). UC Hydroponics recorded the highest mean number of leaves (32.65 ± 1.10), followed by UC Soil (26.13 ± 0.61), Ruma Soil (22.97 ± 0.58), and Ruma Hydroponics (20.98 ± 0.60). The Bonferroni post-hoc test revealed that UC Hydroponics differed significantly from Ruma Hydroponics, UC Soil, and Ruma Soil (all $p < 0.001$). Ruma Hydroponics also differed significantly from UC Soil ($p < 0.001$). However, no significant differences were found between Ruma Hydroponics and Ruma Soil ($p = 0.660$) or between UC Soil and Ruma Soil ($p = 0.150$).

These findings indicate that the hydroponic system generally optimized leaf yield compared to soil-based cultivation, depending on the genotype. This outcome aligns with the work of Kaushal et al. (2023), who observed enhanced leaf production in tomato plants grown under Nutrient Film Technique (NFT) hydroponics compared to soil cultivation. Their study similarly reported significant improvements in plant height, number of leaves, and other vital growth and yield characteristics within hydroponic systems.

This finding is consistent with the work of Olubanjo and Alade (2018), who reported a significantly higher number of leaves in tomato plants grown on rice husk and sawdust substrates than those grown in soil. Specifically, their rice-husk treatment yielded an average of 120.60 leaves per plant compared to 67.40 leaves under conventional soil cultivation.

4.3 Number of branches

Regarding the number of branches, the treatments exhibited a statistically significant difference ($p < 0.001$). UC Hydroponics recorded the highest mean number of branches (11.09 ± 0.35), followed by UC Soil (7.41 ± 0.16), Ruma Hydroponics (7.07 ± 0.20), and Ruma Soil (6.84 ± 0.18). The Bonferroni post-hoc analysis revealed that the mean for UC Hydroponics was significantly different from those of Ruma Hydroponics, UC Soil, and Ruma Soil ($p < 0.001$). However, no significant differences were observed among Ruma Hydroponics, UC Soil, and Ruma Soil. This outcome aligns with Olubanjo and Alade (2018), who noted superior vegetative growth performance in tomato plants cultivated using soilless media compared to soil-based methods.

4.4 Leaf size

Similarly, leaf size differed significantly among the four treatments ($p < 0.001$). UC Hydroponics produced the largest mean leaf size (13.89 ± 0.28 cm^2), followed by Ruma Hydroponics (11.62 ± 0.23 cm^2), UC Soil (6.92 ± 0.14 cm^2), and Ruma Soil (6.83 ± 0.13 cm^2). The Bonferroni post-hoc test demonstrated that UC Hydroponics differed significantly from Ruma Hydroponics, UC Soil, and Ruma Soil ($p < 0.001$). Additionally, Ruma Hydroponics varied significantly from both soil-based treatments ($p < 0.001$). Conversely, the difference between UC Soil and Ruma Soil was not statistically significant ($p = 1.000$). The enhanced leaf size observed in the soilless systems indicates that the hydroponic environment provided more favorable conditions for leaf expansion than traditional soil media.

These findings align with previous research by Kaushal et al. (2023), who demonstrated enhanced vegetative development in tomatoes under soilless and hydroponic cultivation. They reported improved growth characteristics in tomatoes cultivated using the nutrient film technique (NFT)

compared to conventional soil cultivation. Similarly, Olubanjo and Alade (2018) observed superior vegetative performance in tomato plants grown on soilless substrates relative to soil-grown plants. Furthermore, Nasir and Sato (2023) demonstrated that the electrical conductivity of the nutrient solution directly influences tomato growth in hydroponic systems, reinforcing the critical role of nutrient management in modulating plant growth responses.

4.5 Stem girth

Regarding stem girth, the results revealed a highly significant difference among the treatments ($p < 0.001$). UC Hydroponics recorded the highest mean stem girth (1.56 ± 0.03 cm), followed by Ruma Hydroponics (1.37 ± 0.04 cm), UC Soil (0.96 ± 0.01 cm), and Ruma Soil (0.92 ± 0.01 cm). A Bonferroni post-hoc analysis indicated that the stem girth for UC Hydroponics was significantly larger than that of Ruma Hydroponics, UC Soil, and Ruma Soil (all $p < 0.001$). Ruma Hydroponics also differed significantly from both soil treatments ($p < 0.001$). However, no significant difference was observed between UC Soil and Ruma Soil ($p = 1.000$).

The greater stem girth observed in the hydroponic treatments suggests enhanced structural development under soilless cultivation conditions compared to traditional soil media. This outcome corroborates the findings of Olubanjo and Alade (2018), who reported greater stem girths in tomatoes cultivated on a rice-husk substrate (0.5677 cm) than in soil (0.4155 cm). They attributed these variations to the distinct physicochemical characteristics of the growing media and the specific planting methods employed.

The plants at the flowering and fruiting stages are shown in Figure 1.

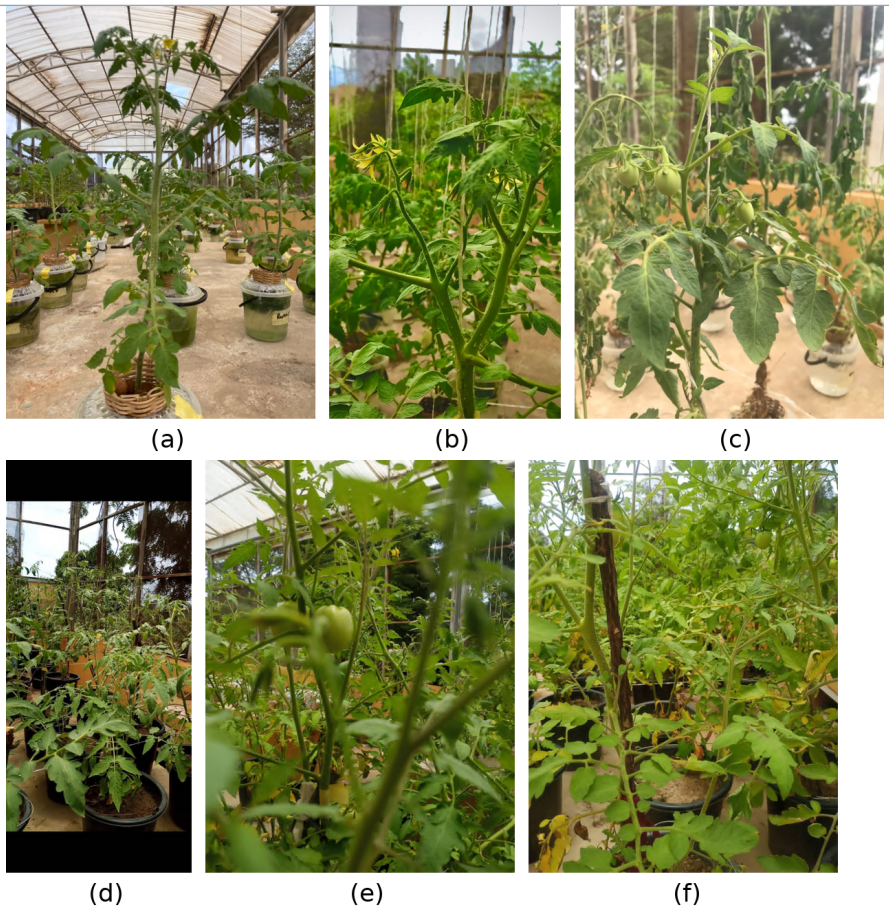


Figure 1. Tomato plants in the hydroponic system at (a, b) flowering and (c) fruiting stages, and in soil at (d) flowering and (e, f) fruiting stages.

4.6 Reproductive parameters

The evaluated reproductive parameters (number of flowers, number of fruits, and fruit size) varied significantly among the four treatment groups. UC Hydroponics recorded the highest mean number of flowers (20.62 ± 1.08), number of fruits (16.78 ± 2.19), and fruit size (5.41 ± 0.49 cm). Ruma Soil followed closely, yielding a mean of 19.95 ± 0.70 flowers and 16.47 ± 1.53 fruits. However, Ruma Hydroponics recorded the second-highest mean fruit size (5.15 ± 0.54 cm), while UC Soil consistently recorded the lowest mean values across all parameters. Overall, the hydroponic treatments yielded a higher mean number of flowers and fruits than the soil treatments, while both hydroponic systems produced larger mean fruit sizes than their soil-based counterparts.

These results align with the findings of Khaleghi et al. (2024), who reported that soilless tomato cultivation increases reproductive parameters, including flower count, fruit count, and other yield-related traits, compared to soil cultivation. They also observed an increased fruit diameter in tomatoes grown in a cocopeat-perlite soilless medium. Furthermore, their study demonstrated that fruit number and diameter are heavily influenced by the interaction between the cultivation system and the nutrient solution, underscoring the critical importance of a balanced, well-managed root-zone nutrient environment during fruit development.

This outcome is further supported by Al-Gaadi et al. (2024), who demonstrated that nutrient solution salinity significantly affects tomato fruit number, fruit weight, and total yield in hydroponic systems. Their findings revealed that excessive salinity reduces overall yield, illustrating that hydroponics can

optimize fruit development only when the root-zone environment is maintained within an ideal range.

The results of this study suggest that hydroponic cultivation provides highly favorable conditions for fruit development, particularly within the UC treatment. This environment is crucial because elevated flower production expands the potential for fruit yield, while a reliable nutrient and water supply directly supports fruit enlargement. Consequently, these findings demonstrate that soilless systems can significantly enhance reproductive and fruit traits when environmental and nutritional conditions are precisely controlled.

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