

Trait Basis and Management Strategies for Stable High Yield in Greenhouse Tomato Production

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Received: 15 Jan., 2026

Accepted: 14 Feb., 2026

Published: 22 Feb., 2026

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Preferred citation for this article:Lin X.X., and Luo M.T., 2026, Trait basis and management strategies for stable high yield in greenhouse tomato production, Plant Gene and Trait, 17(1): 36-55 (doi: [10.5376/pgt.2026.17.0004](https://doi.org/10.5376/pgt.2026.17.0004))

Abstract This study explores the key agronomic trait basis, physiological-ecological mechanisms, and regulatory pathways underlying high and stable yield formation in protected tomato production. Protected tomato cultivation plays an important role in ensuring year-round vegetable supply and increasing yield per unit area; however, yield stability is often affected by environmental fluctuations, suboptimal canopy structure, and mismatched management practices. Based on a systematic review of recent studies, this study summarizes the major trait foundations associated with high and stable yield from the perspectives of plant growth, flowering and fruit set, fruit development, and root characteristics. It focuses on the roles of plant architecture, internode length, the balance between vegetative and reproductive growth, inflorescence number and pollen viability, single fruit weight and fruit enlargement dynamics, as well as root vigor and health in determining yield and its stability. Meanwhile, the effects of environmental factors such as temperature, light, humidity, and CO₂ on tomato growth and fruit set are reviewed, and the contributions of integrated management practices-including optimal planting density, pruning, fertigation, supplemental lighting, pollination techniques, and grafting-are discussed. Finally, future trends in intelligent environmental control, breeding of high-yield and stress-resistant varieties, and green efficient production systems are highlighted, achieving high and stable yield in protected tomato production depends on the coordinated optimization of traits, environment, and management.

Keywords Protected tomato; High and stable yield; Cultivation traits; Environmental regulation; Integrated water and fertilizer management

1 Introduction

Protected agriculture, as an important component of modern agriculture, plays a crucial role in ensuring the year-round stable supply of vegetables, improving land-use efficiency, and enhancing agricultural productivity. Tomato (*Solanum lycopersicum* L.), owing to its high nutritional value, strong adaptability to processing, and stable market demand, has become one of the most widely cultivated and economically valuable vegetable crops worldwide (Banoo et al., 2024; Avasiloaiei et al., 2025). With the intensification of climate change and increasing constraints on arable land resources, traditional open-field vegetable production is facing growing uncertainties. In contrast, protected cultivation can partially control crop growth conditions by regulating environmental factors such as temperature, humidity, and light, thereby extending production cycles and increasing yield per unit area (Banoo et al., 2024). Within global protected horticulture systems, tomato is not only one of the crops with the largest planting areas but is also regarded as a representative model crop for production intensification and technological innovation in controlled-environment agriculture.

However, compared with open-field production, protected environments provide controllable cultivation conditions while simultaneously creating a more complex growth regulation context. Environmental factors such as temperature, light, humidity, and vapor pressure deficit (VPD) are highly coupled across spatial and temporal scales, which can easily lead to microclimatic variations and consequently affect plant growth and fruit development (Dewapriya et al., 2024; Šalagovič et al., 2024). In practical production, protected tomatoes often exhibit fluctuations in fruit set and uneven fruit expansion, resulting in unstable yields and marketable fruit rates. In addition, extreme climatic events, particularly heat stress, can significantly reduce fruit set and the number of fruits per plant. Even in high-tech greenhouse systems, yield losses under extreme high-temperature conditions

may still reach 6%-53% (Kürklü et al., 2025). Insufficient or fluctuating light conditions can also reduce dry matter production and affect fruit quality.

In addition to environmental factors, protected tomato production systems generally require high inputs of water, fertilizers, and energy. If management practices do not match crop requirements, resource-use efficiency may decline and environmental pressure may increase (Avasiloaiei et al., 2025). Population structure and canopy management practices, such as plant spacing, topping, and leaf pruning, can influence light interception capacity, source-sink relationships, and fruit load, thereby regulating yield and quality formation. From the perspectives of crop production science and genetic breeding, yield stability in protected tomatoes depends on key traits such as population structure, light interception efficiency, and dry matter production capacity. These traits are not only controlled by genetic background but are also regulated by the protected environment and cultivation management. Different tomato varieties show significant differences in their ability to maintain fruit set and yield under variations in temperature and microclimatic conditions (Ali et al., 2025).

This study aims to explore the key cultivation traits and their regulatory mechanisms involved in achieving high and stable yields in protected tomato production. It particularly focuses on analyzing the linkage between traditional cultivation experience and findings from modern genomics research. From the perspective of plant traits, the study systematically summarizes the main factors influencing yield stability and analyzes their underlying regulatory bases through genetics and physiological ecology, thereby providing a theoretical basis for constructing a high-yield and stable-production technological system integrating traits-genes-management practices. In addition, this study also examines the roles of integrated regulation strategies-such as climate control, supplemental lighting, integrated water and fertilizer management, and intelligent monitoring and decision-making technologies-in protected tomato production to improve production efficiency, enhance resource-use efficiency, and stabilize fruit quality. Through a systematic summary of cultivation traits related to high and stable yields and their regulatory points in protected tomato production, this study aims to provide scientific references for optimizing protected cultivation management strategies, promoting the breeding of facility-adapted varieties, and developing precision cultivation technologies.

2 Plant Growth Trait Foundations for High and Stable Yields in Protected Tomato Production

2.1 Effects of plant vigor and architecture on canopy photosynthetic efficiency

The achievement of high and stable yields in protected tomato production depends on both strong plant vigor and well-optimized plant architecture. Plant vigor is reflected in traits such as stem elongation rate, leaf expansion capacity, internode formation rhythm, and the ability to sustain branching, flowering, and fruiting. Together, these traits determine the efficiency of plant acquisition of light, spatial resources, and nutrients. The greenhouse environment partially buffers external climatic variability, allowing tomatoes to maintain strong vegetative growth potential. However, excessive vegetative vigor often leads to canopy closure, increased self-shading in upper leaves, and insufficient light penetration to middle and lower canopy layers, ultimately reducing canopy photosynthetic efficiency and dry matter accumulation. Even under similar total leaf area, canopy photosynthesis remains highly sensitive to structural traits, including internode length, leaf size, leaflet morphology, inclination angle, and spatial arrangement. Yield stability therefore depends not on leaf area alone, but on whether a structurally optimized effective leaf area can establish a balanced light distribution within the canopy. Moderate increases in internode length, improved leaf length-to-width ratio, and optimized leaflet arrangement can create a more open canopy and enhance vertical light penetration, thereby improving overall photosynthetic efficiency and dry matter production.

From a population perspective, plant architecture influences not only light interception at the individual level but also the distribution and utilization of radiation within the entire canopy. An ideal architecture typically features an upright stem, moderate internode length, evenly distributed leaves, and upper leaves that are extended but not excessively horizontal, promoting a balanced vertical light gradient. The research conducted by Zhang et al. (2022) based on the functional-structural plant model (FSPM) indicates that the combination of longer internodes and

narrower leaves reduces excessive shading in the upper canopy and redistributes light toward middle canopy layers, improving photosynthetic performance at both plant and population scales. This has led to the concept of a photosynthetic ideotype for greenhouse tomato cultivation. Further studies demonstrate strong interactions between planting configuration and plant architecture. Planting pattern, spacing, and row orientation often exert greater effects on canopy radiation interception and photosynthesis than individual traits alone. When optimized together with appropriate architecture, these factors produce synergistic effects (Zhang et al., 2024a).

In high-density, long-cycle production systems, plant architecture plays a critical role in maintaining canopy photosynthetic efficiency. Excessive density combined with luxuriant growth accelerates light attenuation within the canopy, leading to premature senescence of lower leaves and reduced photosynthetic contribution, ultimately compromising fruit set continuity and yield stability. Conversely, optimizing plant architecture and planting configuration—such as adjusting row spacing, orientation, and canopy thickness—can significantly enhance light interception, promote dry matter accumulation, and improve fruit quality. Yield increases of approximately 3.92%–9.78% have been reported under optimized configurations across different seasons (Li et al., 2024). Therefore, achieving high and stable yields in protected tomato production requires moderate and stable plant vigor combined with a well-balanced architecture that supports both efficient light interception in the upper canopy and adequate light penetration to lower canopy layers.

2.2 Regulatory effects of internode length and leaf distribution on ventilation and light conditions

Internode length is a key structural trait shaping plant architecture in protected tomatoes. It determines the three-dimensional distribution of leaves and influences canopy porosity, light penetration, and the surrounding microclimate. Moderate internode length promotes uniform vertical leaf stratification, reduces leaf overlap, and enhances the penetration of scattered light into lower canopy layers. When internode length increases from approximately 7 cm to 10–12 cm, the canopy becomes more open, vertical light penetration improves, and canopy photosynthetic efficiency can increase by about 10%, particularly under high radiation conditions. Moreover, the combination of longer internodes and narrower leaves facilitates the redistribution of light from upper to middle canopy layers and fruit-bearing zones, enhancing their photosynthetic contribution without substantially reducing total light interception. These findings indicate that internode length functions not only as a morphological trait but also as a key structural regulator of canopy light distribution.

Leaf distribution patterns further regulate canopy ventilation and light conditions. Due to their large and compound structure, densely arranged tomato leaves can create localized shading and high-humidity zones. A balanced leaf arrangement maintains sufficient photosynthetic area while creating interleaf spaces that enhance air circulation, reduce humidity, and shorten leaf wetness duration, thereby lowering the risk of diseases such as gray mold and leaf mold. Variations in leaf area distribution, leaflet inclination, and plant-to-plant structural heterogeneity influence the uniformity of light absorption within the canopy. Although their effects on total canopy photosynthesis may be smaller than those of planting density or spacing, they can significantly alter local microenvironments and inter-plant variability, ultimately affecting yield stability. Therefore, leaf distribution uniformity and canopy ventilation capacity should be considered key criteria in evaluating plant architecture in protected tomato systems.

Beyond light regulation, canopy openness also influences airflow, heat dissipation, and temperature stratification. As canopy closure increases, ventilation efficiency declines, leading to the accumulation of heat and humidity—especially under high-temperature conditions. Li et al. (2025) conducted field measurements and aerodynamic studies show that moderate removal of older leaves can modify airflow pathways, increase within-canopy wind speed, and reduce localized heat accumulation, indicating that leaf management is essentially a process of microclimate optimization rather than simple defoliation. Leaf area index (LAI) serves as an integrative parameter linking leaf distribution, light interception, and ventilation. Excessively low LAI limits photosynthetic capacity, whereas excessively high LAI intensifies shading. Maintaining LAI within an optimal range of approximately 3.0–3.5 allows a balance between light interception and internal light penetration. Thus,

internode length and leaf distribution jointly regulate both canopy structure and microclimate, making them critical determinants of stable yield formation.

2.3 Balance between vegetative and reproductive growth

Maintaining a dynamic balance between vegetative and reproductive growth is fundamental for achieving high and stable yields in protected tomato production. Vegetative growth, including stem and leaf development, leaf area expansion, and root vitality, provides the basis for assimilate production. Reproductive growth, encompassing flower differentiation, pollination, fruit set, and fruit enlargement, directly determines yield formation. Excessive vegetative growth may result in continuous allocation of assimilates to stems and leaves, suppressing flower differentiation and reducing fruit set stability. Conversely, excessive reproductive load can lead to insufficient leaf area, reduced root activity, and premature senescence, ultimately limiting sustained fruit production. Therefore, vigorous growth alone does not guarantee high yield; rather, the key determinant is the maintenance of balanced “source-sink” relationships across growth stages.

Semi-determinate tomatoes exhibit a moderately extended vegetative phase compared with determinate types, while avoiding excessive vegetative growth typical of indeterminate types. This growth habit facilitates coordination between leaf capacity and fruit demand, improving yield-related traits and water use efficiency. These findings suggest that optimal plant types are characterized by a coordinated structural-functional state combining moderately sustained growth with stable reproductive translocation. Light regulation further influences biomass partitioning. Supplemental LED lighting generally increases total biomass and fruit yield, while specific spectral combinations can enhance dry matter allocation to fruits. By regulating leaf thickness, internode elongation, and plant morphology, light quality reshapes the balance between vegetative and reproductive growth. Thus, this balance should be regarded as a dynamic trait jointly shaped by genotype, growth habit, and environmental regulation.

Under stress conditions, this balance becomes even more critical. High temperatures not only affect photosynthesis and vegetative growth but also directly impair pollen viability, stigma development, and fruit set, leading to yield loss even when vegetative growth appears vigorous. Reproductive traits such as flower number, pollen performance, and fruit set rate show closer relationships with final yield than many vegetative indicators (Graci and Barone, 2024). Similarly, under water stress, genotypic differences in vegetative performance do not necessarily translate into stable yields if reproductive development is compromised. Some genotypes maintain strong vegetative growth under stress but still exhibit significant yield reduction due to impaired fruit formation. This highlights that stable assimilate allocation to fruits during later growth stages is a key determinant of yield stability.

3 Traits Related to Flowering and Fruit Set in Protected Tomato Production

3.1 Fundamental role of inflorescence number and flower number in yield formation

The number of inflorescences and the number of flowers directly determine the potential number of fruits in protected tomato production and are among the most fundamental quantitative traits underlying yield formation. In greenhouse tomatoes, the number of marketable fruits per unit area largely depends on how many inflorescences each plant can produce and how many fully functional flowers each inflorescence can ultimately form and retain. Analyses of yield components in indeterminate tomato materials have shown that the number of flowers per inflorescence and the number of successfully fruit-set flowers are significantly positively correlated with fruit number and total yield, and these traits often determine yield potential more directly than plant size alone. The path analysis conducted by Ramana et al. (2025) also demonstrated that both flower number and fruit number have significant direct positive effects on yield. These findings indicate that achieving high and stable yields in protected tomato production depends not only on vigorous vegetative growth, but also on the effective transition from vegetative to reproductive growth, namely, the formation of a sufficient number of high-quality inflorescences and flowers.

At the production level, inflorescence number is usually closely associated with plant vigor, nutrient supply, growth habit, and pruning or branch-retention practices, whereas the number of flowers within each inflorescence determines the upper limit of its fruiting potential. Different inflorescences on the same plant do not contribute equally to yield. Continuous inflorescence studies in greenhouse cherry tomato have found that middle-position inflorescences often outperform some upper or lower inflorescences in terms of flower number, production efficiency, and related biochemical performance, indicating that inflorescence position, local light and thermal environment, and assimilate supply jointly affect the efficiency with which flower number is converted into fruit number (Jerca et al., 2024). Therefore, in protected cultivation, maintaining high differentiation quality of all inflorescences, especially effective middle and upper inflorescences-through rational dense planting, pruning, nutritional regulation, and inflorescence load management is a key step for improving yield stability (Jerca et al., 2024).

From the perspectives of developmental biology and genetic regulation, inflorescence structure itself determines how many flowers can be formed and thus sets the limit for potential fruit number. Tomato inflorescences have a compound branching structure, and the transition rhythm from inflorescence meristem to floral meristem is a major basis for differences in inflorescence branching degree and flower number (Lippman et al., 2008). SINGLE FLOWER TRUSS (SFT), SELF PRUNING (SP), COMPOUND INFLORESCENCE (S), ANANTHA (AN), and related MADS-box transcription factors jointly regulate inflorescence branching and floral organ formation, thereby influencing the number and arrangement of flowers within the inflorescence (Graci and Barone, 2024). More recent studies further indicate that the SEPALLATA-class transcription factor SIMBP21 acts as a negative regulator, and that suppression of its expression can increase the number of flowers per inflorescence and improve fruit yield. At the same time, the miR156a-SPL13 pathway can alter the trade-off among inflorescence number, flower number, and fruit size by regulating inflorescence morphogenesis and lateral inflorescence formation. This indicates that the more inflorescences-more flowers-higher yield pattern in protected tomato production is not a simple linear relationship, but is regulated by the genetic network controlling inflorescence development and exists in dynamic balance with fruit size and resource allocation efficiency (Zhang et al., 2024b).

3.2 Effects of pollen viability and pollination conditions on fruit set rate

Although inflorescence number and flower number determine the upper limit of potential yield in protected tomato production, the actual fruit set rate largely depends on pollen performance and pollination conditions. Pollen production, pollen viability, germination ability, and pollen tube growth rate are all important reproductive indicators affecting tomato fruiting. Higher pollen viability is usually associated with higher fruit set rates and a greater number of fruits per plant. Under prolonged moderate high-temperature conditions, the number of inflorescences itself may not decrease significantly, but declines in pollen viability and the number of effective flowers per inflorescence directly restrict fruit formation, indicating that under fluctuating protected-environment conditions, male reproductive capacity is often a key constraint on stable yield. At the same time, high temperature typically reduces pollen viability and induces flower drop, whereas heat-tolerant materials can maintain higher pollen viability and thus form fruits more steadily under high-temperature conditions.

Although protected tomatoes are typical self-pollinating crops, their anther-cone structure means that effective pollen release often depends on a certain degree of vibration or external assistance. Under protected cultivation conditions, insufficient airflow, excessively high humidity, or environmentally induced stress on floral structures may all reduce pollen release, stigma pollination, and fertilization efficiency. The research conducted by Stroh et al. (2025) indicates protected cultivation conditions can significantly affect pollen quantity, and the first inflorescence often produces less pollen or poorer-quality pollen because of stress during the seedling stage or early reproductive stage. Meanwhile, mechanical vibration, bumblebee pollination, or other supplementary pollination methods can increase the amount of pollen received by the stigma, thereby improving fruit set rate and yield performance (Stroh et al., 2025). This indicates that improving fruit set depends not only on pollen quality, but also on the efficiency with which pollen arrives.

Successful pollination is not equivalent to final fruiting; pollen germination and pollen tube penetration into the ovary are essential processes for initiating fruit development. Tomato fruit initiation is jointly influenced by pollination, pollen tube growth, and fertilization, and that the ability of the pollen tube to pass normally through the style and enter the ovary makes an independent contribution to subsequent fruit development. If pollen cannot germinate or cannot form a normal pollen tube, effective fruit development cannot be initiated even if the flower has already opened and apparent pollination has occurred (Kantoglu, 2024). Therefore, in protected tomato production, simply observing flower opening or pollen release is not sufficient to judge pollination quality; attention must also be paid to pollen germination ability and the continuity of fertilization from the style to the ovary stage.

3.3 Regulatory effects of environmental factors such as temperature and light on flower and fruit drop

Environmental factors such as temperature and light have decisive effects on flowering and fruit set in protected tomatoes, and their regulation of flower and fruit drop is especially sensitive during the flowering and young fruit formation stages. High temperature can interfere with pollen development, stigma and style function, and normal ovary development, thereby reducing fruit set rate and increasing the abscission of flowers and young fruits. Meanwhile, low night temperature can also inhibit pollen viability and pollen germination, induce parthenocarpy, and promote pedicel abscission. Under heat stress, reproductive traits such as pollen viability, fruit set rate, pollen tube growth, and stigma exertion are all significantly impaired and are closely related to yield reduction. Therefore, flower and fruit drop in protected tomatoes is not simply a result of unfavorable climate, but rather the consequence of coordinated interference by environmental stress with floral organ development, hormonal balance, and the fertilization process (Figure 1) (Graci and Barone, 2024).

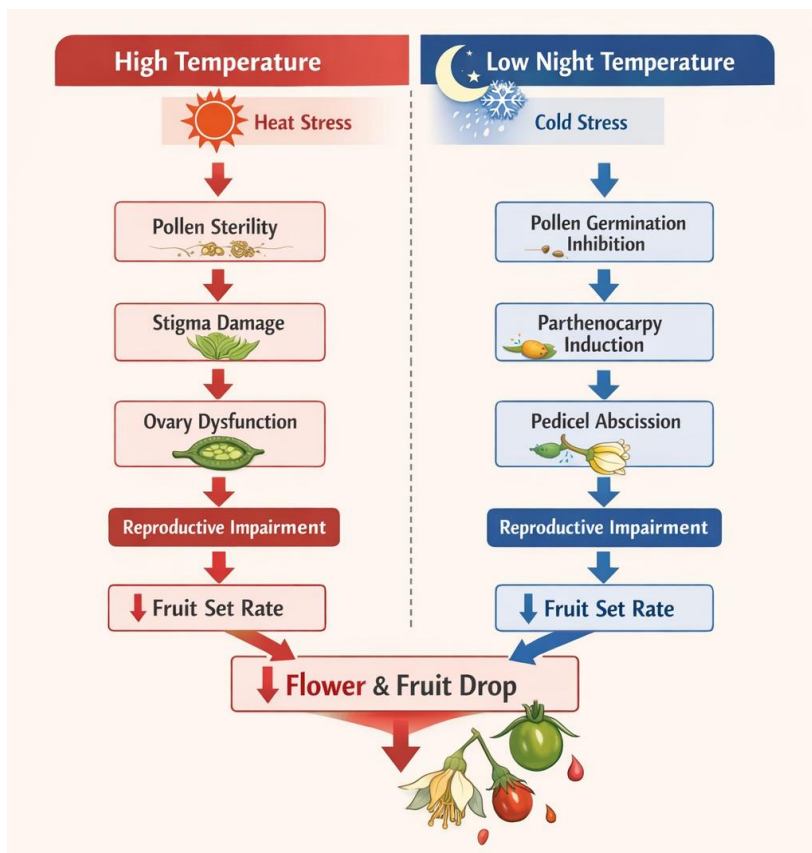


Figure 1 Effects of high temperature and low night temperature stress on reproductive processes and fruit set in tomato
 Image caption: High temperature and low night temperature reduce fruit set in tomato by impairing reproductive processes, although through different pathways; High temperature mainly causes pollen sterility, stigma damage, and ovary dysfunction, whereas low night temperature primarily inhibits pollen germination and promotes pedicel abscission. Ultimately, both stresses lead to increased flower and fruit drop, thereby reducing yield formation and stability

Light affects not only the supply of photosynthetic assimilates, but also directly participates in the regulation of floral organ retention through specific signaling pathways. Under low-light conditions, the transport of assimilates to inflorescences and young fruits decreases, which can easily lead to failure in floral organ competition and subsequent abscission. Recent studies have found that the small peptide signaling molecule SIIDL6 and its downstream calcium-dependent protein kinase SICPK10 constitute an important regulatory module in low-light-induced tomato flower abscission; this pathway promotes flower drop by altering Ca^{2+} signaling status in abscission-zone cells (Fu et al., 2024). This suggests that the problem of flower drop under winter-spring protected cultivation or cloudy low-light conditions is not only the result of insufficient carbon supply, but may also involve the active activation of signaling transduction in the abscission zone. Therefore, from cultivation management to molecular breeding, regulation can be directed toward stabilizing flower retention ability under low-light conditions.

In addition to average environmental conditions, spatial microclimate heterogeneity within the greenhouse can further aggravate differences in fruit set among inflorescences. Different inflorescences on the same plant may experience different light, temperature, and humidity conditions, causing some inflorescences to show higher flower number, pollination efficiency, and fruit retention capacity, while others are more prone to flower drop or small fruit formation. This difference is more obvious in continuous-fruited systems, in large canopies, or under high-density protected cultivation. Therefore, reducing flower and fruit drop in protected tomato production should not be limited to regulating average daily temperature or a single light indicator, but should also emphasize microclimate homogenization within the canopy, improved light exposure around inflorescences, and optimized local ventilation conditions (Jerca et al., 2024).

In addition, humidity and airflow can indirectly influence flower and fruit drop by affecting pollen release, stigma pollination, and disease occurrence. Excessively high humidity may reduce pollen dispersal efficiency, while insufficient airflow weakens anther vibration and canopy heat dissipation, and can easily create a combination of localized high humidity and high temperature, ultimately damaging the fruit set process. Therefore, stable fruit set requires coordinated management of temperature, light, humidity, and airflow. In protected production practice, the risk of flower and fruit drop can be jointly reduced and the temporal stability of fruiting improved through measures such as ventilation, supplemental lighting, regulation of day-night temperature differences, improvement of canopy structure, and the use of mechanical vibration or insect pollination (Fu et al., 2024).

4 Fruit Development and Yield Component Traits in Protected Tomato Production

4.1 Effects of single fruit weight and fruit enlargement rate on yield formation

In greenhouse tomato production, total yield can usually be divided into two major components: fruit number per unit area and average single fruit weight, among which single fruit weight directly affects both per-plant yield and population yield formation. Management practices capable of increasing assimilate supply to fruits or enhancing fruit sink strength often increase single fruit weight and overall yield. For example, supplemental lighting and CO_2 enrichment can significantly enhance plant photosynthesis and dry matter production, while also increasing single fruit weight and per-plant yield, indicating that yield improvement does not rely entirely on increasing fruit number, but to a large extent on strengthening the growth capacity of individual fruits (Figure 2).

At the cultivation management level, single fruit weight is not necessarily better when larger, but should be maintained within an appropriate range coordinated with fruit number, truss load, and late-stage plant vigor. If individual fruits become excessively large while source supply, water transport, or root absorption capacity is insufficient, subsequent trusses may experience intensified competition, leading to uneven fruit enlargement, increased malformed fruits, or reduced yield in later stages. Conversely, under relatively stable fruit set conditions, moderately increasing single fruit weight is often one of the most direct ways to raise yield. Average single fruit weight and aboveground biomass are important positive indicators affecting final yield, and that moderate water deficit treatments can maintain relatively high marketable fruit yield while improving water-use efficiency (Figure 3).

In addition to final fruit weight, the rate of fruit enlargement, its day-night variation, and its developmental dynamics also profoundly influence yield formation. Inter-canopy LED supplemental lighting can increase the relative growth rate of fruits at night and raise the final weight of fruits in middle and later fruit positions, thereby improving fruit size uniformity within the same truss. In contrast, when fruit sink number is increased by increasing branch number, average single fruit weight often declines, even when carbon supply per unit leaf area does not decrease synchronously. This suggests that smaller fruits are not necessarily caused by source limitation, but may also result from reduced sink capacity of individual fruits or intensified competition among multiple fruit sinks. In addition, fruit enlargement rate is jointly influenced by plant hydraulic status and hormonal regulation, further indicating that single fruit weight formation is the result of the coordinated action of carbon assimilation, transport efficiency, and sink activity.



Figure 2 Maturation and attachment characteristics of long-elliptical tomato fruits under facility cultivation condition

4.2 Roles of fruit shape and fruit uniformity in marketability

Fruit shape and uniformity are important appearance traits affecting the marketability of protected tomatoes. For fresh-market tomatoes and cluster-harvested tomatoes, yield does not necessarily equate to high commercial value. Whether fruits are well rounded, whether the shoulders are symmetrical, whether the fruit shape index is stable, and whether fruit size is uniform all directly affect grading, packaging efficiency, transportation damage rates, and consumer acceptance. Traits such as fruit weight, shoulder height, and height-to-width ratio are closely related to commercial classification. Although environmental effects on fruit shape parameters are usually smaller than their effects on chemical traits such as sugar content and dry matter, clear genotype \times environment interactions still exist for fruit size and shape stability. Therefore, under protected cultivation conditions, selecting varieties with stable fruit-shape performance is of great significance for maintaining consistent market quality. Fruit uniformity is not only related to appearance, but also directly affects harvest rhythm and commercial management efficiency.

If fruit enlargement rates differ greatly among fruits on the same truss or the same plant, uneven ripening is likely to occur, increasing the number of harvest rounds, raising the difficulty of manual grading, and reducing packaging standardization. In greenhouse tomato quality control systems, uniform fruit shape, smooth fruit surface, and fewer mechanical or physiological defects are usually important prerequisites for fruits to enter high-grade commercial circulation systems. Surface defects such as fruit cracking, scarring, zippering, and wind scars can significantly reduce commercial value, and fruits may be downgraded even if their weight meets the standard. Therefore, the marketability of protected tomatoes is not determined solely by large fruit, but is instead the combined result of fruit shape stability + size uniformity + skin integrity.

From the perspective of genetic basis, fruit shape, fruit size, and susceptibility to commercial defects are interrelated. GLOBE locus on chromosome 12 can significantly affect the difference between oblate and spherical fruit shapes in large-fruited fresh-market tomatoes, while also influencing fruit size, pedicel morphology, and the tendency for skin defects to occur (Sierra-Orozco et al., 2021). Among these, spherical-fruit materials often have larger fruits, but are also more prone to surface cracking and epidermal defects, thereby creating a trade-off among fruit shape, fruit weight, and marketability (Sierra-Orozco et al., 2021). This indicates that in protected tomato breeding and cultivation, simply pursuing larger fruit does not necessarily lead to higher market returns; fruit shape stability and defect control must also be considered simultaneously. With the development of phenotypic analysis and digital agriculture technologies, evaluation of fruit shape and uniformity is gradually shifting from experience-based judgment to standardization and intelligence. Machine-learning classification systems established using standardized fruit-shape parameters from tools such as Tomato Analyzer have already shown greater stability and consistency than manual evaluation in tomato fruit-shape classification, and can be used for breeding material screening, fruit grading, and supply-chain quality control (Vazquez et al., 2024). In addition, some preharvest growth-regulation measures can improve fruit shape and internal quality to a certain extent. For example, benzylaminopurine (BAP) and gibberellin treatments can alter the fruit shape index of small-fruited greenhouse tomatoes, making fruits shift from elongated forms to more rounded ones, accompanied by changes in soluble solids and some nutritional indicators. This suggests that fruit shape is plastic to a certain extent and can be optimized through physiological regulation (Eissa et al., 2025).

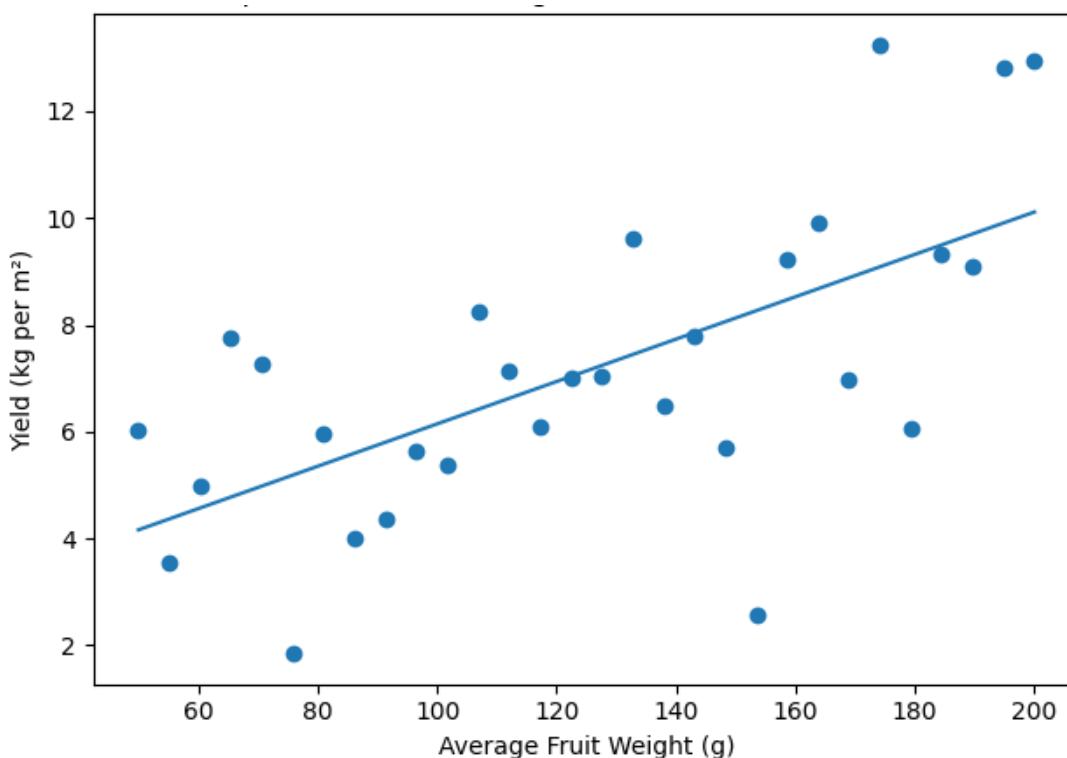


Figure 3 Relationship between average fruit weight and total yield of greenhouse-grown tomatoes under different irrigation treatments

4.3 Characteristics of nutrient allocation and assimilate accumulation during fruit development

Fruit development in greenhouse-grown tomatoes is essentially a continuous process of assimilate translocation and accumulation toward the fruit as the primary sink. During the late growth stage, fruits become the dominant site of dry matter accumulation, accounting for up to 73% of aboveground dry biomass under organic cultivation conditions, indicating a clear shift to fruit-centered resource allocation. Nitrogen and potassium are key macronutrients for maintaining sink activity, particularly under continuous fruiting. Nutrient demand varies across developmental stages: early fruit development is characterized by cell division and sink establishment, regulated by assimilate supply and hormonal signals, whereas the rapid expansion stage depends on sustained inputs of sugars and mineral nutrients to determine fruit weight and quality. Appropriate supplemental lighting and nutrient supply can enhance both yield and quality, while excessive electrical conductivity (EC) may improve quality concentration but inhibit growth, reflecting a trade-off between biomass production and quality (Xie et al., 2024).

At the single-fruit level, assimilate accumulation involves not only sugars and dry matter but also dynamic changes in mineral nutrients and secondary metabolites. Increasing the proportion of blue light can enhance soluble sugars, lycopene, and β -carotene contents while maintaining fruit fresh weight, indicating that carbon allocation affects both fruit size and composition. Mineral elements continue to change during fruit development and postharvest ripening, suggesting that fruit maturation is a dynamic process involving both import and internal redistribution. Thus, fruit quality formation results from the coordinated interaction of carbon assimilation, mineral transport, and metabolic regulation. Environmental and nutrient management further shape these processes by regulating source strength and assimilate transport. Moderate deficit irrigation may reduce yield but improve quality attributes, whereas supplemental lighting and CO₂ enrichment enhance carbon supply, increasing fruit weight and overall yield. The research conducted by Su et al. (2025) demonstrated that appropriate Cl⁻ supply can improve photosynthetic performance and sucrose metabolism, promoting sugar transport to fruits and increasing soluble sugar content (Su et al., 2025). Overall, the coordinated improvement of yield and quality depends not only on total assimilate production but also on their allocation patterns within the fruit.

5 Root Traits and Nutrient Uptake Capacity in Protected Tomato Production

5.1 Effects of root activity and root distribution on water and fertilizer uptake efficiency

Root activity is one of the key factors determining water and nutrient uptake efficiency in protected tomato production. Highly active root systems usually exhibit a higher root tip growth rate, a more developed fine-root system, a larger absorptive surface area, and higher root metabolic activity. As a result, they can respond more rapidly to changes in root-zone water and nutrient availability and convert these resources into the supply needed for plant growth and fruit development. In intensive protected cultivation systems, roots are not merely passive absorbing organs, but the core interface linking irrigation, fertilization, and yield formation. Under drip fertigation, increases in root length, root surface area, and root volume in different soil layers are significantly positively correlated with tomato fruit yield and water-use efficiency. Under appropriate water-nitrogen management conditions (100% ET_c + 250 kg N·ha⁻¹), compared with the no-nitrogen treatment, root length, root surface area, and root volume increased by about 40%-150%, while yield increased by 31.6% and water-use efficiency by 34.4% (Figure 4) (Feng et al., 2024). This indicates that improved root activity is not simply reflected in having more roots, but rather in more efficient resource capture and utilization.

The fine-root system is especially important in this process. Active fine roots with smaller diameters usually account for the main absorptive function of the root system, and their length, surface area, and branching degree directly determine the intensity of contact between roots and the root-zone solution. Studies on aerated irrigation further show that increasing dissolved oxygen levels in the root zone can significantly increase the length and surface area of fine roots (≤ 2 mm), and these fine-root traits are significantly positively correlated with aboveground biomass, fruit yield, nitrogen-use efficiency, and irrigation water-use efficiency (Zhang et al., 2023). Therefore, the high and stable yields of protected tomatoes do not depend simply on a large root mass, but on an efficient root system characterized by abundant fine roots, active absorption, and strong renewal capacity.

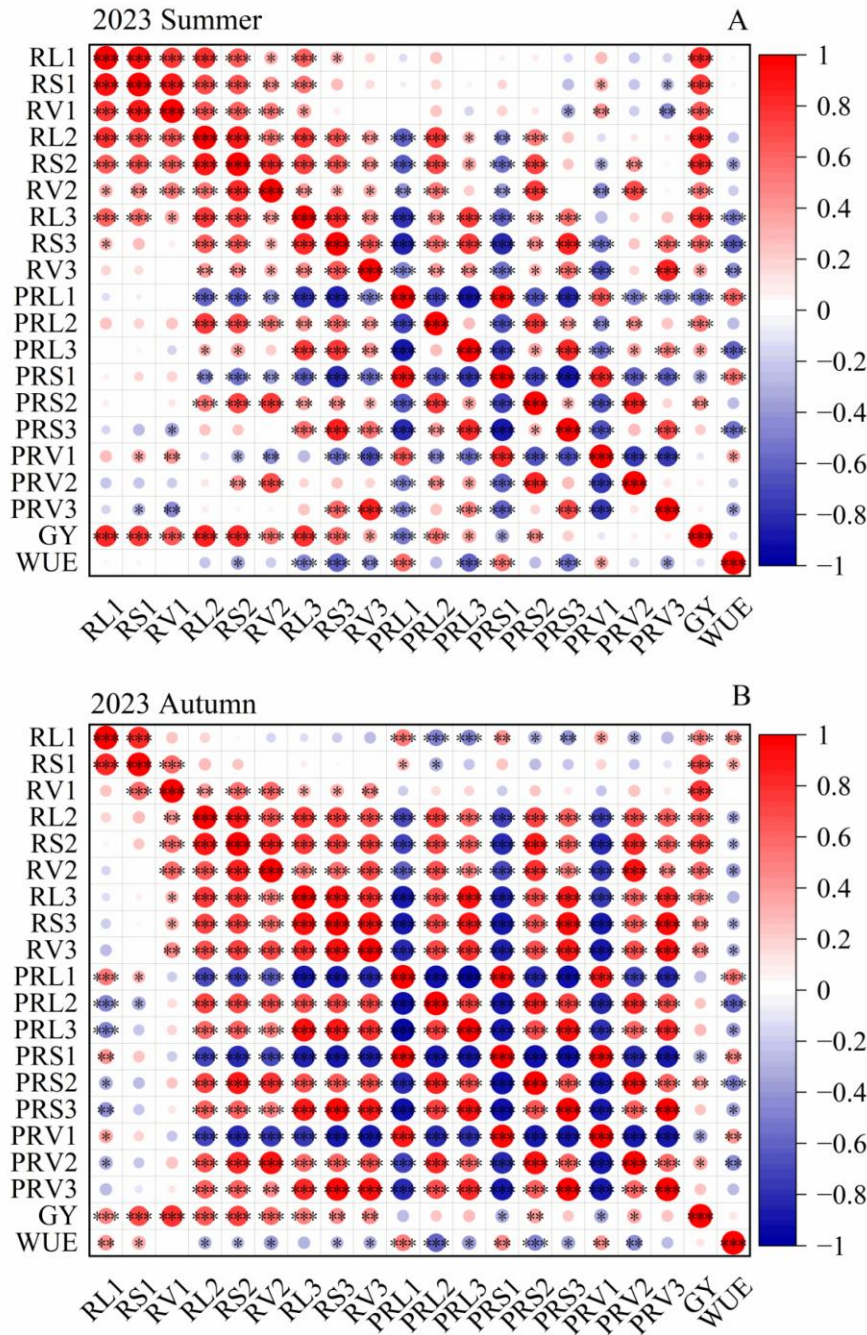


Figure 4 Correlation of root characteristics with fruit yield and water use efficiency (Adopted from Feng et al., 2024)

Image caption: RL1: root length belong to the 0-10 cm soil layer, RS1: root surface area belong to the 0-10 cm soil layer, RV1: root volume belong to the 0-10 cm soil layer, RL2: root length belong to the 10-20 cm soil layer, RS2: root surface area belong to the 10-20 cm soil layer, RV2: root volume belong to the 10-20 cm soil layer, RL3: root length belong to the 20-30 cm soil layer, RS3: root surface area belong to the 20-30 cm soil layer, RV3: root volume belong to the 20-30 cm soil layer, PRL1: Radio of root length belong to the 0-10 cm soil layer to total root length, PRS1: Radio of root surface area belong to the 0-10 cm soil layer to total root surface, PRV1: Radio of root volume belong to the 0-10 cm soil layer to total root volume, PRL2: Radio of root length belong to the 10-20 cm soil layer to total root length, PRS2: Radio of root surface area belong to the 10-20 cm soil layer to total root surface, PRV2: Radio of root volume belong to the 10-20 cm soil layer to total root volume, PRL3: Radio of root length belong to the 20-30 cm soil layer to total root length, PRS3: Radio of root surface area belong to the 20-30 cm soil layer to total root surface, PRV3: Radio of root volume belong to the 20-30 cm soil layer to total root volume, GY: fruit yield, WUE: water use efficiency. (A) 2023 Summer (B) 2023 Autumn (Adopted from Feng et al., 2024)

In addition to root activity, the vertical and horizontal distribution patterns of roots also profoundly affect water and fertilizer uptake efficiency. If roots are excessively concentrated in localized zones, water and nutrients may be depleted too rapidly in those areas, increasing spatial heterogeneity of resources in the soil or substrate and reducing overall use efficiency. In contrast, if roots can form a relatively broad and uniform distribution within the root zone, they are better able to continuously acquire water and nutrients from different spatial locations and buffer short-term fluctuations in supply. In soil-grown greenhouse tomatoes, mulching practices, emitter placement, and irrigation level all significantly alter root length density distribution. For example, under plastic mulch, more roots are concentrated in the top 0-20 cm of soil, whereas without mulch, roots are more often distributed at a depth of about 20 cm, which is related to the more suitable temperature and moisture conditions in the surface soil under mulching (Ge et al., 2025). At the same time, deficit irrigation can cause roots to redistribute either upward or deeper into the soil profile. In potted cherry tomato, increasing the number of emitters per plant can encourage roots to expand more widely, while deficit irrigation promotes deeper root extension. The combination of two emitters + deficit irrigation can create a root distribution that is both wide and deep, thereby increasing root length density, root weight density, yield, and water-use efficiency (Figure 5).

5.2 Fundamental role of root health in plant growth and stress resistance

In addition to root system size and distribution, root health itself is also fundamental to sustained growth and stress resistance in protected tomato production. Root health includes not only intact root structure, high cellular activity, and undamaged absorptive tissues, but also a stable rhizosphere environment, adequate oxygen supply, low pathogen pressure, and a relatively balanced beneficial microbial community. Healthy roots can maintain high water and nutrient uptake capacity and support continuous shoot growth and high photosynthetic assimilation by influencing hormonal signaling, osmotic regulation, and antioxidant systems. Under high-temperature stress, tomato genotypes that maintain higher root dry weight and a higher root-to-shoot ratio usually show higher yield and harvest index, indicating that a larger, healthy root biomass is an important basis for heat tolerance and sustained carbon assimilation (Mohammed et al., 2025).



Figure 5 Spatial distribution of tomato fruits at different maturity stages on plants and management status

The role of root health in stress resistance is especially evident under water stress and nitrogen stress. Drought stress significantly reduces root length, root biomass, and root activity, thereby weakening water and nutrient uptake capacity and leading to reduced shoot growth and photosynthesis. Under high nitrate stress, root structure is also inhibited, with development of both coarse and fine lateral roots being restricted and membrane stability declining, thereby affecting overall uptake and growth performance. Correspondingly, exogenous regulatory measures that improve root structure and vitality often have clear mitigating effects. For example, melatonin and sodium nitroprusside treatments can promote the growth of both coarse and fine lateral roots, increase root activity and antioxidant enzyme activity, and thereby enhance plant adaptation to high-nitrate conditions. Similarly, tannin-based biostimulants can increase root length and root weight under salt stress and upregulate the expression of genes related to root development and salt tolerance, thereby improving nutrient uptake and root salt tolerance.

Root health also determines the plant's basic resistance to biotic stress. Roots are a major entry point for soil-borne pathogens. If roots are damaged, if the rhizosphere microecology is imbalanced, or if aeration is poor, diseases such as root rot and wilt can be easily induced, thereby threatening whole-plant growth stability. Conversely, inoculation with beneficial microorganisms can enhance root health by promoting root growth, improving antioxidant capacity, enhancing rhizosphere nutrient cycling, and competitively suppressing pathogens. *Trichoderma asperellum* or plant growth-promoting rhizobacteria can significantly increase tomato root and shoot biomass, improve soil enzyme activity and nutrient availability, and effectively suppress soil-borne diseases such as *Fusarium oxysporum* (Zhang et al., 2025b). This indicates that root health is not only an inherent plant trait, but is also strongly influenced by the state of the rhizosphere ecosystem.

5.3 Improvement of root development and yield stability through grafting cultivation

In recent years, grafting cultivation has become one of the key technologies in protected tomato production for improving root performance, enhancing stress resistance, and increasing yield stability. Its core mechanism lies in using superior rootstocks with strong root systems, stress tolerance, and disease resistance to compensate for deficiencies of scion cultivars in root absorption, rhizosphere adaptation, and environmental stress tolerance. Through grafting, tomato plants can develop greater total root length, more root tips, a higher root-to-shoot ratio, and stronger root activity by relying on the rootstock, thereby enhancing water and nutrient uptake capacity and improving growth stability under adverse conditions such as low temperature and salt stress. Different rootstocks differed significantly in root traits, and grafted combinations using superior rootstocks increased yield by 14.6%-17.2% compared with nongrafted plants without reducing fruit quality; in some cases, lycopene and ascorbic acid contents were also increased.

The improvement in root development brought about by grafting is not limited to an increase in root quantity, but is more importantly reflected in optimized root function. Superior rootstocks usually have stronger root branching capacity, higher mineral nutrient uptake efficiency, and better osmotic adjustment ability, enabling them to maintain stable resource supply under unfavorable conditions. For example, in coconut coir-based cultivation systems, some tomato rootstocks can increase root and shoot biomass, chlorophyll content, and the uptake of mineral elements such as K, Ca, Mg, Fe, Mn, and Cu, thereby improving both yield and fruit quality. This indicates that grafting can fundamentally strengthen the growth basis of protected tomatoes by improving root growth and mineral nutrient acquisition.

Grafting is particularly valuable in buffering environmental stress and disease pressure. Under deficit irrigation and partial root-zone drying, grafted tomatoes can still maintain relatively high vegetative growth, mineral nutrient uptake, and fruit yield, even with a 30%-40% reduction in irrigation water, while achieving higher water-use efficiency. This indicates that the enhanced root absorption and water regulation capacity provided by the rootstock can significantly improve the resilience of resource use under protected cultivation conditions. In addition, when wild *Solanum* species are used as rootstocks, grafted plants show improvements in plant height, branch number, fruit number, average fruit weight, and yield per plant, while also exhibiting significant resistance to soil-borne diseases such as bacterial wilt (Kamble et al., 2025). Regarding adaptation to high temperatures,

recent studies also indicate that heat tolerance can to some extent be transferred through grafting, although the effect depends on appropriate matching between rootstock and scion (Biermann et al., 2025).

6 Regulatory Effects of the Protected Environment on High and Stable Tomato Yield

6.1 Effects of temperature regulation on tomato growth, development, and fruit set

Temperature is one of the key environmental factors affecting growth, development, and yield stability in protected tomato production. Tomatoes have different temperature requirements at different growth stages, but overall, their growth, flowering, pollination, and fruit development depend on suitable and stable temperature conditions. Tomatoes generally exhibit good growth and fruiting performance when daytime temperatures are about 18 °C-29 °C with relatively lower nighttime temperatures, whereas excessively high or low temperatures can disrupt plant physiological processes and reduce yield stability (Arshad et al., 2024). Under high-temperature conditions, early plant growth rates may temporarily increase, but pollen viability, pollen germination, and pollen tube growth are often inhibited, resulting in poor pollination, reduced fruit set, and increased flower and fruit drop (Jerca et al., 2024). When the average temperature increases from 14 °C-26 °C, the period from flowering to fruit maturity can be significantly shortened, but excessively high temperatures often lead to smaller fruits and reduced fruit set.

Low temperatures can also limit protected tomato production. Under low-temperature conditions, leaf photosynthesis and assimilate transport capacity decrease, plant growth slows, and flower bud differentiation may be inhibited, leading to delayed flowering (Adams et al., 2001). In early spring or winter protected cultivation, excessively low night temperatures often impair reproductive growth and reduce fruit marketability. In addition to average temperature, microclimatic differences within the greenhouse can also influence yield performance. Studies show that even when the difference in average daily temperature within the same greenhouse is only about 3 °C, noticeable differences in plant growth rate and fruit truss weight may occur (Šalagovič et al., 2024). Furthermore, maintaining temperatures around 18 °C-22 °C during flowering and early fruit set is more favorable for inflorescence productivity (Jerca et al., 2024), while maintaining relatively higher air temperature and suitable root-zone temperature during the seedling stage promotes root development and leaf area formation.

6.2 Effects of light intensity and photoperiod on photosynthesis and yield formation

Light is the primary energy source driving photosynthesis and dry matter accumulation in tomatoes, and therefore directly influences the potential yield of protected tomatoes. Light intensity, daily light integral (DLI), and light distribution within the canopy all affect leaf carbon assimilation capacity and fruit development. Although light distribution in large greenhouses is relatively uniform, spatial variation still leads to differences in plant growth and yield; plants located in areas with better light conditions generally achieve higher yields (Šalagovič et al., 2024). Adequate and sufficient light promotes photosynthesis and dry matter accumulation and provides the energy required for flowering and fruit enlargement. The optimal light intensity for inflorescence development and high yield formation in cherry tomato is about 360-384 W·m⁻², whereas insufficient light reduces inflorescence number and fruit set efficiency (Jerca et al., 2024). Under winter greenhouse conditions, increasing light intensity can also significantly promote plant growth and yield formation (Arshad et al., 2024).

When natural light is insufficient, artificial supplemental lighting has become an important technology in protected tomato production. A meta-analysis showed that LED supplemental lighting can increase greenhouse tomato yield by about 40% on average and significantly enhance photosynthetic capacity and chlorophyll content. Inter-canopy lighting not only increases total radiation input but also improves light distribution within the canopy, enhancing light-use efficiency of lower leaves and promoting uniform fruit development. In addition, photoperiod and the allocation of light-dark cycles may also influence yield formation. Under the same daily light integral, extending the light-dark cycle may increase yield in some cases; however, when the total light input remains constant, changes in photoperiod have a limited effect on yield. Therefore, in protected tomato production, ensuring sufficient daily light integral (DLI) and properly scheduling supplemental lighting periods is generally more important (Shibaeva et al., 2024).

6.3 Regulatory effects of air humidity and CO₂ concentration on tomato growth in protected systems

Air humidity and CO₂ concentration are important factors influencing tomato growth in protected environments, and they regulate plant physiological activity by affecting stomatal behavior, transpiration, and carbon assimilation processes. Appropriate air humidity helps maintain stomatal opening and transpiration-driven transport, whereas excessively high or low humidity can negatively affect plant growth. When the air is too dry and the vapor pressure deficit (VPD) is high, transpiration increases and stomata may close, reducing CO₂ assimilation rates. Conversely, excessive humidity restricts transpiration, affects mineral nutrient transport, and increases the risk of physiological disorders such as blossom-end rot. Even when VPD differences within the greenhouse are only about 0.6 kPa, significant differences in plant and fruit growth rates may occur (Šalagovič et al., 2024). In addition, humidity fluctuations can influence stomatal conductance and photosynthetic rates under fluctuating light conditions (Shi et al., 2024).

CO₂ concentration is another important regulatory factor that enhances photosynthetic potential in protected environments. Increasing environmental CO₂ concentration from approximately 400 ppm to 800-1 000 ppm can significantly increase leaf area, chlorophyll content, and net photosynthetic rate, thereby promoting dry matter accumulation and yield formation (Amarasinghe et al., 2025). This stimulatory effect is more pronounced under suitable light and temperature conditions, because photosynthesis responds more effectively to increased carbon supply under these conditions. However, excessively high CO₂ concentrations are not always beneficial. In cherry tomato production, the optimal CO₂ concentration under moderate light conditions is approximately 450-510 ppm, whereas excessively high CO₂ may reduce certain quality parameters through dilution effects (Arshad et al., 2024). Therefore, in protected tomato production, CO₂ regulation must balance the improvement of yield potential with the maintenance of fruit quality.

7 Cultivation Management Measures for Achieving High and Stable Yields in Protected Tomato Production

7.1 Optimization of canopy structure through rational plant density and pruning

Rational plant density and pruning (including side-shoot removal) are important cultivation measures for achieving high and stable yields in protected tomato production. Their core objective is to optimize canopy structure so as to coordinate the relationship among yield per unit area, individual plant light interception, and assimilate distribution. The canopy structure of protected tomatoes directly affects canopy light interception efficiency, the distribution of temperature and humidity within the canopy, and the balance between vegetative and reproductive growth, thereby exerting a significant influence on yield stability (Figure 6). Planting arrangements—such as row orientation, plant spacing, row spacing, and furrow spacing—often have a greater impact on canopy radiation interception, temperature distribution, and dry matter accumulation than individual plant structural traits. Moderately increasing plant spacing can improve light interception by individual plants and enhance fruit development. In protected production systems, moderate dense planting can increase leaf area per unit area and improve canopy light interception. However, excessively high planting density can deteriorate ventilation and light conditions, intensify competition among plants, and increase the risk of disease. In solar greenhouses, adopting an east-west row orientation combined with relatively wider row spacing can significantly enhance canopy light interception and photosynthetic capacity, increasing yields by approximately 4%-10% across different seasons (Li et al., 2024).

In recent years, dynamic planting density strategies have provided new approaches to canopy management in protected tomato production. By maintaining relatively high planting density during early growth stages to maximize canopy light interception, and then reducing density in later stages, it is possible to alleviate problems such as reduced fruit size and quality caused by excessive crowding, thereby balancing high yield and fruit quality (Karpe et al., 2024). Pruning and side-shoot removal further optimize canopy structure by controlling branch number and leaf area distribution, improving canopy ventilation and light penetration while promoting assimilate allocation to flowers and fruits. In high-wire cultivation systems, training a plant into two main stems can increase yield per plant and improve spatial utilization efficiency without increasing plant number. In addition, appropriate leaf removal is also an important component of refined canopy management. Studies show that data-driven leaf

pruning strategies based on light environment monitoring can reduce pruning frequency by approximately 35%-42%, while maintaining yield and increasing soluble solids content (Kim and Kubota, 2025). Under winter conditions, leaf pruning and LED supplemental lighting exhibit clear synergistic effects, with supplemental lighting significantly increasing yield and accelerating fruit maturation.



Figure 6 Demonstration of cultivation management and growth status of greenhouse-grown tomatoes

7.2 Effects of integrated water and fertilizer management on nutrient supply and yield stability

Integrated water-fertilizer management is an important technique for efficient protected tomato cultivation. Its core principle is the precise coupling of irrigation and fertilization to achieve dynamic matching between water and nutrient supply in the root zone, thereby maintaining stable plant growth and improving resource-use efficiency. Compared with traditional fertilization methods, integrated water-fertilizer management emphasizes adjusting water and nutrient supply according to crop growth stages and environmental conditions in order to avoid growth imbalance caused by water stress or excessive nutrient supply. Tomatoes exhibit different water and nutrient requirements at different growth stages. During the seedling and vegetative growth stages, adequate water supply is needed to promote root development and leaf area expansion, whereas during flowering and fruiting stages, stable supplies of nitrogen, phosphorus, and potassium are required to maintain fruit set and fruit enlargement. Under drip irrigation in solar greenhouses, combining soluble organic fertilizers with chemical fertilizers and applying appropriate irrigation levels can significantly increase nitrogen uptake, yield, and water-use efficiency, while also providing more stable economic returns.

Clear synergistic effects exist between irrigation level and fertilization rate. Research indicates that under micro-seepage irrigation, a combination of moderate irrigation and moderate fertilization can achieve higher photosynthetic rates, greater dry matter accumulation, and higher yields, while also improving fertilizer-use efficiency (Liu et al., 2024). In substrate cultivation systems, initiating irrigation when substrate moisture declines to about 70% of its capacity significantly improves water-use efficiency and enhances fruit soluble solids and vitamin C content compared with irrigation at higher moisture levels. In addition, irrigation frequency and real-time monitoring also influence water and nutrient use efficiency. Shorter irrigation intervals under drip irrigation help maintain stable root-zone moisture conditions and promote root growth (Zhang et al., 2025a). Intelligent irrigation control using soil moisture sensors can further reduce irrigation water consumption while improving yield and nutrient uptake efficiency (Wang et al., 2024).

7.3 Application of growth regulators and pollination techniques to improve fruit set

Fruit set rate is an important limiting factor in yield formation of protected tomatoes, especially under suboptimal temperature, light, or humidity conditions. Therefore, the use of plant growth regulators, biostimulants, and assisted pollination technologies has become an important strategy for stabilizing yield in protected tomato production. Certain biostimulants can enhance plant vigor and increase yield by regulating endogenous hormone levels, promoting cell division, and stimulating chlorophyll formation. Applying biostimulants such as Albit and

Turboroot in greenhouse tomato production can increase chlorophyll content and promote vegetative growth; when combined with soil improvement measures, yields can increase by approximately 16%-45% (Avasiloaiei et al., 2025). At the same time, appropriate levels of NPK fertilization are also important for stable fruit set, with moderate fertilization levels optimizing photosynthetic rates and fruit quality.

In addition to growth regulators, canopy structure and environmental conditions also influence fruit set stability. Excessively high planting density or excessive branching can intensify resource competition among fruits, resulting in reduced single fruit weight and increased fruit drop (Karpe et al., 2024). Therefore, rational plant density and pruning management can increase assimilate supply to inflorescences, thereby promoting fruit set and fruit retention. Improving the light environment can also increase fruit set rates. For example, LED supplemental lighting has been shown to increase fruit set rate by about 46% and accelerate fruit maturation. Under protected cultivation conditions, weaker air movement and reduced insect activity often result in lower pollination efficiency compared with open-field conditions. Therefore, pollination efficiency can be significantly improved through manual vibration, mechanical vibration, or bumblebee pollination, which enhance pollen release and fertilization success. These measures help reduce flower and fruit drop and stabilize yield.

8 Future Development Trends in High and Stable Yield Cultivation of Protected Tomatoes

With the rapid development of sensor technology, automation, artificial intelligence, and data science, protected tomato production is gradually shifting from experience-driven management to data- and model-driven systems. A key characteristic of future high-yield and stable greenhouse production will be the use of intelligent environmental control technologies to monitor and regulate key factors such as temperature, humidity, light intensity, CO₂ concentration, irrigation, and nutrient solution supply in real time through closed-loop control systems. This approach enables more precise production management. Currently, high-tech greenhouses have increasingly integrated technologies such as water and fertilizer sensors, supplemental lighting systems, and microclimate control software, forming automated production systems that combine environmental sensing, decision analysis, and operational control. Compared with traditional experience-based management, intelligent control systems can dynamically optimize environmental parameters by integrating real-time and historical data, thereby improving resource-use efficiency and stabilizing yield levels. In recent years, greenhouse control platforms and predictive models based on the Internet of Things (IoT) have further promoted the transition of protected agriculture from passive regulation to proactive prediction. Meanwhile, emerging concepts such as autonomous greenhouses and digital twin greenhouses are providing important directions for the future intelligent upgrading of protected tomato production. In addition to improving yield, intelligent environmental regulation can also reduce environmental burdens by optimizing energy and water-fertilizer utilization efficiency, thereby providing technical support for sustainable protected tomato production.

Against the backdrop of climate change and increasing intensification of protected cultivation systems, the breeding of high-yield and stress-resistant varieties, together with grafting technology, will become important foundations for stable tomato production. Modern tomato breeding is gradually shifting from a single focus on high yield to the improvement of multiple traits including high yield, superior quality, stress tolerance, and adaptability to protected cultivation environments. This transition is increasingly supported by technologies such as marker-assisted selection, molecular design breeding, and gene editing, which are used to develop new varieties resistant to high temperature, salinity, and diseases. Tolerance to stresses such as high temperature and waterlogging in tomato is associated with multiple genetic effects, and some superior hybrid combinations can still maintain relatively high fruit set and yield under adverse conditions. Therefore, future breeding efforts should not only focus on fruit quality and marketability, but also incorporate root system traits, reproductive stability, and stress-resistance physiological characteristics as key selection criteria. At the same time, grafting cultivation can combine high-quality scions with stress-resistant rootstocks, improving plant adaptability to complex environments and extending the fruiting period. Recent studies have also revealed that certain stress-resistance traits can be regulated by rootstocks and transferred to the scion, providing new directions for targeted rootstock breeding and research on rootstock-scion interactions.

Future protected tomato production will not only aim to achieve high and stable yields but must also emphasize efficient resource utilization and environmental sustainability. Consequently, green and efficient protected agriculture systems will become an important development direction. This model emphasizes the integration of technologies such as precision water-fertilizer management, nutrient recycling, renewable energy coupling, and biological pest control to maintain high productivity while reducing carbon emissions and environmental pressure. Compared with open-field production, protected systems often achieve better resource-use efficiency due to higher water-use efficiency and greater yield per unit area. In China's solar greenhouse and plastic tunnel systems, measures such as drip irrigation, integrated water-fertilizer management, and controlled-release fertilizers can significantly reduce carbon emissions, with fertilizer management considered a key factor influencing the environmental footprint of greenhouse production. Furthermore, high-tech soilless cultivation systems in greenhouses demonstrate the potential for circular and low-carbon production through nutrient solution recirculation systems and the use of clean energy. In the future, protected tomato production will also place greater emphasis on integrated pest management (IPM) and biological control technologies, while adapting to different greenhouse structures and regional conditions to develop diversified and sustainable green production systems.

Acknowledgments

The authors wish to thank the anonymous reviewers for their comments and suggestions, which were helpful in improving this work.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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