EFFECTS OF IRRIGATION AND FERTILIZER APPLICATION ON WATER AND FERTILIZER USE AND SOIL ENVIRONMENT IN GREENHOUSE TOMATO (*Solanum lycopersicon* L.)

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by

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LIST OF SYMBOLS

CAT	Catalase
cm	Centimeter
C/N	Carbon/nitrogen ratio
dm^2	Square decimeter
Epan	Pan evaporation
ET	Evapotranspiration
ET_C	Crop Evapotranspiration
Fs	Field water holding capacity
%	Percent
=	Equal
ha	Hectare
g	Gram
$g\ L^{-1}$	Grams per liter
INV	Invertase
K	Potassium
kg	Kilogram
$kg\ hm^{-2}$	Kilograms per hectare
$kg\ kg^{-1}$	Kilograms per kilograms
$kg\ N\ ha^{-1}$	Kilograms of nitrogen per hectare
$kg\ plant^{-1}$	Kilograms per plant
$L\ plant^{-1}$	Liters per plant
min	Minute
mg	Milligram
$mg\ g^{-1}$	Milligram per gram
$mg\ kg^{-1}$	Milligrams per kilogram
$m^3\ ha^{-1}$	Cubic meters per hectare

mm	Millimeter
mM	Millimolar
mL	Milliliter
mL d^{-1}	Milliliters per day
m^3	Cubic meter
mol L^{-1}	Mole per liter
Mha	Million hectares
Mt	Million tons
mg mL^{-1}	Microgram per milliliter
mg L^{-1}	Milligrams per liter
mg H_2O_2 g^{-1}	Milligrams of hydrogen peroxide per gram
mg glucose g^{-1} d^{-1}	Milligrams of glucose per gram per day
N	Nitrogen
NH_3-N g^{-1} d^{-1}	Nitrogen per gram per day
nm	Nanometer
opm	Oscillations per minute
P	Phosphorus
pcs	Pieces
pH	Potential of Hydrogen
PHO	Alkaline Phosphatase
PNP	P-nitrophenol
rpm	Revolutions per minute
r min^{-1}	Revolutions per minute
TN	Total nitrogen
TP	Total phosphorus
TK	Total potassium
t ha^{-1}	Tons per hectare
URE	Urease
μmol PNP g^{-1} h^{-1}	μmol p-nitrophenol released per g soil per hour

$\mu g\ NH_3\text{-}N\ g^{-1}\ d^{-1}$	Micrograms of ammonia nitrogen per gram per day
$\mu g\ mL^{-1}$	Micrograms per milliliter
μL	Microliter

LIST OF ABBREVIATIONS

ANOVA	Analysis Of Variance
ASV	Amplicon Sequence Variant
ACE	Abundance-based Coverage Estimation
AHP	Analytic Hierarchy Process Method
BSA	*Bovine Serum Albumin*
DNA	Deoxyribonucleic Acid
DADA	*Denoising Autoencoder for the Analysis of Amplicon Data*
ICP	Inductively Coupled Plasma spectrometer
GRA	Grey Correlation Analysis
LA	Leaf Area
NUE	Nitrogen Use Efficiency
OTU	Operational Taxonomic Unit
PCA	Principal Component Analysis
PCR	Polymerase Chain Reaction
PCoA	Principal Coordinate Analysis
PFPn	Partial Factor Productivity Nitrogen
RDA	Redundancy Analysis
RNA	Ribonucleic Acid
SPAD	Soil and Plant Analyzer Development
SPAC	Soil-plant-atmosphere continuum
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SNO_3^--N	Soil Nitrate Nitrogen
TMM	Trimmed Mean of M-values
TOPSIS	Technique for Order Preference by Similarity to an ideal Solution
TA	Titratable acid
TSS	Total soluble solids
Vc	Vitamin C
WUE	Water Use Efficiency

LIST OF APPENDICES

KESAN PENGAIRAN DAN APLIKASI BAJA TERHADAP PENGGUNAAN AIR DAN BAJA DAN PERSEKITARAN TANAH PADA TOMATO (*Solanum lycopersicon* L.) DALAM RUMAH HIJAU

ABSTRAK

Pengurusan air dan baja yang cekap adalah penting untuk mengoptimumkan pengeluaran tomato rumah hijau (*Solanum lycopersicon* L.) sambil mengurangkan kesan alam sekitar seperti degradasi tanah, kehilangan nutrien, dan pencemaran. Kajian ini bertujuan untuk: (1) mengkaji kesan corak aplikasi air dan baja ke atas pertumbuhan, fisiologi, pengambilan air, hasil, kualiti buah, nutrien tanah, dan persekitaran mikrob; (2) menilai tindak balas penyerapan nutrien oleh pelbagai bahagian pokok tomato dalam rumah hijau di bawah aplikasi air dan baja yang berbeza; (3) mencadangkan kombinasi optimum isipadu pengairan dan aplikasi bajayang sesuai untuk pengeluaran tomato yang cekap dan berkualiti tinggi dalam rumah hijau. Untuk mencapai matlamat ini, satu eksperimen faktorial telah dijalankan di rumah hijau berkuasa solardi Universiti Yuncheng, Wilayah Shanxi, dengan tiga tahap pengairan—pengairan konvensional (I1, 90%-100% kapasiti lapangan), pengairan defisit ringan (I2, 72%-80% kapasiti lapangan), dan pengairan defisit sederhana (I3, 54%-60% kapasiti lapangan) — digabungkan dengan empat rawatan pembajaan: baja organik larut dan baja kimia (C1), baja kimia larut sahaja (C2), aplikasi asas baja tinja kambing dengan baja kimia (C3), dan baja organik larut sahaja (C4). Rawatan kawalan (CK) tanpa baja juga terlibat, menjadikan jumlah 13 kombinasi rawatan. Hasil kajian menunjukkan bahawa peningkatan pengairan meningkatkan ketinggian pokok, diameter batang, luas daun (LA), dan pengumpulan jisim kering. Di antara rawatan pembajaan, kombinasi baja organik dan kimia (C1) secara signifikan meningkatkan

luas daun (LA), ketebalan batang, hasil buah, nilai SPAD daun, dan jisim kering, dengan jisim kering tertinggi (84.17 g tanaman^{-1}) dan nisbah akar-pucuk (0.112) diperhatikan di bawah pengairan defisit ringan (I2). Kecekapan penggunaan air (WUE) menurun apabila jumlah pengairan meningkat, dengan rawatan C1 menunjukkan WUE tertinggi di semua tahap pengairan. Hasil buah tertinggi direkodkan di bawah I1C1 (2.59 kg pokok^{-1}), sementara I2C1 dikenal pasti sebagai kombinasi air-baja yang optimum untuk pengeluaran tomato yang mampan. Pengambilan nitrogen, fosforus, dan kalium menurun dengan pengurangan pengairan, dengan C1 menunjukkan pengambilan nutrien tertinggi. Aktiviti enzim tanah, kepelbagaian bakteria, dan kandungan bahan organik meningkat secara signifikan di bawah C1, manakala pengairan berlebihan mengurangkan kepelbagaian mikrob dan aktiviti enzim. Pengairan defisit ringan (I2) meningkatkan pH tanah, fosforus tersedia (AP), dan kandungan nitrogen nitrat (NO_3^--N) tanah. Filum bakteria dominan di semua tahap pengairan adalah Actinobacteriota (26.06%), Proteobacteria (25.89%), Chloroflexi (12.42%), dan Acidobacteriota (11.03%), yang berkorelasi dengan aktiviti enzim tanah dan indeks kepelbagaian mikrob. Dengan mengintegrasikan Teknik Kesamaanke Penyelesaian Ideal (TOPSIS), Analisis Hubungan Kelabu (GRA), dan Analisis Komponen Utama (PCA), satu model air-baja yang optimum telah dibangunkan. Tiga aplikasi air-baja yang teratas yang dikenalpasti oleh kaedah masing-masing iaitu: TOPSIS menunjukkan I3C1 > I2C1 > I1C4; GRA menunjukkan I1C1 > I3C1 > I1C4; dan PCA menunjukkan I1C1 > I1C4 > I1C2. Pengairan defisit ringan yang digabungkan dengan baja organik-kimia larut (I2C1) muncul sebagai strategi yang paling berkesan, menyeimbangkan hasil yang tinggi, kesihatan tanah yang lebih baik, dan penggunaan air dan baja yang mampan. Penemuan ini memberikan pandangan praktikal untuk mengoptimumkan pengairan dan pembajaan dalam pengeluaran tomato dalam rumah hijau, menyokong pertanian berkualiti tinggi, cekap sumber yang cekap, dan pertanian mampan yang mesra alam.

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ABSTRACT

Efficient water and fertilizer management is crucial for optimizing greenhouse tomato (*Solanum lycopersicon* L.) production while mitigating environmental impacts such as soil degradation, nutrient loss, and pollution. This study aims to: (1) study the effects of water and fertilizer application patterns on growth, physiology, water consumption, yield, fruit quality, soil nutrients and microbial environment; (2) evaluate the response of the nutrient absorption of various parts of greenhouse tomato under different application of water and fertilizer; (3) propose the optimal combination of irrigation volume and fertilizer application suitable for efficient and high-quality tomato production in greenhouses. To achieve these goals, a factorial experiment was conducted in a solar greenhouse at Yuncheng University, Shanxi Province, with three irrigation levels—conventional irrigation (I1, 90%-100% field capacity), light deficit irrigation (I2, 72%-80% field capacity), and moderate deficit irrigation (I3, 54%-60% field capacity)—combined with four fertilization treatments: soluble organic and chemical fertilizers (C1), soluble chemical fertilizers only (C2), basal application of sheep manure with chemical fertilizers (C3), and soluble organic fertilizers only (C4). A control treatment (CK) with no fertilizer was also included, totaling 13 treatment combinations. The results indicate that increased irrigation enhances plant height, stem diameter, leaf area (LA), and dry matter accumulation. Among fertilization treatments, the combination of organic and chemical fertilizers (C1) significantly improved leaf area (LA), stem thickness, fruit yield, leaf SPAD (Soil and Plant Analysis

Development) value, and dry matter, with the highest dry matter mass (84.17 g plant^{-1}) and root-shoot ratio (0.112) observed under light deficit irrigation (I2). Water use efficiency (WUE) decreased as irrigation volume increased, with C1 treatment exhibiting the highest WUE across all irrigation levels. The highest fruit yield was recorded under I1C1 (2.59 kg plant^{-1}), while I2C1 was identified as the optimal water-fertilizer combination for sustainable tomato production. Nitrogen, phosphorus, and potassium uptake declined with reduced irrigation, with C1 demonstrating the highest nutrient uptake. Soil enzyme activities, bacterial diversity, and organic matter content were significantly improved under C1, whereas excessive irrigation reduced microbial diversity and enzyme activity. Slight deficit irrigation (I2) improved soil pH, available phosphorus (AP), and soil nitrate nitrogen (NO_3^--N) content. The dominant bacterial phyla under all irrigation levels were Actinobacteriota (26.06%), Proteobacteria (25.89%), Chloroflexi (12.42%), and Acidobacteriota (11.03%), which correlated with soil enzyme activities and microbial diversity indices. By integrating the Technique for Order Preference by Similarity to an ideal Solution (TOPSIS), Grey Relational Analysis (GRA), and Principal Component Analysis (PCA), an optimized water-fertilizer model was constructed. The top three water-fertilization application identified by the respective methods were: TOPSIS showed I3C1 > I2C1 > I1C4; GRA indicated I1C1 > I3C1 > I1C4; and PCA revealed I1C1 > I1C4 > I1C2. Light deficit irrigation combined with soluble organic-chemical fertilizers (I2C1) emerged as the most effective strategy, balancing high yield, improved soil health, and sustainable water and fertilizer use. These findings provide practical insights for optimizing irrigation and fertilization in greenhouse tomato production, supporting high-quality, resource-efficient, and environmentally sustainable agriculture.

CHAPTER 1

INTRODUCTION

1.1 Introduction

With rapid development of the agricultural economy in recent years, the greenhouse vegetable industry has increasingly gained prominence in the new agricultural production system (Li et al., 2022). Greenhouse cultivation regulates internal climatic and soil environments to reduce environmental dependence, breaking the constraints of seasonal and temperature fluctuations on vegetable growth (Li et al., 2022; Liantas et al., 2023), which significantly enhances crop yield and quality. This practice yields substantial economic and social benefits (Yang et al., 2016). However, greenhouse vegetable production often leads to water-fertilizer waste and soil degradation issues (e.g., salinization, nutritional imbalance) due to high replanting indices, frequent irrigation, and excessive fertilization (Awadelkareem et al., 2023; Wu et al., 2020). These problems accelerate pest spread and compromise yield and quality. Thus, establishing a practical greenhouse water-fertilizer management model is critical for sustaining high-yield vegetable production and improving greenhouse soil ecology.

Optimizing water-fertilizer management based on crop requirements is crucial for high-quality vegetable production with efficient resource utilization. Regulating water and fertilizer supply timing and patterns can enhance utilization efficiency and mitigate environmental pollution. In greenhouse cultivation, artificial irrigation and fertilization are the primary means of supplying water and nutrients to crops.

Tomato, as the most widely cultivated greenhouse crop (Chen et al., 2023), requires adequate water but is sensitive to waterlogging (Tareq et al., 2020). Irrigation not only meets growth water demands but also regulates soil temperature and leaches soil salinity. However, excessive irrigation can induce pest outbreaks, root hypoxia, nutrient leaching, and elevated greenhouse humidity, reducing yield and quality (Li et al., 2017; Qu et al., 2020). Regarding fertilization, China's annual chemical fertilizer production and consumption exceed 60 million tons, accounting for approximately USD 25 billion in annual expenditure (based on an average price of USD 417/ton) (Shen et al., 2021), with nitrogen application rates reaching 2,000–4,000 kg hm^{-2}—far exceeding crop needs (Lv et al., 2019). This overfertilization causes nitrate accumulation, low nitrogen use efficiency (Lv et al., 2019; Truffault et al., 2019), and increased nitrate content in soil and crops, deteriorating fruit quality (Norse & Ju, 2015). Evidently, sustainable greenhouse tomato production hinges on optimized water-fertilizer management (Wu et al., 2021), necessitating strategies that balance high yields with minimal nutrient loss.

The concept of water-fertilizer coupling, refers to the agroecosystem where irrigation and fertilization are integrated in timing, quantity, and mode to interact and influence crop growth (Liu et al., 2023). Its core lies in organically linking water and fertilizer—key factors for crop growth—to leverage their synergistic effects, enhance productivity and resource efficiency, and achieve the goals of "fertilizer promotion via water" and "water regulation via fertilizer". This approach is vital for conserving water-fertilizer resources and protecting the environment (Moigradean et al., 2008; Wang & Zhang, 2021). Fully water-soluble fertilizers have been shown to increase yields while reducing nitrate leaching (Wu et al., 2020). Water-fertilizer coupling technology is widely recognized as an effective method to improve resource utilization (Dai et al., 2019; Ma et al., 2022; Wang et al., 2018) and mitigate greenhouse gas emissions (Guardia et al., 2017). However, comprehensive data on integrating organic and mineral fertilizers in water-fertilizer systems remain limited (Wu et al., 2020). Thus, clarifying the impacts of water-fertilizer irrigation with soluble organic-inorganic fertilizers on soil environment in tomato production—and identifying optimal management strategies—is essential for sustaining soil health and agricultural sustainability.

Water resources are crucial for human survival and global agriculture (Shen & Chen, 2010). Freshwater scarcity has severely constrained agricultural development. Arid and semi-arid regions encompass approximately 30% of the Earth's terrestrial surface, with an estimated 50% of this geographical classification located within the borders of China (Qu et al., 2020). Agriculture is the largest consumer of freshwater globally; in 2019, China's total water use reached 6,021.20 billion m^3, incurring annual water costs of USD 15.37 billion (at USD 0.04/m^3), with agriculture accounting for 61.16% (3,682.30 billion m^3) (Gu et al., 2023; Ju et al., 2023), yet crop water use efficiency is below 60% (Calzadilla et al., 2011). Controlled environment agriculture necessitates an extensive volume of water; in the year 2012, the average irrigation requirement for controlled vegetable production was quantified at 10,800 m^3 ha^{-1}, culminating in an annual consumption of 16.2 billion m^3, which accounts for 5% of the total irrigation water utilized for agricultural land (Qu et al., 2020). Wastage in this sector exacerbates water scarcity. As China's economy grows, industrial and urban water use increases while agricultural use declines (Pan et al., 2022), intensifying the water shortage in agriculture. Thus, improving water use efficiency in facility vegetable cultivation is vital for sustainable development (Dong et al., 2018). Research indicates that water stress can boost efficiency (Bogale et al., 2016; Wu et al., 2021; Yang et al., 2017), and factors like weather and soil also play roles (Kuschel-Otárola et al., 2020; Zhang et al., 2017). Hence, agricultural research should prioritize enhancing water efficiency over just increasing yields.

China leads the world in chemical fertilizer production and consumption, with 60.23 million tons used in 2015 (Wang, 2019). From 2006 to 2015, fertilizer use increased by 22.2%, but grain yield rose only 24.8%, indicating diminishing returns from simply increasing application (Wang, 2019). In response, China's "Zero Fertilizer Growth Action" in the 13th Five-Year Plan reduced consumption to 54.03 million tons by 2019 (Zhang & Qiu, 2019). However, despite government efforts, over-fertilization persists, especially in facility vegetable cultivation, as farmers prioritize yield and profits. Excessive fertilizer use, including unbalanced NPK ratios and heavy irrigation, has severe environmental and agronomic consequences. It degrades soil organic matter and structure, reduces water and nitrogen use efficiency, and causes nitrogen leaching (Asibi et al., 2022; Liu et al., 2023). This contaminates surface and groundwater, endangering drinking water safety (Shah et al., 2020; Wu et al., 2020) and exacerbating crop diseases while lowering produce quality (Wang et al., 2002). Conversely, scientific fertilization not only supplies essential nutrients (Wang et al., 2021) but also enhances nutrient effectiveness (Ge et al., 2008).

Compared to chemical fertilizers, organic fertilizers offer comprehensive nutrients with sustained effects. They contain proteins, amino acids, and cellulose, which boost soil organic matter and improve its chemical and physical properties, enhancing fertility (Zhang et al., 2018). This stimulates soil microbial activity, enriches organic content, and elevates crop quality (Gong et al., 2019). Expanding organic fertilizer use reduces chemical reliance, enabling high-yield, high-quality vegetable production—a crucial step for green agriculture (Nguyen et al., 2015). However, organic fertilizers, mainly used as base fertilizers, have limitations. Their lower nutrient density, slow mineralization, and complex production processes pose challenges. In agricultural facilities, overuse can lead to nitrogen and phosphorus runoff (Evanylo et al., 2008) and increased heavy metal levels (Xia et al., 2021), despite initial benefits to soil and crops.

Organic agriculture, a prominent sustainable production approach (Mufti et al., 2022), relies on organic fertilizers to enhance soil fertility and manage pests and diseases (Liu et al., 2016). However, current challenges limit its widespread adoption: organic fertilizers face a supply-demand gap due to scarcity and high costs, while their slow mineralization hinders timely nutrient delivery during crops' critical reproductive stages (Wan et al., 2021). Soluble or liquid organic fertilizers offer an advantage over traditional manure and compost, efficiently balancing nutrient uptake and supply to boost fertilizer utilization (Cavalli et al., 2017).

Long-term experience shows that organic and inorganic fertilizers each have unique benefits and drawbacks in agriculture. Thus, developing a fertilization strategy that maximizes yield, quality, and sustainability is crucial. Combining organic additives with chemical fertilizers emerges as a promising approach for sustainable farming (Susanti et al., 2023). Liang et al. (2022) demonstrated that liquid organic-inorganic blends enhance cotton growth and yield. However, whether such blends adequately meet the nutrient needs of greenhouse tomato production remains unclear. This knowledge gap has drawn researchers' attention to optimizing organic-inorganic fertilizer ratios. Identifying ideal water-fertilizer management strategies and determining the optimal blend ratio to improve soil quality are vital for the sustainable development of facility agriculture.

1.2 Problem statements

The response of greenhouse tomatoes to water and fertilizer application patterns can be further studied in the following aspects:

(1) The problems of water and fertilizer waste, soil degradation and declining crop quality in greenhouse vegetable cultivation have not been solved. Current practices, such as intensive irrigation and excessive chemical fertilizer application, lead to low water use efficiency (less than 60% in crops), causing annual water waste costs exceeding USD 2.5 billion (based on 30% inefficiency of 60 billion m^3 water use), serious nitrate accumulation in soil, and accelerated spread of pests and diseases. It is necessary to determine the most suitable application pattern of water and fertilizer that can improve the soil environment (e.g., alleviate salinization and nutrient imbalance) and achieve high-yield, high-quality and efficient production of greenhouse crops, while addressing the contradiction between water scarcity and excessive irrigation in facility agriculture.

(2) At present, there are many research reports on the effects of different fertilizer types on vegetable growth, yield and quality. However, in the water and fertilizer management of facility vegetables, organic fertilizer is still applied as a large amount of one-time application of the base fertilizer, resulting in slow nutrient release and mismatch with crop demand during critical growth stages. The research on integrating organic and chemical fertilizers through water-fertilizer integration systems to optimize tomato growth and soil health is rarely reported, especially regarding the coupling effects on yield formation and environmental pollution reduction.

(3) Previous research on organic fertilizers mainly focused on increasing the application of organic fertilizers under equal fertilizer rates. However, the effects of different fertilization patterns under equal nitrogen application rates on the changes in the facility soil environment and the distribution of nutrients still need to be explored in depth.

Specifically, how the organic and inorganic fertilizer affects soil microbial activity, nutrient leaching, and root uptake efficiency remains unclear, as well as the optimal balance between reducing chemical fertilizer dependency and maintaining soil fertility for sustainable tomato production.

1.3 Research objectives

This study aims to investigate the effects of different irrigation volumes and fertilizer application patterns on tomato growth, yield, water and nutrient use efficiency, and soil environment under water-saving irrigation conditions. Specifically, the research is structured to systematically address the following objectives across different chapters:

(1) Chapter 3: To study the effects of water and fertilizer application patterns on the growth, physiological characteristics of greenhouse tomatoes.

(2) Chapter 4: To reveal the effects of water and fertilizer application patterns on water consumption, yield, quality, water-nitrogen use efficiency of greenhouse tomatoes.

(3) Chapter 5: To evaluate the response of the nutrient absorption of various parts of greenhouse tomato under different water and fertilizer supply modes.

(4) Chapter 6: To investigate the effects of water and fertilizer application patterns on the soil nutrients and microbial environment of greenhouse tomatoes.

(5) Chapter 7: To propose the optimal combination of irrigation volume and fertilization pattern suitable for efficient and high-quality tomato production in local greenhouses.

CHAPTER 2

LITERATURE REVIEW

2.1 Tomato

The cultivated tomato (*Solanum lycopersicum* L.) is a non-woody vegetable in the Solanaceae family (Alordzinu et al., 2021). Tomatoes are inexpensive and nutrient-dense due to their abundance in vitamins, minerals, and antioxidants including phenolic compounds and beta-carotene, which support a healthy diet and guard against cancer and degenerative diseases (Ahmed et al., 2023; Zhang et al., 2024). Tomatoes are the second most popular vegetable worldwide (after potatoes) which is extensively grown all over the world, particularly in dry and semi-arid areas. The main nations that produce tomatoes are China, India, the United States, Turkey, Egypt, and Italy (Agila et al., 2021). In 2019, the total area planted with tomatoes worldwide was 5.03×10^6 ha, while the annual yield was 1.81×10^8 tons (FAO, 2018).

2.1.1 History of cultivation

Tomatoes originated in the Andean Region of South America, where wild varieties are still seen flourishing in their native environment (Rezk et al., 2021). The cherry tomato (*S. lycopersicum* var. cerasiforme), which was most likely cultivated from the red-fruited wild variety *Solanum pimpinellifolium*, is thought to be the likely ancestor of the big-fruited tomato (Ranc et al., 2008). The tomato was first domesticated in the Andes (Peruvian hypothesis), then in Central America (Mexican hypothesis), where it was brought to Europe by the Spanish. From there, it spread throughout Europe and the rest of the world, including southern and eastern Asia, Africa, and the Middle East (Caliskan, 2012; Wakil et al., 2018).

Tomatoes were mostly utilized as ornamentals when they first came to Europe in the 16th century due to their resemblance to poisonous lycopersicon plants, like belladonna and mandarins. As a result, until the late 17th or early 18th century, the fruit in Italy was primarily used as a garnish and was not included into the local cuisine (Bergougnoux, 2014).

According to historical narratives, tomatoes were likely first brought to the provinces of Guangdong and Guangxi during the Wanli Emperor's reign in the Ming Dynasty. At that time, they were cultivated more as decorative plants or medicinal herbs than as food crops. Tomatoes were not frequently grown as a vegetable in China until about a century ago, which marked a significant shift in both agricultural and culinary importance (Zhang & Xiang, 2016).

2.1.2 Variety

Tomato (*Solanum lycopersicon*), with its wild and cultivated forms, is a prime example of a highly diverse plant group (Bergougnoux, 2014). In the last eight decades, over 10,000 tomato varieties have been created as a result of intensive breeding efforts aiming at improving a wide range of qualities like fruit size, shape, and tolerance to environmental challenges and illnesses (Bhattarai et al., 2018).

Tomatoes can be classified in a variety of ways based on their genetic makeup, use, color, size, and ripeness. Tomatoes are divided genetically into hybrids and conventional types, with hybrids usually displaying higher phenotypic variability and superior agronomic response, while conventional types include local varieties and advanced lines with specific market demand (Carrillo-RodrÃguez et al., 2019). Tomatoes can be classified as fresh, canned, or processed, with fresh tomatoes being preferred due to their biochemical characteristics, which include high quantities of ascorbic acid and antioxidants. However, the exact attributes may change depending on ripening and storage circumstances. In terms of fruit color, tomatoes come in a variety of shades, including pink, red, purple, and other colorful variations, with the pink fruit being particularly ideal for fresh eating because of its appealing biochemical features (Molchanova & Kondratyeva, 2024). In terms of size, tomatoes are categorized into large, medium and cherry varieties, each catering to different market needs and consumer preferences. Tomatoes that are picked at different stages of ripeness (such as ripe green, transformed, and red) might acquire identical quality after shelf ripening; hence this classification is essential for choosing harvest time and post-harvest care (Gawęda & Jędrszczyk, 2020).

Tomatoes come in a variety of varieties, each having special traits and applications. Cherry tomatoes are petite and delicious, which makes them perfect for salads and snacking. Some varieties have been investigated for their resistance to breaking and fruit drop (Oluk et al., 2019). Grape tomatoes, comparable in size to cherry tomatoes, are famous in Brazil for their sweetness and versatility in culinary application, and hybrids such as Aiko and Sweet Heaven have high sugar content and antioxidant activity (Eisele et al., 2023). Roma tomatoes are recognized for their elongated shape and substantial flesh and frequently used in sauces and pastas. The San Marzano tomato is a traditional regional Italian variety, noted for its rich flavor and used in cuisine worldwide. Mutations of this variety have offered interesting morphological and compositional diversity while keeping its original type (Dono et al., 2020).

Large, red or pink fruits with an average weight of 150 – 200 grams are the most frequent variety in China (Mu et al., 2017). Sainfoin is becoming more and more popular to grow in China's Hainan Province because of its flavor and nutritional worth, particularly for the Qianxi variety. China still only grows a small portion of its tomatoes for food, even if cherry tomatoes have gained popularity among urban customers (Sun et al., 2023). Tomato plants have two distinct growth habits: determinism and indeterminism, which considerably influence their adaptability for different growing seasons and environments. Specific types with more compact development and definite flowering times are frequently favored for mechanized harvesting in short growing seasons or controlled conditions. These genotypes offer better yields per plant and are easier to handle for pest management and harvesting. The growth season and environmental factors play a major role in the variety selection process. A firm tomato variety should be chosen if an early spring harvest in a greenhouse is advised. Early harvest is preferred because of their regular fruit set and compact growth habit (Xu et al., 2000). The indeterminate varieties are more widely used in the heating glass house production process. In the northwest, processing tomatoes also requires a determinate growth habit without stem cutting and assistance (Korol, 2022).

2.1.3 Physiological and morphological characters

Tomato is an annual plant that can grow up to two meters in height, particularly if its growth behavior is erratic. Its characteristics include constant growth and blooming during the growing season (Kumar et al., 2023). However, because of the favorable climate in South America, tomato plants can be picked year after year due to perpetual growth. The first harvest often occurs 90-120 days after seeding, or 45-55 days after flowering, depending on the cultivar and the surrounding circumstances. Fruit shapes vary from cultivar to cultivar. The color spectrum is yellow to crimson (Burbano-Erazo et al., 2022).

Tomato possesses a variety of physiological and morphological traits that are critical to its cultivation and breeding. Tomato genotypes differed significantly morphologically in terms of fruit weight, pericarp thickness, pericarp number, and soluble dry matter content; mean fruit weights ranged from 74.83 g to 553.11 g, and average pericarp thickness was 7.38 mm (Kiymaci et al., 2024). Tomato plants have a robust tap root system that can reach a depth of at least 50 cm. The main root of the plant produces thick lateral and adventitious roots (Geng et al., 2023). Tomato plants grow in a variety of positions, from erect to prone, depending on variety and environmental conditions. Tomato plants can grow to reach anywhere between 2 and 4 metres tall. The stems of tomato plants are solid, rough, hairy, and glandular, as is typical of the Solanaceae family (Xu et al., 2000). Tomato has a wide range of leaf morphology, which can influence overall growth and fruit quality. The leaves are commonly arranged in a spiral pattern, measuring 15-50 cm in length and 10-30 cm in breadth. These leaves are distinguished by round-to-round leaflets covered in glandular hairs, which aid the plant's defense system and overall health (Bhattarai et al., 2018).

Tomato flowers often have both male and female reproductive components, they are ideal flowers and encourage self-pollination. These regular-shaped flowers have a diameter of 1.5–2 cm and can grow in pairs or in between leaves. The bloom petals are housed in the short, hairy stamens. Tomato flowers usually feature six petals, which are yellow and inverted when ripe and can reach a length of 1 cm. The style, which is elongated and sterile at the top, is surrounded by bright yellow leaves and six stamens in these blooms. The formation of fruit depends on the ovary, which is superior and has two to nine chambers (Kumar et al., 2023). Even though tomatoes are mostly auto flowering plants, heterogametic pollination can happen, particularly when pollination agents like bees and bumblebees are present (Liu et al., 2022). Tomato fruits are typically juicy berries with a diameter of 2 to 15 cm. They can be globular or oblate in shape. Rounded, smooth, or wrinkled, ripe tomatoes might be yellow, orange, or red, whereas unripe tomatoes are green and hairy (Penchovsky & Kaloudas, 2023). Tomato seeds are abundant, kidney or pear shaped, light brown in color, and hairy. The seeds range in weight from 2.5 to 3.5 g. These seeds are not only necessary for plant reproduction and dissemination, but they also have significant agronomic importance because of their impact on crop output and quality (Chen et al., 2023).

2.1.4 Distribution in China

Tomato agriculture in China is extensively distributed, covering various regions from the south to the north, creating apparent regional features and seasonal production patterns. In China, there are four distinct ecological tomato districts based on climate. The provinces of Shandong, Hebei, and Henan have the biggest tomato planting scale.

Southern District: The southern regions of the provinces of Fujian, Guangdong, Guangxi, and Yunnan are included in this district, together with Hainang and Taiwan. This region experiences moderate and humid weather. It is possible to grow tomatoes all year long.

The Middle and Eastern District comprises the following areas: Zhejiang, Jiangxi, Hunan, Hubei, Guizhou, and Sichuan; the southern portions of Jiangsu and Anhui; and the northern portions of the provinces of Fujian, Guangdong, Guangxi, and Yunnan. Four distinct seasons, particularly rainy springs and hot summers, define the district's environment.

Northern District: The entire provinces of Hebei, Shandong, Shanxi, Gansu, Ningxia, Xinjiang, Qinghai, Neimeng, and Tibet are included in the Northern District, as are the northern portions of Jiangsu, Anhui, Henan, and Shanxi. This region has a continental climate, which is characterized by low humidity and abundant light. With a high yield and comparatively large fruit, it is one of the most popular varieties for producing tomatoes.

Northeastern District: The Northeastern District is made up of three northeastern provinces: Heilongjiang, Liaoning, and Jilin. Summers are short in this district while winters are long. Tomato plants have a brief growth season (Xu et al., 2000).

2.1.5 Use of tomato in cooking and medicinal purpose

Tomatoes are available all year and can be eaten raw or cooked. They are used in huge numbers to make soup, juice, ketchup, puree, paste, and powder; they provide ascorbic acid and provide a range of colors and flavors to meals. Furthermore, tomatoes are a staple food in the human diet, appearing both raw and cooked in dishes like pizza, ketchup, and tomato paste (Petrotos & Gerasopoulos, 2022; Chippy et al., 2021).

Tomatoes are highly prized for their nutritional benefits and adaptability across a variety of industries. They are abundant in lycopene, beta-carotene, vitamins, minerals, and other bioactive chemicals that are beneficial to health and frequently employed in the food business (Domínguez et al., 2020; Petrotos & Gerasopoulos, 2022). They are essential for sustaining human health and warding against illnesses including heart disease, stomach and prostate cancers, and vision problems (Anjum et al., 2020).

However, the industrial processing of tomatoes produces a lot of waste, such as peels, seeds, and pomace, which, if improperly managed, could be hazardous to the environment (Petrotos & Gerasopoulos, 2022). What's interesting is that there is room for additional value addition because these by-products are high in minerals and bioactive substances. Tomato peels, for instance, have lycopene, a strong antioxidant with possible anticancer effects, which suggests they could be used in the creation of novel cancer therapies (Jiménez Bolaño et al., 2024). Furthermore, tomato powder generated from sundried tomatoes is used to enrich baked items, increasing their nutritional content with key vitamins and minerals while also improving flavor. This powder is gaining popularity on the worldwide market and helps to prevent post-harvest losses (Ramya et al., 2023). Furthermore, although their efficacy differs for ruminants and non-ruminants, tomato by-products are utilized in animal feed to enhance the nutritional value and quality of animal products (Travieso et al., 2022). The various applications of tomatoes and their byproducts emphasize how crucial they are to environmental sustainability, health, and nutrition.

2.1.6 Consumption of tomato

Tomato is one of the most consumed vegetables globally, with consumption including both fresh produce and a variety of processed goods such as juices, purees, sauces, marmalades, and ketchups (Petrotos & Gerasopoulos, 2022). Tomato consumption varies greatly between areas and population groups, demonstrating its popularity as a staple meal. In the United States, tomatoes are the second most consumed vegetable, with a huge number of consumers ingesting an average of 2.47 cups per day, mostly through tomato products such as sauces (Reimers & Keast, 2016). Globally, consumption rates in the United States and Europe are much higher, with tomato consumption three times the global average in 2001 (Sainju & Dris, 2005). In Mexico, more than 90% of the population consumes tomatoes, with an average of 114.68 g per day (Lares-Michel et al., 2018). In Nepal, annual per capita consumption is approximately 11.97 kg (Ghimire et al., 2018). In Malaysia, the annual per capita consumption in 2018 was about 4.2 kilograms (Alfred et al., 2022). China is one of the biggest tomato consumers in the world (Jin et al., 2023). From 2010 to 2012, Chinese adults consumed an average of 255 g of vegetables, including tomatoes, per day (He et al., 2016). Although China is a significant consumer, the overall consumption of vegetables and fruits is still below recommended levels, indicating a probable rise in tomato consumption (He et al., 2016).

2.2 Plant cultivation

The tomato is a plant native to tropical climes, yet it is grown practically everywhere in the world, including certain areas of the Arctic (Prasanna, et al., 2023). In 2022, the total global tomato area reached 5 million hectares and production reached nearly 186.82 million tons, at an average yield of 36.97 t ha^{-1} (FAO, 2022). China leads the world in tomato production with 64.86 million tons, contributing roughly 34.72 percent of the overall production. India comes in second with 20.57 million tons, contributing 11.01 percent, Turkey with 13.20 million tons, contributing 7.06 percent, and the US with 12.22 million tons, contributing 6.54 percent. China is the country with the largest area planted with tomatoes (1.11 million ha), followed by India (810,000 ha), Turkey (180,000 ha), and the United States (110,000 ha). The United States had the highest tomato yield at 110.71 t ha^{-1}, followed by Spain at 77.75 t ha^{-1}, Turkey at 72.59 t ha^{-1}, Brazil at 72.24 t ha^{-1}, Italy at 62.61 t ha^{-1}, and China at 58.35 t ha^{-1} (Prasanna, et al., 2023).

Tomatoes can be cultivated in both open fields and greenhouses. Growing tomatoes in the field requires less capital than growing them in greenhouses, but more susceptible to environmental factors. As the controlled environment optimizes growing conditions and decreases reliance on external influences, greenhouse gardening often generates higher yields and economic returns than open field growing, but significant initial investment and technical expertise are required (Ostojić et al., 2024).

Global greenhouse cultivation has increased dramatically in recent decades.

Tong et al., (2024) conducted greenhouse cultivation assessed globally in 2019 and mapped the distribution of 1.3 million ha of greenhouse infrastructure, observing a notable rise in greenhouse farming in the Global South since the 2000s, owing primarily to increased agricultural productivity and economic growth. China has spearheaded the global South's greenhouse development, accounting for 61% of total greenhouse cultivation. In 2023, the total newly developed greenhouse area in China reached 1835.87 million hectares (Guo et al., 2024).

2.2.1 Water consumption and utilization by tomato

Irrigation is the key restricting factor for tomato production. Growing tomatoes requires a lot of water (Kiymaz & Ertek, 2015). Some researchers discovered that tomatoes are sensitive to water deficiency (Bai et al., 2023; Sousa et al., 2022). Inadequate irrigation will result in lower yields and smaller fruits (Silva et al., 2022). Under the situation of water shortage and low agricultural water use efficiency in China, it is of great importance to have a deeper understanding of the water use patterns of crops and to explore the irrigation and fertilization methods that are compatible with them.

Hossain et al., (2017) found that in a pot experiment with cucumbers, a strong positive linear relationship was observed between total water consumption and irrigation water volume. The water requirements of tomato plants vary depending on the stage of their reproductive cycle. Several authors concluded that tomatoes are more sensitive to water deficit during flowering and fruiting, when water shortage will significantly diminish output, based on deficit irrigation during specific fertile phases of tomatoes (Atilgan et al., 2022; Fan et al., 2022; Li et al., 2023; Mukherjee et al., 2023). Singh et al., (2023) showed that during tomato development, I1 irrigation (100%

pan evaporation) (Epan) from weeks 1-2, 40% Epan from weeks 3-8, 60% Epan from weeks 9-14, 80% Epan from weeks 15-20, and 100% Epan from weeks 21-24) and I2 irrigation (100% Epan throughout the crop period) resulted in total profile water loss of -14.8 and 26.6 mm, respectively, at a depth of 0-0.30 m. The total crop water use was much reduced under the I1 treatment compared to I2. Yue et al., (2022) discovered that tomato plants' water consumption rose with increased irrigation. Improved nitrogen application enhanced WUE but dropped when the rates reached 420 kg ha^{-1}.

Irrigation and fertilization greatly affect crop water use efficiency. Melons (Miceli et al., 2023) and tomatoes (Mukherjee et al., 2023) showed a notable gain in water use efficiency when their irrigation was reduced. As irrigation water increased, water use efficiency initially rose and then declined; tomato yield increased with increasing irrigation water (Liu et al., 2013); whereas Lu et al., (2019) showed that the efficiency of water use was boosted by deficit irrigation while decreasing tomato yield; According to Chen et al., (2013), decreasing irrigation water during flowering, fruiting, and ripening stages of tomato reduced the average single fruit weight and yield, but increased water use efficiency. Panigrahi et al., (2019) found that drip irrigation combined with mulching reduced water use by 19%, increased water efficiency by 89%, and increased tomato output by 53%.

Water consumption of tomato planted at different times in different regions also varies. In the Netherlands, the annual water consumption of greenhouse tomatoes is about 0.5 to 0.9 L m^{-3}, while the greenhouse tomatoes' daily water use per plant under different salinity conditions ranges from 0.19 to 1.031 (Erdem & Yuksel, 2003). Somnuek et al., (2020) suggests that for the best irrigation schedules in greenhouses, tomato plants should use 100-1200 mL of water each day. High-density tomatoes in the

Xinjiang desert zone consumed the most water between June 26 and August 7, averaging 6.15 mm per day and peaking at 7.3 mm in mid-July (Long et al., 2020).

Other scientists have also investigated how water-fertilizer interactions affect water use efficiency. Shi et al., (2023) showed that while fertilization and irrigation separately had a highly significant impact on spring corn irrigation water use efficiency, their combination had no discernible impact on water use efficiency. Sun et al., (2022) found that when fertilizer was applied at the midpoint of the irrigation event and at a 30 mm irrigation rate, wheat growth was consistently enhanced, leading to high grain yield and water efficiency. Yue et al., (2022) discovered that tomato water consumption efficiency peaked at 1.0 Evapotranspiration (ET) irrigation rate and fertilizer application rate of 320:220:320 kg hm^2 (N: P_2O_5:K_2O).

Comprehensive research at home and abroad has concluded that the research and application of water-fertilizer integration technology, i.e., irrigation and fertilization, still has some problems in China. The lack of perfect and unified irrigation and fertilization system equipment makes the research results not cross reference each other. Further, the nutrient leaching caused by the unreasonable amount of irrigation and fertilization can be the focus of our future research. This experiment will use nitrogen, phosphorus, and potassium fertilizers under varying irrigation levels and fertilization patterns. The goal is to see how much water and fertilizer the tomatoes use in each mode, so that resources aren't wasted on unnecessary fertilization and irrigation, and the water use is improved.

2.2.2 Crop growth and physiological indicators

Water is essential for photosynthesis and other plant metabolic activities, including respiration, and is the primary basic material used by green plants. The first requirement for good yield and high-quality crops is appropriate water conditions. fertilizer is the material foundation for providing a high output of facility vegetables (Zhang et al., 2019). To ensure normal growth and steady yield, scientific and reasonable fertilization can meet the nutritional need of vegetable growth at different fertility stages (Krishnasree et al., 2021).

Irrigation is a significant factor influencing the uptake of water and nutrients in facility crops. In tomato plants, stress from water deprivation dramatically decreased stem thickness, water potential, stomatal conductance, and leaf transpiration rate. This led to leaf stomatal closure and a decrease in leaf photosynthetic rate (Al-Deeb et al., 2023). Water stress altered the growth and developmental processes of crops (Patanè et al. 2015). In drip-irrigated greenhouses, tomato plant height, leaf area, and dry matter content were all found to be significantly and positively linked with irrigation water (Rasool et al., 2023). Wu et al., (2021) demonstrated that as irrigation increased, the aboveground biomass, leaf area index, and plant height were also increased. Wang et al., (2017) observed that when comparing the deficit irrigation (upper irrigation limit of 40% field holding capacity) treatment to the suitable irrigation (upper irrigation limit of 80% field holding capacity), plant height, stem thickness, and leaf area per plant decreased by 30.43%, 20.0%, and 32.10%, respectively. Shahnazari et al., (2008) investigated the regulation of water in potatoes and discovered that while the yield of potatoes irrigated with 30% deficit irrigation was not significantly different from conventional irrigation, the indexes of reflective vegetation and leaf area were enhanced by deficit irrigation, and the amount of nitrogen residue in the soil in the root zone at harvest was lower.

Nutrients are another significant component influencing crop growth, and nitrogen is a crucial nutrient in all agricultural production systems (Rostamza et al., 2011). With sufficient nitrogen fertilizer, the plant leaves grew larger with bright green color, extended functional duration of the leaves, more branches, and the nutrient body was robust and healthy (Szulc et al., 2023). Appropriate nitrogen fertilizer administration during drought stress not only improved the plant's drought resistance (Xiong et al., 2018), but also increased its leaf area (Wu et al., 2021), chlorophyll content (Zhou et al., 2023), and biomass accumulation (Zotarelli et al., 2009). Research has demonstrated that when comparing treatments with excess nitrogen application to those with normal nitrogen application, there were less tomato fruits and lower harvest indices. Additionally, crops are often exposed to osmotic stress and crop growth is inhibited by excessive nitrogen fertilizer inputs (Zhang et al., 2022). Low levels of nitrogen lead to small, pale leaves (lower levels of chlorophyll) or reddish leaves (higher levels of nitrogen, less sugars for the formation of amino acids, and more sugars left over to form anthocyanin glycosides, which give the red color), as well as fewer branches and flowers, and poorly filled grains (Peralta-Sánchez et al., 2023). According to Hui et al., (2017), when irrigation levels are steady, excessive fertilizer application does not stimulate tomato growth or dry matter mass accumulation. Furthermore, compared to traditional furrow irrigation, drip irrigation fertilization boosted tomato dry matter mass by 60% (Xing et al., 2014).

The effects of water and fertilizer on tomato growth and physiological indicators, as well as water-fertilizer interactions, have been explored by scholars worldwide (Du et al., 2017; Wang et al., 2017; Zotarelli et al., 2009). Badr et al., (2010) demonstrated that drip irrigation with totally soluble fertilizer led in the maximum growth rate, total biomass, and leaf area index observed in tomatoes.

Wu et al., (2021) noted that the combined effects of irrigation and fertilization significantly impacted stem thickness, leaf area, dry matter mass, and leaf SPAD value of tomato, and that the appropriate irrigation volume is beneficial to increase the leaf area, dry matter mass, and leaf SPAD value of greenhouse tomatoes. Zhou et al., (2023) found that young apple trees treated with a mild deficit irrigation W2 (65–80% field capacity) and high fertilizer (27-9-9 g N-P_2O_5-K_2O), had the best plant development, stem growth, leaf area, SPAD value, and dry matter.

In summary, under varying water and fertilizer application patterns, researchers have studied crop growth and physiological traits but most of the research objectives were aimed at soil irrigation and fertilizer application patterns and the coupled effects of the two. However, the current research on the organic substitution of fertilizers under water-saving irrigation conditions and the effect of organic or inorganic fertilization on the growth and physiological characteristics of greenhouse crops is still relatively small, which is also an urgent problem that must be tackled. Research in this area should be strengthened with a view to providing more scientific management methods for greenhouse crop production.

2.2.3 Nutrient uptake and requirements by tomato

Most studies of fertilizers on crop growth and nutrient uptake have focused on field crops, while facility vegetable-related studies have focused on processing tomatoes. These studies often involve only one vegetable crop and a small number of types of fertilizer application or nutrient elements and focus on the effects in terms of dry matter accumulation, uptake and utilization of elements such as nitrogen, phosphorus or potassium. To improve the efficiency of water and fertilizer use and to promote the healthy development of modern and water-saving agriculture, typical characterization studies and comprehensive analyses with attention to critical periods are needed.

Adequate nutrient supply and proper irrigation are fundamental for achieving optimal tomato growth, high yields, and good fruit quality. This literature review synthesizes current research on the nutrient and irrigation requirements of tomatoes, aiming to provide a comprehensive understanding of this crucial area in tomato cultivation. The absorption of nitrogen (N), phosphorus (P), and potassium (K) is crucial for optimal tomato growth, with a notable demand for potassium. Research indicates that for every 1000 kg of tomato production, approximately 7.8 kg of N, 1.3 kg of P, and 15.9 kg of K are absorbed, reflecting a nutrient absorption ratio of roughly 100:26:180 (Ozores-Hampton et al., 2015). This high potassium requirement is consistent across various studies, emphasizing the importance of balanced fertilization.

In addition to macronutrients, tomatoes also require secondary macronutrients and micronutrients. Among them, secondary macronutrients include calcium (Ca) and magnesium (Mg); micronutrients, on the other hand, include such examples as iron (Fe), zinc (Zn) and boron (B). Calcium, for example, is essential for cell wall stability and can prevent physiological disorders such as blossom - end rot. Magnesium is a key component of chlorophyll and is involved in photosynthesis. Deficiencies in these micronutrients (and other essential micronutrients) can lead to stunted growth, compromised fruit quality, and heightened susceptibility to pests and diseases. A field trial in the Chengdu Plain found that applications of calcium, magnesium, and zinc fertilizers increased tomato yield by 10%, reduced nitrate content, and improved quality; in contrast, application of manganese fertilizer reduced yield under this experimental condition. These results highlight that the role of mineral nutrients in tomato production varies by element—with some being crucial for growth and quality (Qin et al., 2008). While the significance of micronutrients in tomato growth is well - established, biostimulants have emerged as another key element in modern agricultural practices aimed at optimizing tomato nutrient management and overall crop performance. Biostimulants have emerged as a significant aspect in modern agriculture, and their application in tomato cultivation is garnering increasing attention. Some biostimulants can be derived from organic fertilizers. For instance, in the production of certain bio - organic fertilizers, raw materials like livestock manure and crop residues are used. During the fermentation process of these organic materials, various beneficial microorganisms multiply, and the decomposition products may include substances with biostimulant properties. These are substances or microorganisms that, when applied to plants, seeds, or the rhizosphere, stimulate natural processes to enhance nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality, independent of their nutrient content (Maach et al., 2021).

It was proposed by Xin et al., (2014) that the rapid buildup of biomass in the aboveground portion of tomato plants is stimulated for about five days following N intake. Dolker et al., (2017) stated that dry matter buildup and nutrient uptake by the plant were improved when the availability of organic nutrients was increased during fruit ripening. Plant growth phases can be optimized, and productivity can be raised by adjusting the timing of nutrient solutions. Research indicated that cucumber seedlings had minimal uptake of nitrogen, phosphate, and potassium, with a notable surge in nutrient uptake during the anthesis stage (Elad et al., 2021). The experimental results of