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Training Practices and Continuous Fruiting Management in Protected Cucumber Cultivation

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Abstract This study analyzes the biological basis of training and continuous fruiting in protected cucumber cultivation and discusses major training operations, canopy responses, fruit-load regulation, harvest coordination, and the interaction of training with water, nutrients, temperature, light, and planting density. A stage-based management framework is proposed in which canopy structure, functional leaf area, source-sink balance, fruit load, and harvest renewal are treated as connected components rather than separate practices. Recent developments in imaging, three-dimensional phenotyping, sensors, and artificial intelligence are also considered. Future protected cucumber production is expected to move from fixed training schedules toward dynamic plant management based on measurable crop status. Such an approach may improve yield stability and resource-use efficiency while reducing premature plant senescence during long production cycles. This study is expected to provide a practical reference for optimizing training practices and improving the stability of continuous fruit production in protected cucumber cultivation.
Keywords Protected cultivation; Cucumber; Training practices; Continuous fruiting; Canopy management; Fruit load

1 Introduction

Cucumber (*Cucumis sativus* L.) is widely grown under protected conditions because of its rapid growth, strong response to favorable environmental conditions, and ability to produce marketable fruits over a relatively long period. Greenhouses, plastic houses, and soilless cultivation systems allow better control of temperature, irrigation, mineral nutrition, humidity, and light than open-field production. These conditions support intensive cultivation and repeated harvesting, but they also place greater demands on crop management. A greenhouse cucumber plant continues to form new nodes throughout much of its production cycle. Fruits may already have been harvested from lower nodes while new leaves, flowers, tendrils, and young fruits continue to develop near the growing point. Yield is therefore accumulated through many successive harvests rather than obtained at one final harvest. Management at one stage can influence plant performance several weeks later. Excessive leaf removal, heavy fruit retention, or unsuitable water and nutrient supply may disturb the balance between current fruit development and subsequent vegetative growth. For this reason, greenhouse cucumber production increasingly considers photosynthesis, dry matter formation, fruit quality, water use, and nutrient use together with yield (Gajc-Wolska et al., 2021; Qu et al., 2022).

Protected cultivation also exposes cucumber plants to marked seasonal differences. Natural radiation may be insufficient during winter, whereas high temperature and excessive solar radiation can restrict growth during summer. Supplemental lighting, shading, ventilation, heating, and CO_2 regulation are commonly used to modify the crop environment. Studies using HPS and LED lighting have shown that both the amount and distribution of light can influence cucumber photosynthesis, nutrient demand, leaf function, senescence, and yield (Kowalczyk et al., 2020; Gajc-Wolska et al., 2021). Plant architecture must therefore be considered together with greenhouse conditions. A dense canopy may intercept considerable radiation but leave lower leaves strongly shaded, whereas an excessively open canopy may fail to use the available light efficiently.

Training provides a direct way to regulate this architecture. Vine guidance, pruning, pinching, lowering, lateral shoot management, and leaf removal allow a naturally climbing and branching cucumber plant to occupy a

controlled vertical space. Their purpose is not simply to produce an orderly canopy. These operations determine where leaves and fruits are located, influence light penetration and air movement, and affect the accessibility of plants for management and harvesting. Vertical systems commonly retain a main stem while lateral shoots are removed or restricted. When the stem reaches the upper support wire, it may be lowered, leaned, pinched, or redirected according to the production system. Samba et al. (2023) found that different training methods affected cucumber growth and productivity in hydroponic cultivation. Maeda et al. (2024) further showed that changing the spatial arrangement of source and sink organs influenced leaf area, dry matter production, and fruit yield. Training therefore has physiological consequences as well as practical value.

Leaf pruning is an important part of this process. Lower leaves gradually age and receive less light as the canopy develops. Removing old, damaged, or poorly functioning leaves can improve canopy openness and facilitate crop operations, but excessive defoliation reduces the photosynthetic surface available to support fruit development. The important issue is not simply whether leaves should be removed, but which leaves should be removed and when. This decision becomes particularly important during continuous fruiting because vegetative and reproductive organs compete for the same resources. Expanding leaves, growing stems and roots, flowers, and developing fruits all require carbohydrates and mineral nutrients. Fruits become strong sinks during rapid enlargement. Excessive fruit load may increase short-term reproductive demand but weaken new vegetative growth and reduce fruit uniformity. Too few fruits can have the opposite effect, directing more resources toward stems and leaves and producing an overly dense canopy.

Fruit demand also changes continuously because fruits at different nodes develop asynchronously. Harvesting removes mature sinks, while newly set fruits gradually become major sinks. Water and nutrient requirements consequently vary with canopy size, radiation, temperature, and reproductive load. Fertigation research indicates that fixed input schedules may not adequately match cucumber demand when environmental or root-zone conditions change (Kim et al., 2022; Qu et al., 2022). Sensor-based irrigation offers another approach, as environmental and crop measurements can support more responsive water management (Behzadipour et al., 2024). These relationships become particularly important in long production cycles. Heavy fruiting, root-zone stress, low winter radiation, excessive temperature, nutrient imbalance, and severe pruning may gradually reduce plant vigor and accelerate senescence. Maintaining an active growing point, healthy roots, and sufficient functional leaf area is therefore necessary not only for the current harvest but also for later fruit production.

This review examines protected cucumber cultivation through the interconnected processes of plant training, canopy formation, resource acquisition, dry matter allocation, fruit-load regulation, and continuous harvesting. Particular attention is given to light interception, photosynthetic function, source-sink relationships, and plant vigor. By linking these processes across early, peak, and late fruiting stages, the study aims to provide a practical basis for coordinating training practices with fruit-load and environmental management and for maintaining stable production throughout extended protected cucumber cultivation.

2 Biological Basis of Training and Fruiting in Protected Cucumber

2.1 Growth and branching characteristics

Cucumber has an indeterminate growth habit in many greenhouse cultivars. The main stem extends by repeated node formation, while leaves, tendrils, flowers, fruits, and potential lateral shoots arise in association with these nodes. In protected production, this basic architecture provides both an opportunity and a problem. Vertical growth allows efficient use of greenhouse volume, but unrestricted branching rapidly creates a dense and difficult canopy.

The main stem functions as the principal structural axis in many commercial systems. Each newly formed leaf increases potential photosynthetic surface, and the position of leaves along the stem creates a vertical light gradient. Upper leaves usually receive more direct radiation, while older lower leaves become increasingly shaded as the canopy expands. Lateral shoots add new leaves and potential fruiting sites. Their value depends on training system, cultivar, season, and available space. If every lateral is retained, competition for light and assimilates rises quickly. If all are removed without considering crop vigor, useful photosynthetic area or fruiting sites may also be lost.

Tendrils help cucumber plants climb naturally, but supported greenhouse plants do not depend on them in the same way as plants growing without strings. They may become entangled with leaves, fruit pedicels, neighboring plants, or support lines. Consequently, tendril management is usually treated as part of routine canopy work rather than as a yield-forming operation in its own right.

Recent three-dimensional studies show how complex cucumber architecture becomes under greenhouse conditions. Wang et al. (2025) used terrestrial laser scanning to reconstruct cucumber populations and quantify canopy heterogeneity and light interception. The study emphasizes an important point for training research: plants that appear similar when viewed from the aisle can differ considerably in leaf angle, overlap, height, and local light environment.

2.2 Relationship between vegetative and reproductive growth

Vegetative and reproductive growth depend on the same plant resource system. Leaves support carbon assimilation, stems provide transport and structural extension, roots acquire water and mineral nutrients, and fruits become strong sinks for assimilated carbon. A productive cucumber therefore needs vigorous vegetative organs, but excessive vegetative growth does not necessarily mean high fruit yield. The useful condition is a dynamic balance in which enough new leaf area is produced to replace aging tissue while fruit demand remains compatible with source capacity.

Environmental conditions can shift this balance. Low light limits carbohydrate supply and may make a fruit load that is acceptable in summer too heavy in winter. High temperature can accelerate developmental processes and respiration, changing the relation between leaf production and fruit growth. Supplemental light may strengthen source capacity and support a larger reproductive demand. Experiments with greenhouse cucumber under LED and HPS systems have demonstrated differences in gas exchange, chlorophyll status, leaf aging, nutrient uptake, and yield (Kowalczyk et al., 2020; Treder et al., 2021; Gajc-Wolska et al., 2021).

Training interacts with these effects because it changes the amount and location of functional leaf area. Removing lateral shoots reduces competing growing points, but it also removes potential leaves. Pinching stops extension of a selected shoot and redistributes subsequent growth. Removing old leaves may reduce respiration and shading in the lower canopy, yet removing active leaves too early reduces current source strength. There is therefore no universally optimal pruning intensity independent of crop condition.

2.3 Source-sink relationships during fruit development

The source-sink concept provides a useful framework for understanding continuous fruiting. Mature illuminated leaves act as major carbohydrate sources, while young leaves, shoot tips, roots, flowers, and fruits are sinks. Sink strength varies with organ size, developmental stage, metabolic activity, and environmental conditions. In cucumber, rapidly enlarging fruits can dominate assimilate distribution, which explains why fruit number has a strong effect on vegetative growth and later fruit development.

A fruit-load decision is therefore also a source-sink decision. Keeping an additional fruit does not merely add one potential marketable unit. It increases current demand on the plant and may influence the growth of other fruits, new leaves, the root system, and the shoot apex. Conversely, removing a weak or poorly positioned fruit can release resources for stronger fruits and new growth. This is why uniform fruiting is often more useful than short periods of extreme fruit retention followed by weak production.

Maeda et al. (2024) explored source-sink organization directly through a training system in which leaves and fruits were separated onto different axes. Their results showed that changes in leaf area index and organ arrangement altered dry matter production and yield components. The experiment does not imply that one arrangement should be adopted universally, but it clearly demonstrates that canopy design, source area, and fruiting sites are physiologically connected.

Root function also belongs to the source-sink system in a broader sense. Roots supply water and mineral nutrients, while receiving carbohydrates from the shoot. Heavy reproductive demand combined with weak root conditions

can therefore produce a feedback problem: fruit growth draws carbohydrates, root growth becomes restricted, and the weakened root system supplies less water and nutrients to new leaves and fruits. Long-cycle cultivation should avoid management patterns that repeatedly push the plant into this condition.

2.4 Effects of protected environments on plant architecture

Greenhouse architecture modifies solar radiation, temperature, air movement, humidity, and CO_2 concentration before these factors reach the crop. The canopy then modifies them again. Dense leaves reduce light at lower levels and restrict air circulation. Plant training is therefore one of the few management tools that changes both plant form and the local environment around individual organs.

Light is especially important. Ding et al. (2022) found that changing plant density altered cucumber performance and fruit quality under greenhouse conditions, showing that canopy occupation per unit area is as important as the form of an individual plant. Lower density gives each plant greater access to space and light, while high density may increase early interception but also intensify competition and shading. A productive density is therefore related to training system, season, cultivar vigor, and expected crop duration rather than being a fixed biological constant.

Light quality and distribution can also be manipulated. LED interlighting places radiation deeper in the canopy instead of supplying all supplemental light from above. Studies on cucumber have reported changes in photosynthetic activity and yield under different top-lighting and interlighting systems (Freitas et al., 2021; Gajc-Wolska et al., 2021). Continuous-light experiments also indicate that some mini-cucumber production systems can tolerate long photoperiods under controlled LED conditions, although such responses remain cultivar- and environment-dependent (Lanoue et al., 2021).

Temperature affects growth rate, respiration, transpiration, flower development, and fruit expansion. Qu et al. (2022) demonstrated significant interactions among air temperature, irrigation, and fertilization frequency in greenhouse cucumber. More recent work examining elevated temperature, CO_2, and irrigation further supports the need to manage water in relation to the thermal and atmospheric environment rather than by a fixed calendar (Du et al., 2026).

3 Training Practices in Protected Cucumber Cultivation

3.1 Vertical training and vine guidance

Vertical training uses greenhouse height to separate foliage and fruiting positions and to keep paths open for crop work. Plants are commonly attached to strings running from the crop row to overhead support wires. As the main stem grows, it is guided around or clipped to the support. In high-wire systems the stem is maintained as a continuing axis and later lowered and leaned when it approaches the upper structural limit (Figure 1).

The advantage of this arrangement is continuity. New leaves and fruits remain near an accessible upper production zone while harvested stem sections are gradually moved downward. The system also makes fruit location more predictable and can simplify visual inspection and harvesting. Yet high-wire training demands frequent labor. Rapid cucumber growth means that missed guidance operations can lead to bent stems, entanglement, shading, or irregular fruit position.

Alternative systems may pinch the main stem at a selected height and use lateral shoots for later production. Samba et al. (2023) compared training approaches in a greenhouse nutrient-film system and showed that plant architecture can influence yield performance. Maeda et al. (2024) tested an even more specialized arrangement in which the vertical axis served mainly as a leaf-bearing source and a lateral axis carried fruit. These studies show that the choice of training method changes the distribution of both photosynthetic and reproductive organs.

In practical production, the appropriate system depends on crop duration, labor supply, greenhouse height, cultivar, hydroponic layout, and the desired degree of mechanization. A training method that produces a high biological yield may still be unsuitable if it makes fruit difficult to find or greatly increases labor. Future systems are therefore likely to be evaluated on yield, crop physiology, worker efficiency, and compatibility with automation together.

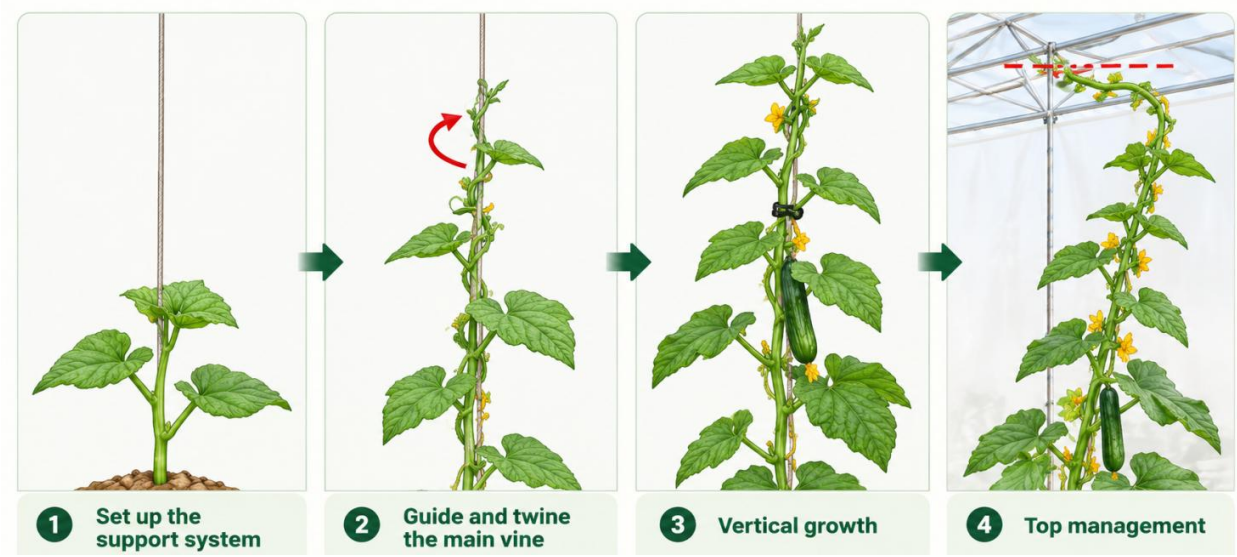


Figure 1 Schematic illustration of vertical training and vine guidance in protected cucumber cultivation
Image caption: (1) Support system installation: Support wires are installed above the planting rows, and plants are connected to them using hanging strings; (2) Vine guidance and twining: As the main vine elongates, it is guided upward along the string and secured in place; (3) Vertical growth: The main vine is maintained as the primary growth axis, allowing leaves and fruits to be distributed along the plant; (4) Top management: When the main vine approaches the greenhouse roof, lowering or leaning techniques are applied to adjust its growth direction and maintain continuous fruiting

3.2 Main stem and lateral shoot management

Main-stem training is widely used because it creates a relatively simple canopy. Lateral shoots are removed when young so that they do not form large competing branches. Early removal is less disruptive than removing a long, well-developed shoot later because less biomass and assimilated carbon are discarded.

The biological effect, however, depends on plant vigor. A vigorous plant under good light may tolerate strict single-stem training and continue forming sufficient leaf area. Under some systems or late-season conditions, selected lateral shoots can contribute useful leaves or new fruiting positions. The question is therefore not whether laterals are good or bad; it is whether their source contribution and reproductive value exceed the shading and competition they create.

Lateral management should also consider the age profile of the canopy. When the lower main stem has lost many functional leaves, a carefully managed lateral may help renew photosynthetic area. In contrast, uncontrolled lateral development in an already dense upper canopy reduces light penetration and makes disease inspection and harvest more difficult.

Timing matters. Small lateral shoots can be removed with little disturbance. Delayed pruning creates larger wounds and wastes dry matter already invested by the plant. A regular inspection schedule is therefore more important than occasional severe pruning. Training should be viewed as a series of small corrections that keep architecture near the desired state.

3.3 Pinching and growing-point management

Pinching removes a growing point and stops extension of a selected stem or lateral shoot. In cucumber production it may be used when a shoot reaches the training wire, when a lateral has produced the intended number of leaves or fruits, or when canopy height must be controlled. The operation changes apical dominance and can stimulate growth from other buds.

The effect of pinching depends on where and when it is performed. Early pinching can restrict the future source area if the remaining canopy is too small. Late pinching may provide little benefit if the shoot has already entered

an overcrowded zone. Maeda et al. (2024) pinched the main stem at the upper wire as part of a training system designed to separate leaf and fruit functions. Their work demonstrates how pinching can be used as a structural tool rather than merely a way to shorten a plant.

Growing-point management is also relevant to crop renewal. A healthy apex continuously creates young leaves that will become the next source organs. Damage, nutrient stress, high temperature, or excessively heavy fruit load can weaken apex development. A plant may still carry fruits in the short term while its future canopy is already declining. Growers should therefore evaluate growing-point strength together with harvest numbers.

Uniformity is useful. If plants within the same row differ greatly in height and growing-point strength, a single schedule for lowering, pruning, and fruit retention becomes less effective. One goal of early training is thus to create enough structural uniformity that later crop management can be applied consistently without forcing weak plants to carry the same load as strong ones.

3.4 Leaf pruning and canopy renewal

Leaves change function as they age. Young expanding leaves are initially net importers of assimilates; mature leaves become important sources; old and deeply shaded leaves eventually contribute less to canopy carbon gain. Leaf pruning attempts to remove tissue whose cost or interference exceeds its contribution while retaining enough active area for fruit growth.

Lower leaf removal has several practical benefits. It can open the crop base, improve visibility, facilitate harvesting and sanitation, and reduce contact between foliage and wet surfaces. It may also improve airflow within a dense canopy. Yet severe defoliation can reduce photosynthesis and expose fruits to an altered radiation environment. The desirable canopy is therefore neither maximally dense nor maximally open.

Leaf position matters as much as leaf number. Upper leaves intercept strong light, while middle-canopy leaves can contribute substantially when light penetrates effectively. LED interlighting studies are relevant because they show that improving radiation deeper in the canopy can preserve photosynthetic activity of leaves that would otherwise operate under low light (Freitas et al., 2021; Gajc-Wolska et al., 2021). Under such systems, removing a lower leaf according to age alone may be less appropriate than judging its health and illumination.

Canopy renewal should be gradual. In a long-cycle crop, old leaves are continuously removed while new leaves are continuously produced near the apex. The objective is to maintain a relatively stable population of effective leaves despite the physical movement of the plant through a high-wire system. The actual number required varies with cultivar, light, density, and fruit load; universal fixed leaf counts should therefore be treated cautiously.

3.5 Tendril and senescent organ removal

Tendrils, aborted flowers, damaged fruits, yellow leaves, and other senescent organs are often removed during routine crop work. Their direct effect on yield is generally smaller than that of leaf or fruit management, but their removal can improve canopy order and reduce interference with other operations. Tendrils can coil around neighboring leaves, fruit stems, support strings, or developing shoots. Where labor permits, removing them while young helps maintain a clean vertical canopy. The operation should not become so aggressive that healthy stems or leaves are damaged. It is best combined with other routine tasks such as vine guidance and lateral removal.

Senescent tissues deserve greater attention because they can indicate broader plant problems. Natural aging of the lowest leaves is expected in a long-cycle crop, especially after those leaves become heavily shaded. Rapid yellowing across a larger canopy zone, however, may reflect root stress, nutrient imbalance, excessive fruit demand, or unfavorable temperature. Removing the visible symptom without correcting the underlying cause does not restore plant vigor.

Sanitation is another reason for timely removal. Dead and damaged tissue can retain moisture and complicate disease management. Removed material should not be allowed to accumulate within the crop. Training work is therefore connected not only to architecture and source-sink balance but also to general greenhouse hygiene.

4 Effects of Training Practices on Canopy and Plant Performance

4.1 Canopy structure and light distribution

A greenhouse canopy is a three-dimensional radiation-capturing system. Total leaf area determines the potential surface available for light interception, but arrangement determines how evenly that light is distributed. A dense upper canopy may intercept a high proportion of incoming radiation while leaving lower leaves strongly shaded. More open architecture can distribute radiation deeper, although too little leaf area allows valuable light to pass through without being used.

Training modifies both components. Removing laterals decreases overlap. Guiding stems vertically changes leaf position. Lowering a crop moves older stem sections downward while maintaining a new active zone near the top. Leaf removal creates local gaps that may improve illumination of neighboring leaves. The outcome depends on how these operations alter whole-canopy geometry rather than on the number of organs removed.

Three-dimensional phenotyping now makes these effects measurable. Wang et al. (2025) reconstructed greenhouse cucumber canopies with terrestrial laser scanning and quantified variation in light interception among plant representations. Boogaard et al. (2021) showed that combining 3D point clouds with spectral data can improve segmentation of cucumber plant parts. These methods provide a path toward describing canopy architecture more objectively than visual scoring alone.

Such measurements also explain why training recommendations may differ among seasons. During low-light periods, capturing available radiation is a priority and excessive leaf removal may be costly. During high-radiation periods, preventing extreme self-shading remains important, but shading screens or other environmental controls may also be needed. Yu et al. (2023) found clear growth responses to shading and supplemental lighting in summer cucumber cultivation, illustrating the interaction between canopy management and the external light regime.

4.2 Photosynthetic capacity and leaf function

Leaf area alone does not determine source capacity. Leaf age, nitrogen status, light exposure, temperature, stomatal behavior, and stress history influence photosynthetic rate. A smaller well-illuminated canopy may sometimes use light more effectively than a larger, strongly self-shaded one. On the other hand, reducing leaf area too far limits total carbon assimilation even when the remaining leaves have high photosynthetic rates.

Research on supplemental lighting provides useful evidence. Gajc-Wolska et al. (2021) reported that LED lighting affected gas exchange and commercial yield in autumn-winter cucumber cultivation. Treder et al. (2021) also observed growth and yield responses to different supplemental-light spectra. Wang et al. (2021), working with cucumber seedlings, found that red and blue LED supplementation influenced photosynthesis, dry matter accumulation, and associated physiological processes. These results cannot be transferred directly into a universal pruning rule, but they reinforce the dependence of leaf value on the light environment.

Leaf aging should therefore be evaluated functionally. A lower leaf that is green, healthy, and illuminated may still contribute to fruit filling. A yellow or damaged leaf in deep shade has a much smaller future role. Training that removes tissue according to position alone ignores this difference.

The source requirement also changes with fruit load. When many fruits are expanding, retaining a sufficient functional canopy becomes especially important. After a large harvest, temporary sink demand falls, and resources may shift toward new leaves, roots, and subsequent fruit cohorts. Good management takes advantage of this natural fluctuation instead of maintaining the same pruning intensity every week.

4.3 Ventilation, humidity and canopy microclimate

Leaves create resistance to airflow and release water vapor through transpiration. Dense cucumber canopies can therefore develop a microclimate that differs from greenhouse air measured above the crop. Relative humidity near inner leaves may remain high, while air movement becomes weak. These conditions affect transpiration, nutrient transport, leaf wetness risk, and disease development.

Training can improve canopy porosity. Removing excessive lateral shoots and old lower leaves creates pathways for air movement. More uniform spacing reduces clusters of overlapping foliage. This does not mean that ventilation problems can be solved through pruning alone. Greenhouse ventilation rate, external humidity, heating strategy, and irrigation timing remain major drivers. Still, architecture determines how effectively environmental control reaches individual leaves.

An overly open canopy can produce the opposite problem under strong solar radiation. Leaves and fruits may experience abrupt changes in radiation and temperature after severe pruning. Water demand can also change. This is one reason to avoid removing a large amount of foliage at once.

Microclimate should therefore be considered at the canopy scale rather than only from one greenhouse sensor. The future use of distributed temperature and humidity sensors could help growers identify zones where canopy density produces persistent local stress. Training decisions could then be targeted rather than applied uniformly across all plants.

4.4 Dry matter allocation and plant vigor

Dry matter production results from carbon assimilation, while allocation determines how that dry matter is divided among leaves, stems, roots, and fruits. Fruit yield depends not only on how much biomass a plant produces but also on what proportion reaches marketable fruits without weakening the structures needed for continued production.

Training changes allocation directly by removing organs and indirectly by changing source-sink relationships. Removing a young lateral prevents further investment in that branch. Removing an active leaf reduces source tissue. Fruit thinning reduces reproductive sink strength. Pinching removes a growing sink and can redirect assimilates to remaining organs.

Maeda et al. (2024) found that a training treatment with greater leaf area could produce greater total dry matter even though fresh fruit yield depended on fruit number and distribution. This distinction is important. High vegetative biomass is not identical to high commercial yield, while high short-term fruit allocation is not automatically compatible with long crop life.

Plant vigor should consequently be judged from several signs: stem growth, internode pattern, leaf size and color, growing-point activity, root-zone condition, rate of fruit filling, and the appearance of new flowers. A plant that continues harvesting but produces progressively smaller leaves is already losing future source capacity. Continuous fruiting management should react before yield decline becomes obvious.

5 Continuous Fruiting Management

5.1 Flowering and fruit-setting management

Modern protected cucumber production often uses cultivars with strong female flowering and, in many cases, parthenocarpic fruit development. This supports reliable protected production because commercial fruit set does not depend entirely on pollination. Even so, the presence of a flower does not mean that every potential fruit should be retained.

Flower and young-fruit development should be considered in relation to node position, plant vigor, canopy size, and season. Early in plant establishment, fruit retention at very low nodes may compete strongly with root and leaf development before an adequate source system has formed. Removing some early reproductive organs can allow the plant to establish stronger vegetative capacity before entering sustained harvest.

Later, flower retention can increase as the canopy and root system become more capable of supporting fruit growth. Under low winter light or after a period of stress, temporary reduction in reproductive demand may be necessary. Under strong light and favorable root conditions, the plant may support a greater fruit load.

Computer vision is making flower monitoring more feasible. Xu et al. (2023) developed a YOLO-based system for cucumber flower detection under greenhouse conditions. Such technology has significance beyond automated

counting. Repeated flower observations could eventually provide a non-destructive indicator of reproductive activity and help connect flowering patterns with later fruit load and yield.

5.2 Fruit load regulation

Fruit load is one of the strongest management levers in continuous cucumber production. It can be described as the number and developmental distribution of fruits supported by the plant at a given time. A balanced load allows fruits to reach market requirements while new leaves and roots continue to develop. An excessive load slows individual fruit growth and can weaken the plant; an insufficient load may result in unnecessary vegetative growth and lost yield opportunity.

The appropriate load is dynamic. Two plants with the same number of fruits may experience very different sink demand if one carries mostly small newly set fruits and the other carries several fruits in rapid expansion. The useful management unit is therefore not fruit number alone but fruit number together with size, developmental stage, and plant source capacity.

Fruit load also needs to reflect radiation. In low light, assimilate supply decreases while fruit demand may remain high. Carrying the same load that was appropriate under brighter conditions can cause imbalance. This principle helps explain why management recipes based only on fixed numbers often perform inconsistently across seasons.

Continuous observation is more useful than occasional correction. Fruit retention can be adjusted gradually by removing weak or excessive young fruits. This prevents severe source-sink shocks. Where strong plant-to-plant variation exists, weaker plants should not be forced to follow the same load as the strongest plants simply for visual uniformity.

5.3 Fruit thinning and abnormal fruit removal

Fruit thinning is the selective removal of young fruits to improve the balance and quality of the remaining crop. It is particularly useful when several fruits develop in close sequence on a plant that lacks sufficient source capacity to fill all of them uniformly.

The decision should consider fruit shape, position, growth rate, plant vigor, and nearby fruit load. Poorly developing or visibly abnormal fruits are unlikely to justify continued investment of assimilates. Removing them early wastes less plant resource than allowing them to remain until they are large but unmarketable.

Thinning should not become automatic removal according to a rigid node pattern without observing the plant. Strong plants under favorable radiation may support a heavier load. Plants recovering from root stress or low-light periods require a more conservative approach.

Fruit-quality responses to plant environment also support careful load management. Ding et al. (2022) showed that plant density affected several quality traits even when area-based annual yield was maintained. This indicates that fruit quality is shaped by the amount of resource available to individual plants, not simply by total crop yield. Load regulation can be viewed as another way of managing the amount of source resource available per fruit.

5.4 Coordination of harvesting and new fruit development

Harvest is part of crop regulation rather than merely the final removal of a product. A marketable cucumber fruit remains a strong sink until it is picked. Delayed harvest therefore keeps assimilates tied to an organ that has already reached commercial value and may slow development of younger fruits.

Frequent harvesting is especially important in vigorous protected crops where fruit growth can be rapid. Removing marketable fruit releases sink pressure and makes resources available to younger fruits, roots, leaves, and the shoot apex. A stable harvest schedule also helps maintain a more even size distribution of fruits on the plant.

Harvest frequency interacts with market specifications. Fruit size at harvest differs among cucumber types and markets. Management must therefore use the commercial target rather than a universal fruit length or mass. The

principle remains the same: once a fruit has reached the required market stage, unnecessary retention can interfere with subsequent production.

Automation research has focused heavily on this stage. Mao et al. (2020) developed deep-learning methods for cucumber recognition in complex plant backgrounds, and Wang et al. (2022) improved greenhouse cucumber fruit detection using color-space information. Bai et al. (2022) also addressed cucumber segmentation and recognition under complex environments. These systems were developed largely for robotic harvesting, but their sensing capability could also support fruit-load assessment. If fruit number, location, and approximate developmental stage can be recorded continuously, harvesting and crop regulation could eventually share the same data stream.

5.5 Prevention of premature plant senescence

Premature senescence is often the cumulative result of several small imbalances rather than one single cause. Heavy fruit load reduces resources available for renewal. Root-zone salinity or poor aeration restricts water and nutrient uptake. Low light limits carbohydrate production. Excessive leaf removal reduces source area. Repeated high temperature increases respiratory cost. The plant may continue producing fruit for a period, but new leaf size, root activity, and fruit uniformity gradually decline.

Maintaining functional leaf area is one defense. Old leaves should be removed as they lose value, while excessive removal of active leaves should be avoided. Maintaining root-zone stability is equally important. Soilless and fertigation studies show that cucumber responds to nutrient-solution composition, irrigation scheduling, and substrate conditions (Randhe et al., 2022; Roosta et al., 2025).

Mineral nutrition also changes through the crop cycle. Kowalczyk et al. (2020) showed that supplementary lighting influenced nutrient demand in winter cucumber production. More recent potassium-fertigation research has reported effects on yield, fruit firmness, stomatal behavior, and resource-use efficiency (Sonali et al., 2026). These findings support the view that nutrient management should respond to crop demand rather than remain fixed throughout a long fruiting period.

Recovery periods may occasionally be useful. A temporarily weakened crop can be managed with lower fruit load, conservative pruning, and careful water and nutrient supply until new vegetative growth improves. The aim is not to stop production but to prevent a short-term stress episode from becoming irreversible decline.

6 Coordination of Training, Nutrition and Environmental Management

6.1 Training practices and water-nutrient management

Training changes both water demand and nutrient demand because it changes leaf area, transpiration surface, growth rate, and fruit load. Removing leaves reduces transpiring area immediately. A period of rapid canopy expansion increases demand. Heavy fruit growth raises the requirement for mineral nutrients associated with metabolism, osmotic regulation, and fruit development.

Irrigation should therefore respond to radiation, crop size, root-zone water status, substrate characteristics, and drainage rather than simply follow a fixed time interval. Randhe et al. (2022) examined fertigation strategies in soilless cucumber and showed that nutrient-solution replenishment affected plant growth and yield. Kim et al. (2022) demonstrated that nitrogen response differed according to greenhouse soil nutrient status, warning against applying the same fertilizer rate to soils that already differ strongly in nutrient supply.

Qu et al. (2022) extended this principle by evaluating irrigation and fertilization frequency under different air temperatures. Their results showed interactions among environmental and management factors, supporting a more integrated view of greenhouse input management. Behzadipour et al. (2024) used environmental and crop-related measurements in an intelligent irrigation system and reported improved water-use performance without a corresponding loss of crop quality. These studies indicate a shift from input schedules based mainly on calendar time toward decisions based on crop demand.

Training records could become part of this approach. A major leaf-pruning event, fruit-thinning operation, or change in plant density alters the crop's effective demand and should be recognized by irrigation and fertigation management. In advanced production systems, such events could be entered into a crop model or automatically detected.

6.2 Temperature and light management during fruiting

Temperature and light jointly determine much of the crop's carbon economy. Light supplies energy for photosynthesis, while temperature influences enzyme activity, development, respiration, transpiration, and fruit growth. Managing one without considering the other can create imbalance.

During winter or extended cloudy conditions, low radiation becomes a major limitation. Supplemental lighting can increase photosynthetic opportunity and support a stronger fruit load. Treder et al. (2021) compared HPS and LED spectral treatments in winter cucumber, while Gajc-Wolska et al. (2021) documented photosynthetic and yield responses under HPS and LED systems. Freitas et al. (2021) evaluated LED interlighting in mini-cucumber, demonstrating the value of bringing light deeper into the canopy.

Lighting also interacts with nutrient demand and leaf longevity. Kowalczyk et al. (2020) reported differences in mineral nutrient requirements and yield under supplementary-lighting treatments. Łaźny et al. (2024) later examined cucumber grown with different substrate and lighting combinations and found associated changes in physiological performance and fruit quality.

Summer presents a different problem. Excess radiation and heat may increase stress even while average daily light remains high. Shading can reduce extreme load, but too much shading lowers photosynthesis. Yu et al. (2023) studied shading combined with supplemental lighting during summer greenhouse cucumber production, illustrating the need to manage the daily and seasonal distribution of light rather than assuming that more light is always better.

6.3 Plant density and canopy management

Plant density determines how much floor area and greenhouse volume are available to each plant. Training determines how efficiently that space is occupied. These two decisions should be made together.

At high density, the canopy closes quickly and captures radiation early, but competition among plants also develops earlier. Leaf overlap increases, lower-canopy light declines, and ventilation becomes more difficult. More severe pruning may then be required to maintain canopy openness. At low density, individual plants can develop a larger source area and receive more light, but excessive spacing may reduce total light interception per unit greenhouse area.

Ding et al. (2022) found that a relatively low cucumber density could improve fruit-quality characteristics without reducing total annual yield under their greenhouse conditions. This result should not be converted into a universal density recommendation because greenhouse structure, cultivar, season, and training system differ. Its wider lesson is more useful: yield per plant and yield per unit area respond differently to density.

Training can partly compensate for density differences. A lower density may allow more leaf area or selected lateral growth per plant. A higher density generally requires stricter control of laterals and overlapping leaves. Supplemental interlighting may also change the density response by improving illumination of inner leaves.

A rational design therefore begins with expected radiation, crop duration, cultivar vigor, and training method, then selects density accordingly. Adjusting density without changing canopy management, or changing training while leaving density assumptions untouched, can create avoidable source-sink and microclimate problems.

6.4 Dynamic management across growth stages

Protected cucumber changes rapidly, so management should change with it. During early establishment, the priority is to build roots, stem structure, and functional leaf area. Severe fruit demand during this stage can restrict the plant before adequate source capacity develops.

During early fruiting, reproductive demand begins to increase. Irrigation and mineral supply rise with canopy size, while fruit retention must still respect plant strength. Training should maintain a clear main structure without excessive loss of healthy leaf area.

Peak fruiting places the greatest pressure on source-sink coordination. Many fruits may be present at different stages, water and nutrient uptake are high, and harvesting is frequent. Small management errors become more costly because fruit demand is already high. Canopy renewal, fruit thinning, irrigation, fertigation, and harvesting therefore need close coordination.

Late production requires a different strategy. Older roots and stems may have accumulated stress, natural radiation may change with season, and lower leaves have already been removed. The goal shifts from building maximum canopy to preserving enough active leaf and root function to support profitable later harvests. Lowering, renewal, reduced fruit load, or more conservative pruning may be used depending on the system.

7 Integrated Strategy for Continuous Cucumber Production

7.1 Early fruiting stage

The early fruiting stage is a transition from plant construction to commercial production. The canopy is still expanding, roots are increasing their effective volume, and the first fruits begin to compete with these vegetative sinks. Management should avoid allowing early fruit demand to restrict the structural capacity needed for the following months.

Training at this stage should establish a clear stem position, remove unnecessary competing laterals while they are small, and maintain healthy leaves. The growing point should remain vigorous. Early fruits that are poorly positioned, abnormal, or excessive relative to plant size can be removed.

Irrigation and nutrient supply should follow increasing transpiration and biomass rather than jump immediately to peak-fruiting levels. Root-zone stability is important because a strong root system developed at this stage supports later load.

Uniform plant structure is also desirable. Weak plants can be given a lighter fruit load rather than being forced to match stronger neighbors. This small early adjustment may prevent a persistent gap in vigor later.

7.2 Peak fruiting stage

Peak fruiting requires the most active balancing of source and sink. The plant should maintain enough healthy leaves to support the current crop while continuing to form new leaves near the apex. Fruit load, harvest timing, and canopy density must be evaluated repeatedly rather than according to a fixed weekly number.

Old lower leaves can be removed as they lose function, but active middle and upper leaves should be protected. New lateral shoots that would cause heavy shading should be removed early. Fruit thinning should focus on weak, excessive, or abnormal fruits before substantial assimilates have been invested in them.

Water and nutrient management should respond to high transpiration and reproductive demand. Rapid changes in radiation can alter daily water use substantially, especially in soilless culture. Environmental sensors and drainage measurements become particularly valuable at this stage.

Harvest should be frequent enough to remove fruits at the required commercial stage. Timely harvesting reduces unnecessary sink competition and helps maintain a regular sequence of developing fruit. It also gives workers repeated opportunities to inspect canopy condition and identify declining plants.

7.3 Late fruiting stage

The late fruiting stage is commonly limited by declining source capacity, root aging, accumulated stress, seasonal changes in radiation, or all of these factors together. The correct response is rarely to maintain the same fruit load and pruning intensity used at peak production.

Canopy renewal becomes more important. Healthy newer leaves should be retained, while old leaves that no longer contribute effectively can be removed. High-wire crops may continue to be lowered and leaned so that the active apex remains in a favorable position. Where system design allows, selected renewal growth can replace exhausted sections of canopy.

Fruit load may need to be reduced. This is particularly important if new leaves become smaller, internodes shorten abnormally, fruit filling slows, or root-zone performance declines. Protecting the remaining productive life of the plant may be more profitable than retaining every possible fruit.

Nutrient management should also avoid the assumption that an older crop always requires more fertilizer. Uptake capacity can decline, and salt accumulation may become problematic in long-cycle systems. Input should follow measured demand and root-zone conditions.

7.4 Integrated “canopy-source-sink-fruit load” management

An integrated management model can be summarized as canopy structure-functional leaves-resource supply-fruit load-harvest renewal. Each component affects the others.

Canopy structure controls how light reaches leaves and how air moves through the crop. Functional leaves determine much of the photosynthetic source capacity. Roots, water, mineral nutrients, CO_2, temperature, and light determine how effectively those leaves function. Fruit number and developmental stage determine major sink demand. Harvest removes mature sinks and creates capacity for the next fruit cohort.

Management should move through this cycle repeatedly. If the canopy becomes too dense, targeted shoot or leaf removal can improve light distribution. If source capacity becomes weak because of low light or stress, fruit load should be moderated. If fruit load falls too far under favorable conditions, vegetative growth may become excessive and reproductive retention can be increased. If harvest is delayed, mature fruits continue competing with new fruits and disturb the balance.

This framework avoids the common mistake of treating individual practices as independent prescriptions. “Remove a leaf”, “retain a fruit”, “increase irrigation”, or “lower the plant” are not complete decisions until the condition of the whole crop is considered.

Quantitative methods can strengthen the framework. Leaf area, light interception, flower number, fruit number, stem growth, root-zone moisture, electrical conductivity, and harvest rate are all measurable. The aim is not to replace experienced growers with a single formula, but to make plant status visible enough that management becomes more repeatable and less dependent on subjective impressions.

8 Conclusions

Training practices are a central part of protected cucumber production because they determine how the plant uses greenhouse space and how its photosynthetic and reproductive organs are arranged. Vertical guidance, lateral shoot management, pinching, leaf pruning, canopy renewal, and the removal of unnecessary organs should therefore not be regarded as separate routine operations. Together, they shape canopy structure, light interception, air movement, leaf function, dry matter production, and the physical accessibility of fruits.

Continuous fruiting makes this relationship more important. A protected cucumber plant is required to maintain vegetative renewal while supporting flowers and fruits at several developmental stages. The resource demand of these organs changes from day to day. Excessive fruit load can weaken roots, new leaves, and the growing point, whereas insufficient reproductive demand can encourage an overly vegetative canopy. Stable production depends on keeping this balance within a range that allows current fruits to develop without sacrificing the next production cycle.

The practical implication is that fruit management should be linked to canopy condition. Fruit retention should take account of functional leaf area, plant vigor, radiation, root condition, and the developmental stage of existing fruits. Abnormal or weak fruits are best removed early, while marketable fruits should be harvested promptly so

that they no longer compete unnecessarily with younger sinks. The useful objective is not the largest possible fruit number at a particular moment, but a continuous sequence of marketable fruits supported by a healthy plant.

Leaf management follows the same principle. Old, shaded, yellow, or damaged leaves eventually become appropriate candidates for removal, but green functional leaves remain an essential source for fruit development. Heavy defoliation can reduce crop carbon supply even when it makes the canopy appear cleaner. Gradual canopy renewal is more compatible with long production cycles than occasional severe pruning.

Training cannot be separated from the greenhouse environment. Light level determines potential photosynthesis and therefore affects how much fruit load a plant can support. Temperature influences development, respiration, water demand, and fruit growth. Plant density changes the light and space available to each plant. Irrigation and mineral nutrition support the changing demand of leaves, roots, and fruits. Management practices should consequently be coordinated rather than optimized one by one.

A useful integrated approach can be described as a canopy-source-sink-fruit-load system. Canopy architecture controls the distribution of radiation. Functional leaves provide photosynthetic source strength. Roots and greenhouse environmental management determine the resources available for growth. Fruits create reproductive sink demand. Harvest removes mature sinks and allows the next set of fruits to develop. Every pruning or fruit-management decision acts somewhere within this cycle and can affect later stages.

Future research should connect these technologies with clear biological decision rules. Detecting a fruit, leaf, or growing point is useful, but the next step is to determine what the detected condition means for crop management. A successful precision system will need to connect canopy structure with radiation, fruit load with source capacity, and environmental demand with water and nutrient supply. It will also need to operate across different cultivars, seasons, and greenhouse systems.

For commercial production, the most valuable system is unlikely to be the one with the greatest number of sensors or the most complex algorithm. It will be the one that supports timely decisions with enough accuracy to improve crop consistency, labor efficiency, resource use, and economic return. Training and continuous fruiting management provide a suitable framework for this development because they connect visible plant architecture directly with crop physiology and harvest performance.

Protected cucumber cultivation should therefore move away from viewing training as a fixed sequence of manual operations. It is better understood as continuous regulation of the plant's productive structure. When canopy architecture, functional leaf area, resource supply, fruit load, and harvest renewal are managed together, the crop has a better chance of maintaining vigorous growth and regular fruiting over an extended production period. This integrated perspective offers a practical basis for improving both present greenhouse management and future precision cultivation systems.

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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