Genomics and Applied Biology 2026, Vol.17, No.2, 72-84
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Research Insight Open Access

Effects of Vertical Training Systems on Growth and Yield of Cucumber

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Genomics and Applied Biology, 2026, Vol.17, No.2 doi: 10.5376/gab.2026.17.0007
Received: 29 Jan., 2026
Accepted: 05 Mar., 2026
Published: 18 Mar., 2026

Preferred citation for this article:
Xu H.Y., 2026, Effects of vertical training systems on growth and yield of cucumber, Genomics and Applied Biology, 17(2): 72-84 (doi: 10.5376/gab.2026.17.0007)

Abstract Vertical training systems have been widely adopted in cucumber production due to their potential to improve land-use efficiency and crop productivity. This study systematically evaluates the effects of different vertical cultivation methods on cucumber growth, yield, and fruit quality. Based on field experiments with multiple training systems, key growth indicators including plant height, leaf area, photosynthetic performance, and root development were analyzed. The results showed that vertical cultivation significantly enhanced light utilization, improved canopy structure, and promoted physiological activity, leading to better vegetative growth. In addition, yield per plant and total yield were markedly increased, while fruit quality, including appearance and nutritional composition, was also improved. Furthermore, vertical systems contributed to higher resource use efficiency in water and fertilizer, and reduced the incidence of pests and diseases. Economic analysis indicated that although initial investment may be higher, the overall economic returns were favorable. A regional case study further confirmed the practical applicability and scalability of vertical cultivation in cucumber production. These findings provide a theoretical basis and technical support for optimizing cucumber cultivation systems in modern facility agriculture.

Keywords Vertical cultivation; Cucumber; Growth characteristics; Yield; Resource use efficiency

1 Introduction

Cucumber (*Cucumis sativus* L.) is a major greenhouse vegetable worldwide because of its short growth cycle, high productivity, and strong consumer demand for fresh fruits throughout the year (Singh et al., 2018; Samba et al., 2024). Under protected cultivation, environmental factors such as light, temperature, humidity, and water supply can be precisely managed to enhance growth and yield. However, canopy architecture and vertical training systems are equally critical, as they determine how efficiently plants intercept light, use space, and allocate assimilates to fruits. In many regions, growers still rely on empirically chosen or traditional trellis systems, which may not fully exploit the yield potential of modern cucumber hybrids. Systematic evaluation of vertical training configurations is therefore important for improving productivity and resource use efficiency in greenhouse cucumber production (Choi et al., 2023).

Research in different countries demonstrates that plant training and pruning markedly affect vegetative growth, yield components, fruit quality, labor requirements, and even root traits. In high-wire systems, varying the number of stems per slab alters stem length, leaf biomass, fruit number per plant, and water use, with one-stem systems often balancing yield and workload efficiently. Comparative studies of single-head, umbrella, and low-middle training under protected conditions have shown that single-head vertical training can increase vine length, leaf area, fruit number per vine, and marketable yield, while reducing deformed fruits (Shivaraj et al., 2020; Dulam et al., 2024). Other work comparing umbrella- and V-type vertical systems with a lowering-and-coiling method found that modified vertical training improved total and marketable yield and better maintained productive leaf area over time (Premalatha et al., 2006). In hydroponic NFT systems, lowering versus pinching training changed root biomass, xylem sap bleeding rate, and canopy biomass distribution, with implications for long-term productivity. Reviews of Japanese greenhouse cucumber emphasize that training, pinching, and lowering methods are central levers for yield improvement alongside environmental control. Collectively, these findings indicate that optimized vertical training systems are a key, but still incompletely standardized, technology for intensifying cucumber production under protected cultivation.

Despite these advances, knowledge gaps remain regarding how specific vertical training systems interact with cultivar type, greenhouse structure, and local climate to determine growth dynamics, yield, and fruit quality. Previous studies often compare only a limited set of training methods, or focus on single aspects such as yield or root traits, without integrating a full set of morpho-physiological and productivity indicators across the crop cycle. Moreover, many growers continue to trail vines on overhead wires without formal training, allowing excessive fruit load that can compromise fruit size, quality, and uniformity. Against this background, the present study on the effects of vertical training systems on growth and yield of cucumber aims to (i) quantify how alternative vertical training configurations influence vine growth, leaf area development, and flowering; (ii) assess their impacts on yield components, total and marketable yield, and incidence of deformed fruits; and (iii) provide practical recommendations for selecting suitable vertical training systems under protected conditions. By linking detailed growth measurements with yield performance, this work seeks to contribute a clearer experimental basis for optimizing canopy architecture and improving the efficiency and profitability of greenhouse cucumber production.

2 Overview of Vertical Cultivation Methods

2.1 Definition and types of vertical cultivation

Vertical cultivation generally refers to producing crops in stacked layers or vertically arranged structures rather than on a single horizontal plane, thereby multiplying the effective growing area per unit of land (Figure 1) (Beacham et al., 2019). In controlled-environment systems, these layers are combined with artificial or supplemented light, precise climate regulation, and soilless culture to decouple plant growth from outdoor weather and soil constraints (Van Delden et al., 2021). By organizing plants on shelves, towers, or vertically inclined panels, vertical cultivation can significantly increase yield density while maintaining uniform environmental conditions within the production unit.

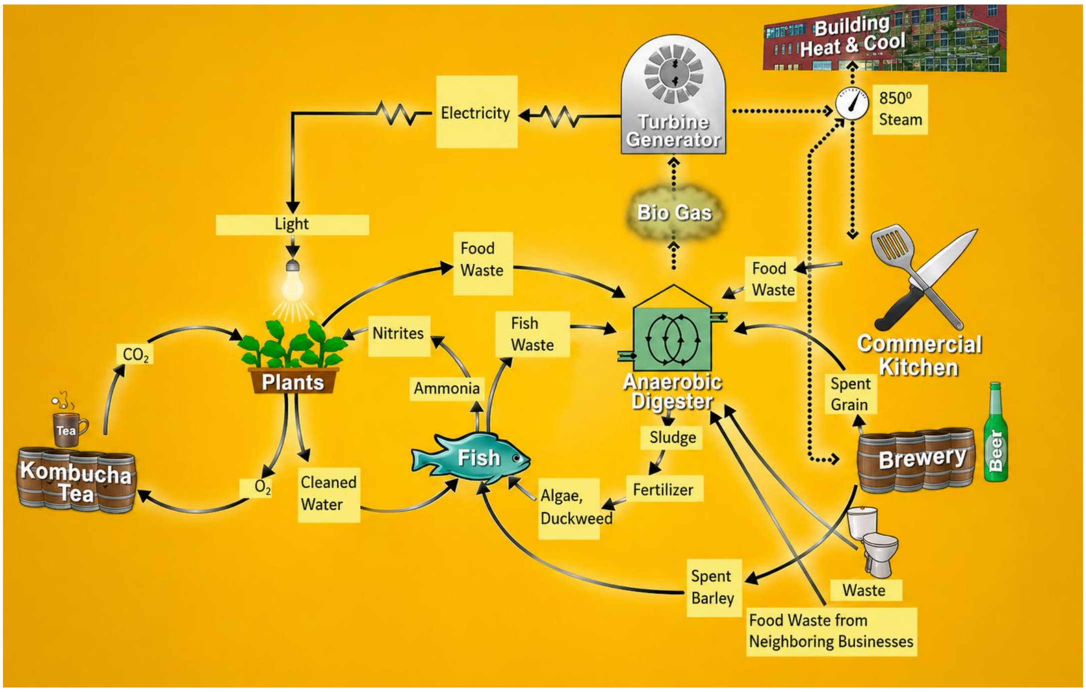

Figure 1 An illustration of an integrated food production through a closed-loop system (Adopted from Beacham et al., 2019)

Within this broad concept, vertical cultivation can be divided into systems using stacked horizontal platforms and those based on vertically oriented growing surfaces such as towers or walls (Malabadi et al., 2024). Stacked horizontal systems adapt greenhouse benches into multi-tier racks, often irrigated with hydroponic techniques like nutrient film technique (NFT), deep-water culture, or drip-fed substrates. Wall or tower systems place plants in columns or panels through which nutrient solution moves from top to bottom, improving space use in narrow footprints and on building facades. Across these system types, hydroponics and aeroponics are the dominant irrigation methods, reflecting the shift from soil-based cultivation toward recirculating, high-efficiency water and nutrient management (Eldridge et al., 2020).

2.2 Development history of vertical cultivation technology

Historically, protected cultivation evolved from simple greenhouses to high-tech facilities with precise control of climate and irrigation, providing the technical foundation for vertical cultivation (Jain et al., 2023). Early concepts of “vertical farms” emphasized skyscraper-like glass structures in cities, enabled by advances in hydroponics, aeroponics, and greenhouse engineering . Initial development focused mainly on engineering feasibility-stacking structures, nutrient delivery, and artificial lighting-often driven by visionary architectural projects and small experimental units rather than commercial scale (Al-Kodmany, 2018).

In the last decade, vertical cultivation has shifted toward resource efficiency, resilience, and circularity, as climate change and urbanization intensified interest in local food production (Van Gerrewey et al., 2021). Recent work emphasizes energy-efficient LEDs, water and nutrient recycling, and integration of beneficial microbiota to enhance resilience and reduce fertilizer and pesticide inputs. At the same time, the sector has expanded rapidly in North America, Asia, and Northern Europe, with many start-ups and pilot farms, while scientific and policy communities now scrutinize economic feasibility, environmental performance, and scalability (Orsini and Zauli, 2023). These developments mark the transition from conceptual demonstrations toward data-driven optimization and standardization of vertical cultivation technologies.

2.3 Application of vertical cultivation in facility agriculture

In facility agriculture, vertical cultivation is mainly implemented in indoor farms and advanced greenhouses as a way to intensify production within limited space and decouple output from seasonal variability (Grishin, 2025). Multi-layer systems in controlled-environment rooms allow year-round production of leafy vegetables and herbs, using precisely managed lighting, temperature, humidity, CO_2, and nutrient supply to achieve high yields per unit floor area (Van Delden et al., 2021). Such systems can substantially reduce water use compared with field production, while the enclosed environment lowers pest pressure and can minimize pesticide needs.

Greenhouses and urban protected structures are increasingly integrating vertical units-racks, towers, and rooftop systems-to expand growing area, particularly in regions with scarce arable land or harsh climates. In small-scale and regional contexts, vertical cultivation inside greenhouses has been proposed as a way to multiply the effective cropping area while using existing heating and structural infrastructure more efficiently (Grishin, 2025). In urban settings, abandoned warehouses, containers, and building rooftops are converted into vertical facilities supplying fresh produce close to consumers, reducing food miles and supporting local food security strategies. As digital technologies such as IoT, automation, and AI-based control advance, vertical cultivation within facility agriculture is expected to become increasingly precise, standardized, and scalable (Carpineti et al., 2024; Rathor et al., 2024).

Vertical cultivation reorganizes crop production into stacked or vertical layers, supported by controlled-environment and soilless technologies, to greatly increase output per unit land. Its development has progressed from visionary skyscraper farms toward commercially tested, resource-efficient systems focused on resilience and circularity. Within facility agriculture, vertical cultivation now underpins intensive indoor farms and greenhouse add-ons that offer high, year-round yields and reduced resource use, especially in land- and water-limited or urban environments.

3 Growth and Development Characteristics of Cucumber

3.1 Biological characteristics of cucumber

Cucumber (*Cucumis sativus* L.) is a cucurbit crop with a vining habit, simultaneous vegetative and reproductive growth, and continuous fruit set along the main stem and branches, making shoot architecture central to cultivation and yield (Liu et al., 2021). Leaves, tendrils, male and female flowers, and fruits arise from nodes, and changes in meristem activity or organ identity can strongly modify plant stature and reproductive capacity.

Fruit traits such as length, diameter, surface wax, spines, and flesh thickness are highly variable and controlled by multiple developmental and genetic factors, including regulators of cell division, hormone responses, and sugar transport. These traits influence market class, consumer preference, and handling, and are key breeding targets for improving productivity and postharvest performance (Grumet et al., 2022).

3.2 Environmental requirements for growth

Light quantity strongly affects cucumber seedling morphology, root architecture, and biomass, with higher daily light integral producing compact, vigorous seedlings but reducing photon yield (Figure 2) (Wang et al., 2021). In plant factories, suitable photosynthetic photon flux and daytime temperature combinations (e.g., around 260 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 25-28 °C) improve seedling quality indices important for grafting and transplant performance.Temperature, irrigation, and nutrient supply interact to determine integrated growth and yield in greenhouse cucumbers, with air temperature exerting particularly strong effects. Optimized combinations of irrigation amount, substrate moisture, and nitrogen or calcium application enhance yield, fruit quality, and water and fertilizer use efficiency, especially under changing or warm climates (Bello et al., 2023).

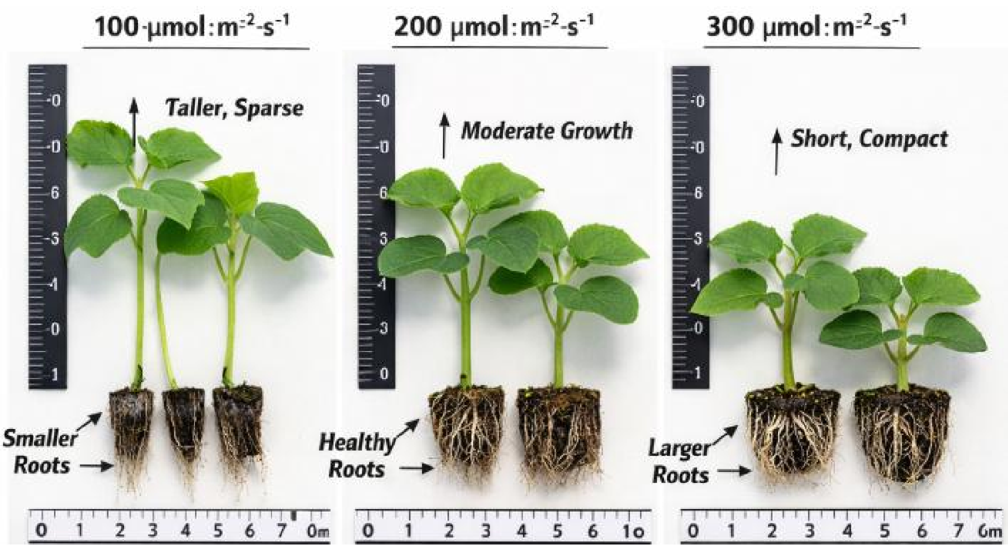

Figure 2 Effects of different light intensities on cucumber seedling morphology and biomass accumulation. Higher daily light integral results in more compact and vigorous seedlings, but may reduce photon yield (Adopted from Wang et al., 2021)

Water and nutrient management are critical in both open-field and protected systems; moderate deficit drip irrigation with adjusted nitrogen can increase yield in arid regions while reducing leaching (Bello et al., 2023). In hydroponic culture, quantitative nutrient management based on solar radiation maintains yield while improving nutrient use efficiency and reducing nutrient waste per unit fruit produced (Samba et al., 2024). Fertilization form and frequency also shape cucumber performance in greenhouses; integrated nutrient management combining mineral fertilizers with organic sources and biofertilizers improves vegetative growth, flowering behavior, and marketable yield compared with sole chemical or organic inputs. Soilless culture with well-formulated nutrient solutions further promotes vegetative and reproductive traits, photosynthetic pigments, and fruit quality relative to soil culture.

3.3 Key physiological factors affecting yield

Yield formation in cucumber depends on biomass production and source-sink dynamics; modeling of cultivars and their F_1 hybrid shows that internal source-sink ratio, fruit set, and fruit sink strength jointly determine high yield. Adjustments that increase the proportion of biomass allocated to fruits and enhance sink strength raise individual fruit weight and overall productivity (Wang et al., 2020). Regulation of sink-source relationships also occurs at molecular and epigenetic levels. DNA methylation and non-coding RNAs in leaves modulate expression of genes involved in photosynthesis, carbohydrate metabolism, and hormone signaling, thereby altering carbon partitioning to fruits and affecting fruit length and dry weight.

Plant hormones are another major physiological lever; auxin broadly regulates organ development (root, stem, leaf, tendril, flower, and fruit) and mediates responses to multiple abiotic and biotic stresses, influencing overall plant vigor and yield stability (Sharif et al., 2022). Exogenous plant growth regulators such as gibberellins and auxins can modify source-sink relations and improve fruit set and yield traits when appropriately managed (Dalai et al., 2020). Water and nutrient use efficiencies, photosynthetic capacity, and chlorophyll content directly support yield.

Coupled water-potassium management and alternate drip irrigation regimes with moderate nitrogen increase chlorophyll, photosynthetic rates, and water and potassium use efficiency, resulting in higher yields and better fruit quality (Li et al., 2024).

Cucumber yield is determined by its vining, continuously fruiting biology; by precise control of light, temperature, water, and fertilization; and by key physiological processes including source-sink balance, hormone regulation, and resource-use efficiency. Modern studies highlight that optimized environmental management and fine-tuning of carbon allocation and hormonal signals are central to realizing the yield potential of cucumbers under vertical training systems.

4 Experimental Design and Research Methods

4.1 Experimental materials and site conditions

The experiment will be conducted in a protected greenhouse located at a research farm with a subtropical monsoon climate, where cucumbers are commonly grown as an off-season crop for higher economic returns (Kumar et al., 2024). A commercial greenhouse cucumber hybrid with indeterminate growth and suitable for high-wire or vertical training will be selected, similar to cultivars used in studies on training and pruning systems under protected conditions (Singh et al., 2018). Seeds will be sown in trays filled with a soilless substrate and later transplanted to raised beds or growbags arranged according to the experimental layout, following common protected-cultivation practice for cucumber spacing and plant density.

The greenhouse will be naturally ventilated and will allow basic environmental control of temperature, humidity and irrigation, as recommended for low-tech or passively ventilated structures used for cucumber in hot or variable climates (Wang et al., 2024). Plants will be grown in a soilless medium (e.g., cocopeat-perlite) or well-drained soil, with fertigation managed to maintain adequate moisture and nutrient supply throughout the crop cycle (Goyal et al., 2023). The general irrigation regime will be designed to match crop water requirements under greenhouse conditions, in line with approaches used to derive crop coefficients and optimize water use efficiency in vertically trained cucumber.

4.2 Experimental treatments

The experiment will adopt a factorial randomized block design to compare different vertical training systems while keeping other cultural practices uniform, similar to studies where pruning and training factors are combined to assess growth and yield (Singh et al., 2018). Treatments will include at least three vertical training methods such as single-head (high-wire) training, umbrella or modified-umbrella training, and a low-middle or multi-stem training system, all widely used in greenhouse cucumber production (Liu et al., 2020).

Within each training system, standardized pruning rules will be applied (e.g., removal of early flower buds to a defined stem height, or regulation of lateral shoots) to maintain a clear canopy structure and comparable fruit load, following approaches where flower buds are removed up to specific heights to study interaction with training type. Plant density, irrigation, fertilization, and pest management will be kept consistent across treatments to ensure that observed differences in growth and yield can be attributed mainly to the training systems, as is common in controlled comparisons of high-wire versus modified-umbrella trellising (Liu et al., 2020).

4.3 Data collection and statistical analysis methods

Data collection will focus on key growth traits (vine length, number of nodes, leaf number and leaf area), phenology (days to first harvest), and yield components (fruit number per plant, average fruit weight) to capture the effects of training systems on canopy development and productivity, similar to previous greenhouse cucumber experiments (Singh et al., 2018). Total and marketable yields per plant and per unit area will be recorded, along with fruit quality indicators such as length, diameter and incidence of deformed fruits, following metrics used in trellising and training comparisons (Liu et al., 2020).

Measurements will be taken at defined intervals throughout the crop cycle, and all data will be subjected to analysis of variance (ANOVA) appropriate for factorial or randomized block designs to test for significant effects of training method on growth and yield. When treatment effects are significant, mean separation will be performed using the least significant difference (LSD) test at the 5% probability level, consistent with statistical procedures commonly applied in cucumber training and pruning studies (Qu et al., 2022). All analyses will be conducted using standard statistical software, and assumptions of ANOVA (homogeneity and normality) will be checked before final interpretation of treatment effects.

5 Effects of Vertical Cultivation on Cucumber Growth Indicators

5.1 Effects on plant morphology

Vertical training systems reshape cucumber canopy structure by altering stem number, vine length, and leaf distribution along the wire. In high-wire systems, single-stem or horizontally trained plants tend to develop greater vine height, more nodes, and larger leaf area compared with some twin-stem or modified systems, indicating that training intensity and stem number directly affect elongation growth and leaf expansion (Shirahmadi et al., 2017). Under protected conditions, single-head training consistently increases vine length and leaf area at different growth stages, reflecting more efficient capture of light and assimilate allocation to the main stem (Shivaraj et al., 2020).

When stem number per slab or vine direction is modified, plant height and node number often decrease, but total fruits per plant may rise, showing a shift from vegetative to reproductive allocation. Comparative studies of single-head, umbrella, and low-middle systems report that single-head training produces the highest vine length and leaf area, which correlate with improved yield attributes and better canopy architecture (Shivaraj et al., 2020). Measurements of leaf area index in high-wire and umbrella-type systems further suggest that an optimal range of leaf density is required to balance light interception with adequate penetration into the lower canopy (Kile et al., 2024).

5.2 Effects on photosynthetic characteristics and physiological indicators

Vertical training modifies the spatial distribution of leaves, which in turn affects light interception, photosynthetic activity, and physiological status. In high-wire cucumber, training methods that maintain a more uniform, upright canopy improve light penetration and reduce shading of lower leaves, supporting more even photosynthesis across canopy layers (Figure 3) (Kile et al., 2024). Experiments combining high-wire cultivation with intracanopy lighting show that improved light distribution enhances net photosynthesis and photosynthetic capacity, with increases in Rubisco carboxylation rate and electron transport capacity leading to higher yield (Pettersen et al., 2010).

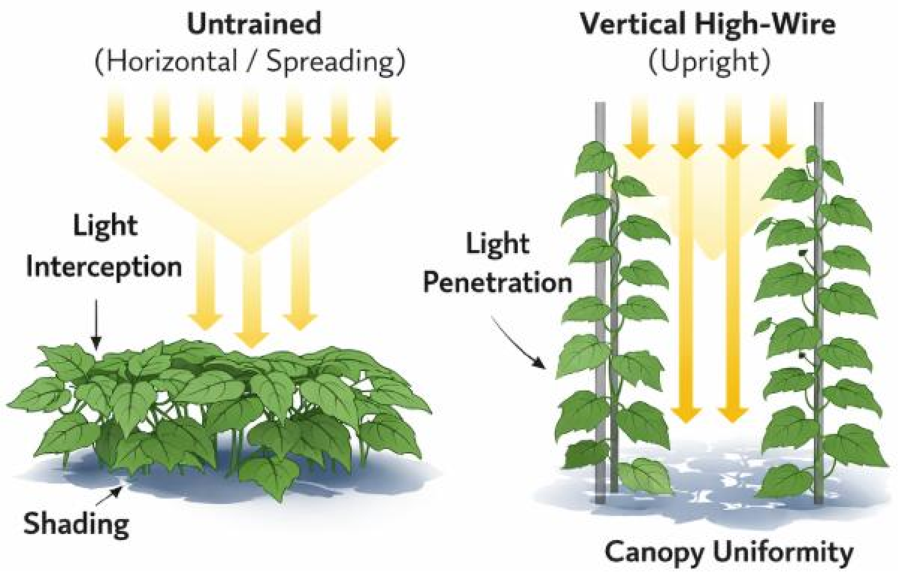

Figure 3 Effects of vertical training on canopy architecture and light distribution in cucumber cultivation systems. Upright canopy structures improve light penetration and reduce shading, enhancing overall photosynthetic performance (Adopted from Kile et al., 2024)

Physiological indicators such as chlorophyll content, chlorophyll fluorescence parameters, and pigment distribution respond to canopy structure and light environment created by training. In high-wire systems supplemented with LED interlighting, older, lower leaves maintain higher chlorophyll and carotenoid contents and improved photosynthetic performance indices, which are closely associated with increased productivity (Kowalczyk et al., 2022). Vertical canopies that facilitate better removal of old leaves and exposure of fruits to light also support more favorable microclimates, potentially improving gas exchange, nitrate reductase activity, and stress resistance, thereby sustaining photosynthetic efficiency over long cropping cycles.

5.3 Effects on root development

Vertical training also influences below-ground development through changes in source-sink balance and carbohydrate allocation. In hydroponic NFT systems, lowering training (LT), which maintains a continuous main stem without severe pinching, leads to significantly higher root dry weight, greater root dry/fresh weight ratio, and faster xylem sap bleeding rate than pinching training (PT), indicating enhanced root biomass and activity under LT (Samba et al., 2024). The greater remaining aerial biomass in LT plants suggests that a stronger root system supports sustained shoot growth and long-term productivity in vertically trained cucumbers.

In contrast, intensive pinching redirects assimilates to regrow shoots at the expense of roots, reducing root biomass and activity even though individual leaves and main stem diameter in upper canopy layers may be larger. Root morphological traits and physiological activity are closely linked to stress resilience and nutrient uptake; studies under combined biotic and potassium stress show that root length, surface area, volume, and tip number respond sensitively to environmental conditions, strongly affecting plant height and leaf area (Shi et al., 2025). Together, these findings indicate that vertical training regimes that minimize severe, repeated pinching and maintain stable canopy growth tend to favor more robust root systems, supporting higher and more stable yields in long-cycle cucumber cultivation (Samba et al., 2024).

Vertical training systems profoundly influence cucumber growth by reshaping plant morphology, redistributing light within the canopy, and altering the balance between shoot and root development. High-wire and single-stem systems generally promote greater vine length and leaf area, while training that preserves a uniform, well-lit canopy improves photosynthetic performance. At the same time, training methods that avoid excessive pinching support stronger root systems with higher activity, which underpins sustained productivity and stress resilience in intensive, long-term cucumber production.

6 Effects of Vertical Cultivation on Cucumber Yield and Quality

6.1 Effects on yield per plant and total yield

Vertical training systems markedly influence fruit number per plant and yield per unit area by altering canopy structure, leaf area, and light interception. Single-head or high-wire systems often increase vine length and leaf area, leading to more fruits per vine and higher yield per plant and per hectare under protected conditions (Shivaraj et al., 2020). In one study, a single-head system produced about 23 fruits per vine, 5.9 kg vine^{-1} and 133 t·ha^{-1}, clearly outperforming umbrella and low-middle systems in both total and marketable yield.

Other vertical configurations, such as modified-umbrella or multi-stem high-wire, can raise fruit number per plant but may not always increase yield per area if plant density and stem number are not optimized (Choi et al., 2023). In a smart-greenhouse high-wire system, treatments with six stems per slab produced more fruits per plant than those with four or eight stems, yet total yield per m^2 remained similar across treatments (≈13 kg·m^{-2}), indicating a trade-off between per-plant productivity and planting density. Comparisons of high-wire, V-shape, and horizontal systems also showed the highest monthly marketable yield per plant in high-wire training, especially in low-light periods (Shirahmadi et al., 2017).

6.2 Effects on fruit quality

Vertical training affects fruit appearance through its impact on light exposure, canopy microclimate, and fruit load regulation. High-wire training increased fruit length and reduced the proportion of deformed fruits compared with umbrella and low-middle systems, improving visual quality and uniformity (Shirahmadi et al., 2017; Shivaraj et al., 2020). Systems that enhanced light penetration into the canopy produced darker green fruits with higher chlorophyll content and extended shelf life, as darker skin color was associated with delayed yellowing.

Nutritional quality can also respond to training-induced changes in light and source-sink balance. In a comparison of training systems, fruits from V-shape plants showed higher total soluble solids and potassium content, suggesting that canopy structure and fruit position modify sugar and mineral accumulation (Shirahmadi et al., 2017). Other management factors such as substrate and fertigation interact with training to shape quality: soilless culture on organic substrates increased vitamin C and improved color parameters and soluble solids relative to perlite or soil, indicating that vertically trained plants in optimized substrates may combine high appearance quality with enhanced nutritional components (Roosta et al., 2025).

6.3 Effects on commercial value and marketability

Commercial value of cucumbers under vertical training is largely determined by the proportion of marketable yield, fruit uniformity, and shelf life. Single-head training systems consistently delivered higher marketable yield per hectare and the lowest percentage of deformed fruits, directly improving the share of fruits meeting grading standards (Shivaraj et al., 2020). In a pruning-training interaction study, pruning up to 75 cm combined with single-head training produced the highest marketable yield (≈150 $t \cdot ha^{-1}$), showing how canopy management can substantially raise saleable output (Dulam et al., 2024).

Training systems that improve canopy light exposure also enhance shelf life and reduce postharvest losses, thereby increasing effective marketable yield along the supply chain. Trellis and high-wire systems, compared with ground culture or poorly ventilated canopies, produced more uniform, darker green fruits with fewer culls and better disease control, contributing to higher grades and price potential. In hydroponic and NFT systems, lowering training facilitated labor for harvest and leaf removal, supporting future automation while maintaining high total and marketable yields per area, which further strengthens economic viability and commercial attractiveness of vertically trained cucumber production (Samba et al., 2024).

7 Ecological and Economic Benefit Analysis of Vertical Cultivation

7.1 Effects on resource use efficiency

Vertical training integrated with precise irrigation can substantially improve water use efficiency in greenhouse cucumber. Vertically trained vines grown in soilless media showed well-defined crop coefficients across growth stages, allowing irrigation to closely match evapotranspiration and avoid excess drainage (Goyal et al., 2023). In high-wire systems, modifying stem number per slab changed drainage and retained volume; a single-stem treatment achieved lower water use per kilogram of fruit than multi-stem treatments while maintaining similar yield per unit area, indicating more efficient conversion of applied water into marketable yield (Choi et al., 2023).

Training interacts with fertigation management to determine fertilizer use efficiency and economic return. In greenhouse trials, higher fertigation levels combined with single-stem training improved yield and net returns per unit area, reflecting better exploitation of applied nutrients under vertically managed canopies (Patel and Saravaiya, 2018). In an NFT system comparing lowering versus pinching training, water use efficiency did not differ significantly, but nutrient use efficiency was higher under pinching because lowering training promoted more vegetative biomass relative to fruit, showing that canopy architecture can shift how nutrients are partitioned between growth and yield. Efficient light use is also critical: supplemental LED systems with well-distributed toplighting and interlighting increased light use efficiency and gross margins compared with HPS, especially when paired with vertically organized canopies that intercept radiation more uniformly (Kowalczyk et al., 2020).

7.2 Effects on pest and disease occurrence and control

Vertical and trellis systems can modify the microclimate and fruit-soil contact, influencing disease occurrence. In open-field comparisons, trellised cucumbers had reduced soil-borne disease incidence and improved fruit quality relative to untrained plants, as elevated canopies enhanced air exchange and reduced contact with infested soil. Similarly, trellis culture in pickling cucumber lowered Phytophthora capsici fruit rot compared with ground culture, largely because fruit were held off the soil surface and canopy conditions became less favorable for infection (Ando and Grumet, 2006).

In protected systems, canopy management through vertical training also interacts with pest control and integrated management strategies. Trellising in slicing cucumbers slightly reduced downy mildew severity, but did not increase marketable yield, so was not recommended as a primary control measure compared with fungicides and host resistance (Keinath, 2019). Under greenhouse conditions, biologically based pest control programs using parasitoids and predators achieved strong suppression of whiteflies, aphids, thrips and spider mites with yields comparable to chemical control, offering pesticide-free produce and lower production costs; such programs are well suited to vertically trained cucumbers where canopies and walkways facilitate release and monitoring of natural enemies (Adly and Sanad, 2024).

7.3 Cost input and economic benefit analysis

Vertical high-wire systems influence both start-up costs and ongoing profitability. Conventional single-head high-wire production requires high plant density and thus large transplant numbers, raising initial crop establishment costs (Hao et al., 2010). A twin-head "V" high-wire system achieved similar growth and yield to single-head training while using only half the number of transplants, improving cost-effectiveness for year-round greenhouse production by reducing start-up plant material expenditure without sacrificing yield or quality.

Economic analyses that integrate fertigation regimes and training show that resource-optimized vertical systems can generate strong financial returns despite higher input intensity. In greenhouse cucumber, higher fertigation rates combined with single-stem training increased yield per unit area and produced high net returns over a short crop cycle, particularly when subsidies for protected cultivation infrastructure were available (Patel and Saravaiya, 2018). Broader assessments of protected cucumber production indicate that soilless and hydroponic systems, often using vertical or high-density configurations, greatly increase yield and gross income compared with traditional soil methods, although they also raise energy and input costs and require careful management to maintain favorable energy-economic ratios (Hesampour et al., 2022; Bilal et al., 2024).

8 Case Study: Application Practice of Vertical Cucumber Cultivation in a Certain Region

8.1 Overview of the case area and cultivation model

Many successful applications of vertical training in cucumber focus on protected cultivation, typically greenhouses or polyhouses in regions with climatic constraints such as hot summers or off-season production windows (Kumar et al., 2024). In these facilities, cucumbers are often grown in soilless systems (NFT or rockwool growbags) with fertigation and environmental control, enabling long cropping cycles and intensive vertical training on wires or strings (Somma et al., 2021).

In high-tech or smart greenhouses, planting density and stem number per slab are carefully adjusted, for example using high-wire systems with four to six stems per slab to balance canopy development and water use (Choi et al., 2023). In newly developed NFT systems, grafted cucumbers trained by lowering or pinching are cultivated from late winter to early summer to exploit favorable light and temperature while maintaining continuous vertical canopies.

8.2 Growth and Yield Performance in Actual Production

Under commercial or near-commercial conditions, vertical training systems regularly achieve yields far above traditional field cultivation. High-wire systems in smart greenhouses reached about 13 $kg·m^{-2}$, roughly 1.6 times typical Korean greenhouse yields, demonstrating the combined effect of vertical training and improved environment (Choi et al., 2023). In NFT "Kappa land" systems, lowering training produced 15.4 $kg·m^{-2}$ total yield and 13.8 $kg·m^{-2}$ marketable yield, alongside very long stems and high node numbers that support sustained production.

Single-head training in protected cucumber cv. 'Malini' delivered yields of about 5.9 kg per vine and 133 $t·ha^{-1}$, with high marketable yield and few deformed fruits, confirming strong performance in farmer-oriented greenhouse trials (Shivaraj et al., 2020). In open-field summer production, vertically staked plants at appropriate population densities achieved early and total yields comparable to much denser creeping systems, but with higher yield per plant and fewer non-marketable fruits (El-Zawily et al., 2000).

8.3 Analysis of promotion effects and existing problems

Promotion of vertical training systems can raise land and water productivity, improve fruit quality and uniformity, and reduce labor for some tasks. In greenhouse studies, single-stem or single-head training increased marketable yield and reduced deformed fruits, directly strengthening commercial returns and supporting wider adoption among growers (Patel and Saravaiya, 2018; Shivaraj et al., 2020). Smart-greenhouse high-wire models also show stable weekly yields aligned with solar radiation, which helps planning labor, market supply, and contracts, further enhancing the attractiveness of the technology (Choi et al., 2023).

However, several constraints limit large-scale dissemination. NFT and high-wire systems require substantial initial investment, technical skill in fertigation and climate management, and careful matching of stem number and plant density; for example, six stems per slab increased fruits per plant but did not raise yield per m^2, highlighting management complexity (Choi et al., 2023). In NFT, lowering training improved yields and labor efficiency for leaf removal and harvest but reduced nutrient use efficiency because more biomass was diverted to vegetative growth instead of fruits. In open-field systems, vertical training gave high per-plant yield only at lower populations, so farmers must balance trellis cost against plant density and total farm output (El-Zawily et al., 2000).

9 Conclusions and Prospects

Vertical training systems clearly enhance greenhouse cucumber performance by optimizing canopy structure, light interception, and source-sink balance. Single-head high-wire training frequently increases vine length, leaf area, and number of fruits per vine, leading to higher yield per plant and per hectare under protected conditions. In smart and high-tech greenhouses, training one main stem per slab also improves water consumption patterns, stabilizes weekly yield, and simplifies canopy management compared with more complex multi-stem arrangements. Different vertical configurations (single-head, V-shape, modified-umbrella, lowering vs. pinching) allow trade-offs between per-plant yield, yield uniformity, and labor inputs. Modified-umbrella systems can produce more fruits per plant than high-wire at a given density, whereas high-wire can deliver more consistent weekly yields, especially in low-profile greenhouses. Lowering training in NFT hydroponics achieves higher total and marketable yield per unit area and stronger root systems, while also simplifying old-leaf removal and harvest, which favors future automation.

Despite clear benefits, current studies are often confined to specific cultivars, greenhouse types, and climate zones, limiting broad generalization. Many experiments use single seasons or short cycles, so long-term impacts of vertical systems on root vigor, cumulative yield, and resource use efficiency across multiple cycles are not fully documented. Interactions between training, fertigation level, and protected structure are usually tested in factorial designs but within narrow environmental ranges, leaving gaps for extreme climates or low-input systems. Methodological limitations include small plot sizes, limited replications, and focus on a restricted set of response variables such as yield and basic quality traits. Economic analyses attached to training studies are rare; most work emphasizes biological performance and only a few integrate net returns or cost-benefit assessment of transplant number, labor requirement, and infrastructure investments. Labor time for different training methods is sometimes discussed qualitatively, but quantitative labor productivity data and mechanization feasibility are still insufficient for robust techno-economic recommendations.

Future work should integrate vertical training with resource-efficient irrigation and fertigation to improve sustainability in water-scarce regions. Development of crop coefficients for vertically trained cucumbers in soilless media already provides a basis for precise irrigation scheduling; further coupling with smart irrigation and optimized EC management could maximize water and nutrient use efficiency while maintaining high yields. Combining vertical systems with circular or cascade hydroponics and aquaponics may also reduce nutrient losses and enhance environmental performance in intensive greenhouse production. There is strong potential to link vertical training with automation, labor saving, and economic optimization. Lowering systems that align vines and fruits in predictable positions are promising for robotic leaf removal and harvesting, reducing labor bottlenecks in long-term crops. Comparative studies of high-wire versus modified-umbrella systems suggest that plant density, sequential planting, and choice of trellis should be tailored to farmer goals for yield level versus harvest uniformity, supported by more comprehensive cost-benefit analyses and decision tools. In the future, integrating training system design with cultivar selection, grafting strategies, and protected-structure optimization will broaden the application prospects of vertical cucumber systems and support profitable, high-quality production under diverse greenhouse conditions.

Acknowledgments

I extend our sincere gratitude to the anonymous reviewers for their valuable and insightful comments, which have greatly strengthened this paper.

Conflict of Interest Disclosure

The author affirms 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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