

Research Insight

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Effects of Trellis Systems on Yield and Fruit Quality of Luffa

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Abstract Sponge gourd (*Luffa cylindrica*) is an important cucurbit vegetable widely cultivated in tropical and subtropical regions due to its high nutritional value and economic significance. Trellising cultivation is a key agronomic practice that influences plant architecture, canopy microclimate, resource utilization efficiency, and ultimately fruit yield and quality. Different trellising systems, including horizontal pergola, A-frame, fence, and vertical training systems, create distinct growing environments that affect photosynthesis, flowering, fruit set, and assimilate partitioning. This review summarizes the biological characteristics of sponge gourd and the theoretical basis of trellising cultivation, and examines the effects of various trellising systems on plant growth, yield formation, fruit quality, and production efficiency. Furthermore, representative case studies are analyzed to compare the performance of different trellis configurations under diverse cultivation conditions. The economic and ecological benefits of trellising cultivation, including labor efficiency, disease management, and sustainable production, are also discussed. Current research limitations and future directions, such as the development of innovative and intelligent trellising technologies, are highlighted. This review provides a comprehensive reference for optimizing sponge gourd cultivation practices and improving productivity and fruit quality in sustainable horticultural systems.

Keywords Sponge gourd; Trellising system; Yield formation; Fruit quality; Sustainable cultivation

1 Introduction

Sponge gourd (*Luffa cylindrica*) is an emerging, climate-smart cucurbit with growing importance for both food and industrial fiber. It is described as an “emerging high potential crop in Asia” but remains underutilized in many regions, with farmers often relying on traditional practices and limited technical guidance on morphology, floral biology, and yield optimization. Beyond its role as a vegetable, sponge gourd provides plant-based fiber and is highlighted as a niche “opportunity crop” with multiple utilities in food and industrial sectors, yet still undervalued due to limited research and product development (Mashilo et al., 2025). Reviews also emphasize increasing interest driven by health benefits, climate resilience, and market demand, and call for improved agronomic packages and high-yielding varieties to support commercialization at local and international levels.

In Sri Lanka and other producing areas, yields remain constrained by poor management; for example, farmers often allow vines to trail on fences or the ground, practices that are associated with reduced yield and fruit quality and lack of systematic trellis use. At the same time, multivariate and varietal studies show substantial genetic variability for yield, nutritional traits, and quality in sponge gourd, underscoring the crop’s potential if supported by suitable production technologies (Chithra et al., 2024). Within cucurbit production systems more broadly, trellising has become a key cultural practice to intensify production, improve canopy microclimate, and enhance yield and marketable quality. In cucumber, trellised plants show consistently taller vines, larger leaves, more leaves, and higher marketable yield than untrellised plants, along with reductions in non-marketable fruits. Classic studies comparing trellis versus ground culture in field cucumber reported up to 100% increases in marketable yield under trellising, with more uniform dark-green fruits, higher Fancy grades, and fewer culls. Trellising also facilitated better control of foliar and fruit diseases by improving aeration, reducing humidity, and allowing more effective fungicide coverage. In hydroponic Beit Alpha cucumber grown in low-profile greenhouses, comparisons of high-wire and modified-umbrella systems showed that trellis architecture can shift the balance between total fruit number and yield consistency, suggesting that trellis design must be matched to growers’ yield and labor objectives.

Beyond cucurbits, perennial climbing fruit crops such as passion fruit also rely heavily on support systems, where simple trellis arrangements have been associated with the highest productivity and superior fruit quality compared with more complex “T” and total trellis systems. For sponge gourd specifically, trellising and training systems are increasingly recognized as central components of improved production technology, yet their effects on yield and fruit quality are still being defined. In Sri Lankan sponge gourd, evaluation of three trellising methods showed that horizontal trellising was “ideal” under local conditions, achieving an average yield of 8.4 t ha⁻¹; trellis type did not significantly change fruit length and diameter, but did significantly alter fruit number per plant.

A recent study comparing four above-ground training systems—bower, single plant training, netting, and ground trailing—found that bower trellising produced the maximum yield, fruits per plant, fruit length, fruit width, and vine length, with substantial percentage yield increases of up to 71% over ground trailing, further supporting the value of structured support for sponge gourd vines. In subtropical Mexico, open-field sponge gourd cultivation with “trellis mesh” oriented to optimize light exposure and row spacing tailored to the long vines has been shown to support good yields and efficient management, and even allows the use of circular trellis designs to maximize space. Related work in ridge gourd, another *Luffa* species, demonstrates that different trellis geometries (e.g., pandal versus T-trellis) affect not only yield and benefit-cost ratio but also fruit quality traits, implying that trellis system choice can be a fine-tuning tool for both productivity and market value in *Luffa* crops.

2 Cultivation Characteristics of Sponge Gourd and Theoretical Basis of Trellising

Overall, sponge gourd has high but underexploited agronomic and economic potential, and trellising is a critical, yet still inadequately optimized, component of its cultivation. Evidence from sponge gourd and related cucurbits indicates that well-designed trellis systems can substantially increase yield, improve fruit quality, and facilitate disease and crop management. However, the specific effects of different trellis architectures on sponge gourd yield components and quality traits remain insufficiently characterized, justifying focused research on the effects of trellis systems on yield and fruit quality of *Luffa*.

2.1 Biological characteristics and growth requirements of sponge gourd

Sponge gourd (*Luffa cylindrica*) is a monoecious cucurbit bearing separate male and female flowers on the same plant, with flowering starting about 6-7 weeks after seeding and an initially high proportion of male flowers. The crop produces long climbing vines and cylindrical fruits which, when fully mature and dried, form fibrous sponges typically 17-20 cm in length with densely arranged fibers. As a short-day species, sponge gourd thrives under cool temperatures and shorter photoperiods, with kharif conditions providing particularly favorable environments for vigorous vegetative growth, flowering, and fruit set (Vidya et al., 2025). Growth and yield are also shaped by soil and nutrient conditions.

In subtropical Mexico, plants established by direct seeding on fertile Luvisols amended with an organo-mineral substrate reached vine lengths of nearly 39 m and produced 5-20 fruits per plant, whereas plants on less fertile Andosols showed shorter vines and lower fruit size and weight (Fernández-Lambert et al., 2025). Optimized fertilization regimes combining reduced mineral N and P with K and bio-fertilizers have produced vine lengths around 2.8 m, earlier flowering, and yields up to 30.8 t ha⁻¹ together with improved fruit quality traits such as higher soluble solids and ascorbic acid.

2.2 Vine growth patterns and spatial distribution characteristics

As a climbing cucurbit, sponge gourd exhibits vigorous, indeterminate vine growth with substantial variation in vine length and branching among genotypes and environments. In seasonal evaluations, individual inbred lines have produced vines exceeding 8 m in length with high numbers of branches and extended harvest durations, illustrating the inherently expansive canopy potential of this crop (Vidya et al., 2025). Direct-sown plants in open-field systems have attained mean plant lengths above 30 m, reflecting an ability to explore large horizontal or vertical spaces when physical support and resources are not limiting. Early establishment factors such as shallow sowing depth promote more vigorous vine elongation and leaf development, indicating that initial root–shoot balance and resource capture strongly influence later canopy expansion.

Cucurbit vine architecture is also shaped by genetic regulation of branching, tendril development, and shoot indeterminacy. In cucumber, a model cucurbit, shoot architecture is determined by coordinated control of branch outgrowth, tendril identity, and vine length, with leaves and flowers produced continuously from axillary meristems along the vine. Comparative phylotranscriptomic work in Cucurbitaceae shows that specialized tendrils and climbing habit are linked to a cucurbit-specific tendril identity gene, reflecting evolutionary innovation that enables vertical exploration of surrounding vegetation and supports (Guo et al., 2020). These genetic and anatomical features underpin the ability of sponge gourd vines to distribute foliage and fruits three-dimensionally, but without deliberate training they often trail along fences or the ground, leading to suboptimal spatial distribution and compromised yield and quality.

2.3 Ecological and agronomic principles of trellising cultivation

Trellising modifies the ecological environment experienced by sponge gourd canopies by altering light distribution, air movement, and plant-soil interactions. In general crop canopies, modern management seeks to optimize stand-level light use efficiency rather than individual plant competitiveness, with canopy modeling highlighting that more uniform light distribution within the canopy can improve productivity and close yield gaps. Studies in trellised orchard systems show that espalier-type training can enhance light distribution efficiency per unit leaf area, although total productivity then depends on the balance between leaf area and light interception. Applied to climbing vegetables, trellis structures create vertically layered foliage where upper leaves intercept direct radiation while lower leaves receive filtered light, supporting photosynthesis throughout the canopy and improving microclimatic conditions for flowers and fruits (Figure 1).

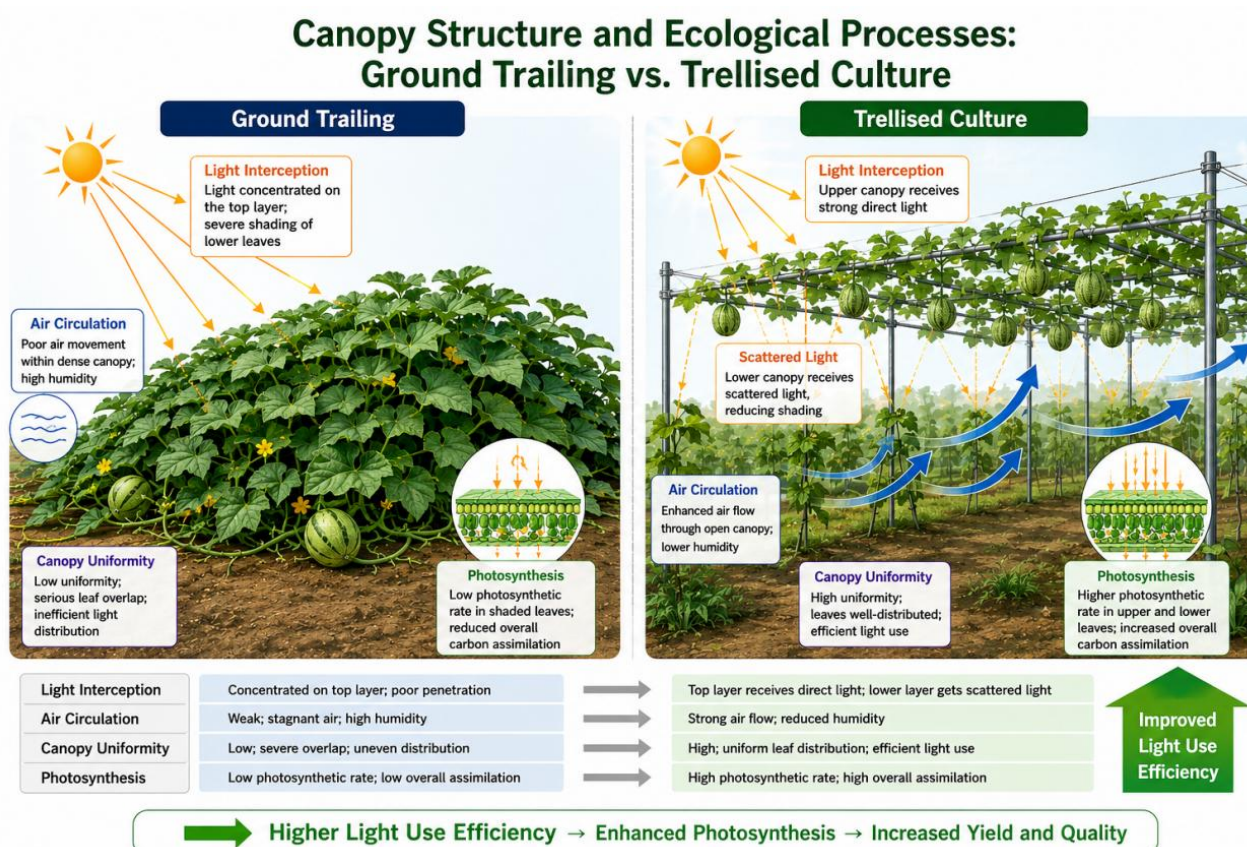


Figure 1 Conceptual illustration of how trellising systems modify canopy architecture, light interception, and air circulation in sponge gourd cultivation

For sponge gourd and related cucurbits, these ecological effects translate into concrete agronomic benefits. In Sri Lanka, supporting vines on horizontal trellises increased fruit yield and quality compared with prostrate growth, providing a basis for developing a full agronomic package for the crop. Comparisons of training systems show that above-ground structures such as bower or high trellis consistently produce higher yields, greater fruit size,

and longer vines than ground trailing, underscoring the importance of lifting the canopy to exploit vertical space and reduce shading within the foliage layer (Thakur and Pathania, 2025). Beyond yield, trellising simplifies management operations, enables better disease surveillance, and facilitates integration with practices such as mulching, nutrient management, and direct sowing layouts that orient trellis mesh to optimize natural light exposure and space use in diverse soils and climates.

3 Major Trellising Systems and Their Technical Characteristics

3.1 Horizontal pergola trellis system

Horizontal pergola or bower systems create an overhead canopy that maximizes interception of solar radiation and leaf area, which can substantially increase yield and fruit quality in climbing crops. In sponge gourd, above-ground bower training produced the highest yield, fruit number, and vine length compared with netting and ground trailing, indicating that an overhead horizontal framework effectively exploits the vigorous vine habit (Thakur and Pathania, 2025). Similar pergola systems in grape and kiwifruit have been associated with higher productivity and improved quality composition, supporting the general principle that spreading canopies on horizontal roofs enhances assimilation and crop performance when light is abundant (Danko et al., 2024).

However, traditional pergolas can be labor-intensive and difficult to manage due to their height and dense canopy, which complicates pruning, harvesting and plant protection. In grapevine, horizontal pergola trellises are reported to increase yields 2-3 times relative to vertical systems but require more time-consuming manual operations with arms raised above the head, highlighting ergonomic and cost constraints. New “mobile pergola” or modified overhead designs attempt to retain the yield gains of horizontal canopies while permitting temporary vertical positioning during pruning and harvesting, illustrating a broader trend toward pergola-inspired but more manageable systems that could be relevant for intensive *Luffa* cultivation.

3.2 A-frame and fence trellis systems

T-type and A-frame trellises represent intermediate architectures between horizontal pergolas and strictly vertical systems, often using sloped or cross-arm structures to support hanging vines. In ridge gourd, a T-trellis achieved the highest marketable yield (24.8 t ha⁻¹) among six systems, outperforming ground trailing and simple staking while providing a better benefit-cost ratio than the locally common pandal system, which produced similar yields but higher costs (Sen et al., 2023). These results suggest that for *Luffa* crops, moderately elevated, cross-armed trellises can balance canopy expansion, fruit exposure, and construction costs, making them attractive for organic and smallholder systems.

For other cucurbits, A-frame, V, and inverted-V trellises have been tested alongside bower, netting, and cage systems, with bower often giving the highest yield per hectare but inverted-V trellises showing superior benefit-cost ratios, indicating economic advantages despite slightly lower yields (Singh et al., 2023). Farmers may also use simple fence-like supports; while detailed quantitative data for fence systems in *Luffa* are limited, experiences from ridge gourd and bottle gourd imply that structured supports consistently outperform ground trailing in fruits per plant, total yield, and net returns, pointing to broad benefits of moving vines off the soil surface.

3.3 Vertical training and innovative three-dimensional trellis systems

Strictly vertical or high-wire trellising arranges shoots upward along single or double planes, improving plant density, pollination efficiency, and management access. In sponge gourd, cultivation on a 3-m high trellis increased yield by 33.41% over control and produced yields comparable to bower systems, leading to recommendations for both bower and high trellis training in commercial practice. Vertical training in cucumber and bottle gourd similarly enhanced fruit number per plant, total yield and uniformity, especially when combined with optimized plant growth regulators or bower-type support, underscoring the value of precise canopy orientation in cucurbits (Manna and Singh, 2024).

Emerging three-dimensional and multi-layered systems extend vertical concepts by creating stacked or umbrella-shaped canopies that manage light gradients and microclimate more precisely. In kiwifruit, an

umbrella-shaped trellis derived from overhead pergolas more than doubled yield relative to a traditional pergola while maintaining external fruit quality and improving internal quality through better shading of the fruiting canopy (Deng et al., 2023). Outside orchards, innovative tower-based vertical cultivation devices partition three-dimensional space into chambers with differentiated light, temperature and humidity, achieving large water savings and more efficient use of vertical volume, which conceptually parallels multi-tier trellising for high-density vine crops. Together, these developments indicate that future Luffa trellis designs may evolve toward configurable, three-dimensional systems that fine-tune light interception, labor efficiency, and fruit quality beyond what simple horizontal or single-plane vertical trellises can provide.

4 Effects of Trellising Systems on Sponge Gourd Growth and Development

4.1 Effects on plant morphological characteristics

Trellising and training systems markedly shape vine architecture, vegetative growth, and canopy structure in climbing crops, with clear implications for Luffa and related cucurbits. In organically grown ridge gourd, six trellis types produced distinct vine growth responses: the farmer-standard pandal trellis favored somewhat more vigorous vegetative growth, whereas a T-trellis gave slightly higher yields and better fruit quality despite similar growth metrics, indicating that subtle architectural changes can redirect assimilates without necessarily increasing total vine size. In greenhouse cucumber, a single-head training system produced the longest vines and largest leaf area at multiple growth stages compared with umbrella and low-middle systems, showing that more vertical, simplified training can promote extension growth and canopy expansion under protected conditions (Shivaraj et al., 2020).

Similar structural effects are evident in perennial trellised fruit crops. In dragon fruit, a single-pole training system promoted “balanced growth,” whereas a T-trellis enhanced vegetative expansion with wider plant spread but also induced stress symptoms such as canopy overheating and photodamage, illustrating that vigorous morphological growth can be decoupled from functional canopy health (Karunakaran et al., 2026). In grape, fan-shaped and divided-canopy trellis systems increase shoot vigour, shoot leaf area and total leaf area per vine relative to vertical single-curtain systems, confirming that three-dimensional trellis designs can generate larger, more voluminous canopies that must then be managed to balance vegetative and reproductive sinks.

4.2 Effects on leaf photosynthetic performance

Trellis-induced canopy architecture strongly conditions the light environment and thus leaf-level photosynthesis. In high-density mango, a Y-trellis form improved photosynthetic photon flux density in both upper and lower canopy layers compared with open-centre and espalier canopies, and this arrangement supported higher net photosynthetic rates and stomatal conductance at both heights, indicating that moderate light interception with better vertical distribution enhances whole-canopy gas exchange (Kishore et al., 2023). In dwarf mango trained as open-vase versus espalier-trellis, digital canopy modelling showed that the espalier system increased light distribution efficiency per unit leaf area and, when normalized by leaf area, achieved a small productivity advantage, underscoring that trellis geometry can improve photosynthetic efficiency even when total leaf area is reduced (Cheesman et al., 2025) (Figure 2).

Comparative studies in pear and peach further link trellis systems with photosynthetic performance. Pear trees trained on a flat-type trellis exhibited higher net photosynthetic rates than a freestanding system, especially in interior canopy leaves on the sunny side, and transcriptomic analyses implicated enhanced light-harvesting and circadian-clock regulation under the open trellis architecture. In peach, a planar 2D “fruiting wall” training system had lower overall light interception than a 3D Quad-V canopy but achieved 15%-20% higher net photosynthetic rates and better water-use efficiency, particularly maintaining higher photosynthetic efficiency in the shaded lower canopy, illustrating that trellis-driven light uniformity can outweigh total intercepted radiation for photosynthetic performance (Chatzieffraimidis et al., 2025).

4.3 Effects on flowering, fruit set, and assimilate allocation

Training and trellising interact with flowering and fruiting through their influence on canopy microclimate, source-sink relations, and competition among reproductive structures. In dragon fruit, a single-pole system

advanced floral initiation (26 days to flowering) and supported higher yields than T-trellis or pyramid forms, suggesting that more favorable light distribution and reduced stress within the canopy can accelerate flowering and enhance fruit set (Karunakaran et al., 2026). Under the same species, experiments in trellised pitaya showed that leaving more cladodes per meter increased flowering intensity, but fruit set and fruit size were largely independent of pruning level; instead, fruit weight declined when more than one fruit developed per cladode, and flower bud drop increased on cladodes bearing many flowers, indicating strong intra-shoot competition for assimilates between flowers and developing fruits (Chiamolera et al., 2023).

Canopy Structure and Light Distribution Comparison

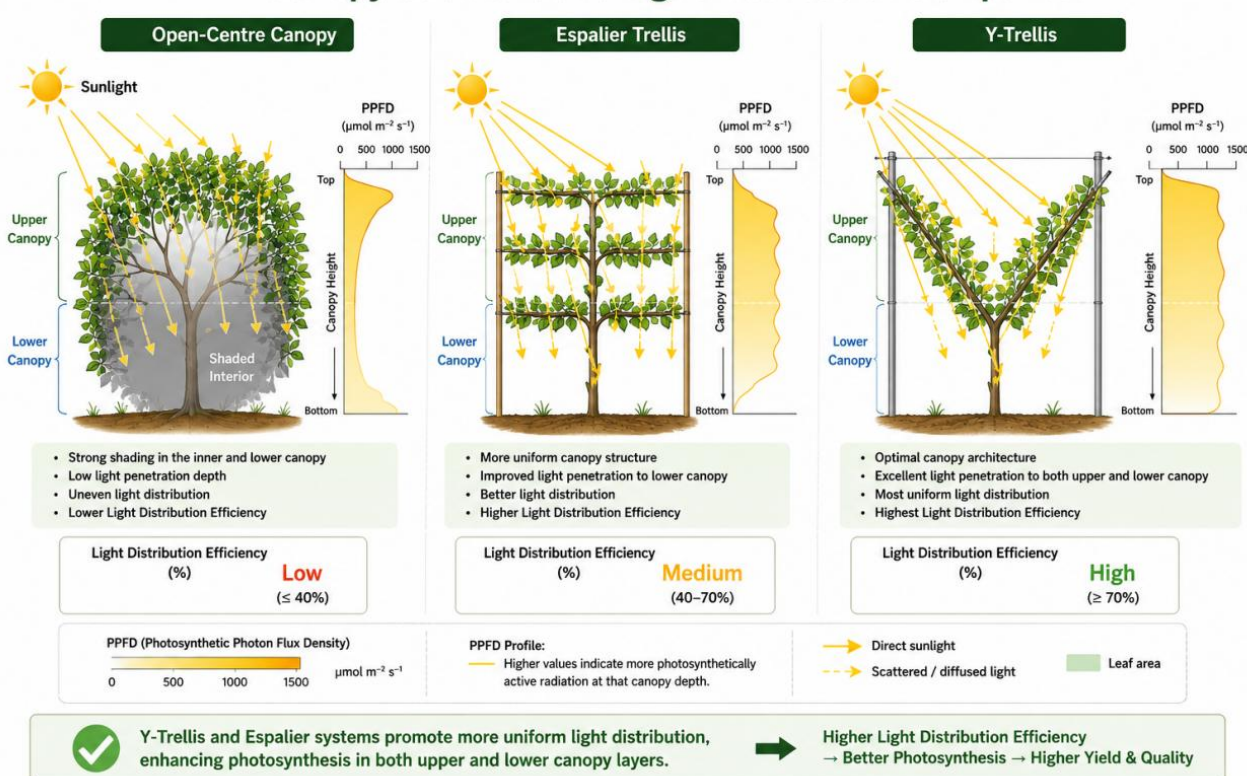


Figure 2 Conceptual comparison of canopy light distribution under open-centre, espalier, and Y-trellis training systems

Cucurbit studies illuminate how resource status and canopy structure affect sex expression and assimilate allocation. In monoecious cucumber, increased nutrient supply raised the number of female flowers and altered the male:female ratio, while pollination level changed female flower numbers during later flowering and affected fruit growth and seed set, yet the total number of fruits and overall seed output per plant did not increase proportionally, implying that reproductive allocation is buffered and not always optimally matched to initial flower production (Gao et al., 2021). Simulation work in cucumber canopies shows that when total biomass production is low, a greater fraction of assimilates is partitioned to leaves and stems to increase light interception, reducing allocation to fruits and increasing investment in side shoots; this demonstrates a structural-functional feedback whereby canopy architecture and light capture demands can divert assimilates away from reproductive sinks.

5 Effects of Trellising Systems on Yield Formation

5.1 Effects on fruit number and individual fruit weight

Trellising systems markedly influence fruit number per plant in Luffa and related cucurbits. In sponge gourd, above-ground training on bower and netting systems significantly increased fruits per plant compared with ground trailing, with the bower system giving the highest fruit number and total yield (Thakur and Pathania, 2025). Similar patterns appear in bottle gourd, where bower training produced the highest number of fruits per vine and yield per hectare, outperforming ground trailing and other training systems.

Effects on individual fruit weight are more nuanced. In sponge gourd, single-plant vertical training produced the highest average fruit weight, whereas the bower system maximized fruit number and overall yield, indicating a trade-off between fruit size and fruit load under different trellises. In bottle gourd, trailing systems increased fruit number and total fruit weight per plant, but training systems altered fruit diameter and other size traits, suggesting that trellis design can shift assimilate allocation between fruit number and individual fruit mass (Singh et al., 2023).

5.2 Regulatory mechanisms of trellising systems on yield components

Differences in fruit number and weight among trellis systems are closely linked to canopy light distribution and the balance between vegetative and reproductive sinks. In hydroponic cucumber, a modified-umbrella trellis increased fruit number and fruit weight per plant relative to a high-wire system, largely because directing apical meristems downward improved light access to the most photosynthetically active leaves within the canopy. Modeling work shows that increased solar radiation interception raises individual cucumber fruit weight, while excessive shading in umbrella-type systems reduces lower-canopy contribution and can trigger fruit abortion, illustrating how trellis-driven LAI and light gradients regulate yield components (Kile et al., 2024).

At the physiological level, trellises also alter hormonal balances and assimilate partitioning. In kiwifruit, an umbrella-shaped trellis more than doubled yield compared with a traditional overhead pergola, partly by promoting vegetative growth of canes in the most productive diameter class and creating an upper shading canopy that improved pigment accumulation and hormonal status in the fruiting zone. The most productive cane zones under this system contained higher levels of cytokinin and auxin and favorable ratios with gibberellin and abscisic acid, suggesting that trellis-induced changes in canopy structure can indirectly regulate flower bud differentiation and fruit set through hormone dynamics (Deng et al., 2023).

5.3 Yield enhancement under different ecological conditions

Trellis systems interact strongly with ecological conditions such as season, radiation level and planting density to shape yield responses. In sponge gourd, above-ground training on bower or netting markedly increased yield over ground trailing under open-field conditions, with yield gains up to 71% in some systems, showing that elevating the canopy improves performance in typical subtropical environments (Thakur and Pathania, 2025). Off-season trellis cultivation of bottle gourd further indicates that while absolute yield per area can be lower in hotter or less favorable seasons, trellis-based systems may still provide higher net returns due to advantageous market prices, highlighting economic resilience across seasons.

In greenhouse cucumbers, interactions between canopy structure, light environment and trellis type are especially pronounced under low irradiance. Inter-lighting within a high-wire canopy improved photosynthetic characteristics of lower leaves but did not increase total fruit production because extreme leaf curling reduced horizontal and vertical light interception, demonstrating that architectural responses can negate potential gains from improved light distribution. Modeling of intracanopy lighting similarly predicted that, in the absence of such morphological issues and with unchanged partitioning, fruit yield could increase by about 8%, largely through enhanced light absorption, emphasizing that under constrained light climates, trellis-lighting combinations must maintain favorable canopy architecture to fully realize yield enhancement (Trouwborst et al., 2011).

6 Effects of Trellising Systems on Fruit Quality

6.1 Effects on external fruit quality attributes

Trellis systems often improve external appearance traits such as color uniformity, size, and shape, which are critical for Luffa market acceptance. In acorn squash, trellised plants produced fruits that were more uniformly black-green and firmer than those from ground culture, indicating reduced blemishes and more consistent epidermal development under supported growth (Adeeko et al., 2024). Trellising also increased fruit length in greenhouse cucumber, where a high-wire system produced the longest fruits, suggesting that vertically oriented canopies can favor more elongated, regular fruit shape (Figure 3).



Figure 3 Representative comparison of fruit appearance under ground-trailing and trellised cultivation systems

External size and mass may likewise benefit from combined trellis and floor management. In spaghetti squash, using both trellis and mulch gave the greatest number of fruits per plant and the largest fruit weight, while also supporting longer and wider fruits compared with other combinations, indicating synergistic effects of vertical support and soil surface protection on fruit growth (Kartika and Karyana, 2017). For bottle gourd, bower training significantly increased fruit length relative to ground trailing, even though fruit diameter could be slightly reduced, implying that supported systems may shift proportions toward more cylindrical, market-preferred shapes (Singh et al., 2023).

6.2 Effects on nutritional quality characteristics

Evidence from cucurbits and other trellised crops indicates that canopy architecture can alter internal composition, including sugars, acids, and secondary metabolites. In trellised acorn squash, fruits showed very high dry matter and soluble solids at harvest, and trellised plants had higher carotenoid, ascorbate, and antioxidant contents than ground-grown plants, reflecting enhanced accumulation of both energy reserves and health-promoting compounds (Adeeko et al., 2024). Similarly, in table grapes, a T-trellis system increased total anthocyanin, flavonoid, proanthocyanidin and monoterpene contents compared with a V-trellis, demonstrating that trellis geometry can modulate phenolic and aroma profiles important for nutritional and sensory quality (Wang et al., 2023).

Trellis-related changes in microclimate and sink–source balance can also influence basic quality indices such as soluble solids and titratable acidity. In greenhouse cucumber, training systems affected total soluble solids and potassium content: fruits from V-shape systems had the highest soluble solids and K, suggesting that certain vertical arrangements promote greater sugar and mineral accumulation. For sweet acorn squash grown on trellises,

dry matter and soluble solids remained high even after extended cold storage, with TSS values around 19-20 °Brix, indicating that trellis-grown fruits can maintain dense, sweet flesh and nutritional richness over time.

6.3 Effects on marketability and postharvest quality

Trellis systems frequently enhance overall marketability by increasing the proportion of marketable fruit and extending shelf life. For spaghetti squash, the use of trellis and mulch together produced more marketable fruits and heavier fruit weight, which directly improves pack-out and economic return per plant. In cucumber, trellising doubled marketable yield compared with ground culture and reduced the proportion of fruits with defects such as yellow belly, jumbo size, and distortion, indicating fewer downgraded culls and a higher share of Fancy-grade produce.

Shelf life and storability can also benefit from trellis-based systems through effects on firmness, color retention, and disease incidence. In long English cucumber, training systems that increased canopy light penetration produced darker green fruits with longer shelf life, linking trellis-induced light exposure to chlorophyll retention and delayed surface yellowing. For trellised, greenhouse-grown sweet acorn squash, appropriate cold storage (10 °C-15 °C with reduced humidity) allowed up to 3 months of shelf life with minimal quality loss, and trellis cultivation produced uniformly colored, high-quality fruits that responded well to postharvest treatments such as hot water brushing to reduce rots, supporting steady, extended marketing (Adeeko et al., 2020).

7 Case Study: Comparative Performance of Different Trellising Systems on Sponge Gourd Yield and Quality

7.1 Comparison of horizontal pergola and a-frame trellis systems

Horizontal pergola and related overhead systems can greatly increase canopy area and light interception but differ from A-frame or T-type structures in labor needs and yield response. In grape, pergola trellises allow maximum “green mass” and solar energy assimilation, raising yields by 2-3 times compared with vertical systems, though management becomes much more labor-intensive due to overhead work (Kharibegashvili et al., 2021). A mobile pergola design mitigates these drawbacks by shifting between horizontal and vertical positions, maintaining pergola-level yield while simplifying pruning and harvesting, which illustrates the trade-off between productivity and ergonomics inherent in fully horizontal systems.

A-frame or T-type trellises usually provide intermediate canopy height and partial horizontal spread. In organically grown ridge gourd (*Luffa acutangula*), a T-trellis produced the highest marketable yield (24.8 t ha⁻¹) and the best benefit-cost ratio among six trellis types, slightly outperforming the locally used pandal system despite similar vegetative growth (Sen et al., 2023). In passion fruit, a horizontal “T” system achieved intermediate productivity between simple and total trellis structures, reflecting that partially horizontal designs may not always maximize yield but can balance structural cost, fruit quality, and cultural operations (Cleves-Leguizamo, 2021).

7.2 Production efficiency analysis of fence trellis and vertical training systems

Fence-like and simple vertical trellises emphasize linearly arranged canopies, favoring ventilation, pollination and access. In Colombian passion fruit, a simple vertical trellis reached 30.5 t ha⁻¹ with 73% first-quality fruit, outperforming a horizontal T-trellis and a full “barbecue” system in both productivity and quality while also enabling higher planting density and mechanization. Similarly, long-term records from Colombian orchards indicate that simple trellises combine good phytosanitary management, efficient foliar spraying, and ease of structural repair, leading to stable high-quality yields over 18-24 month cycles (Cleves-Leguizamo, 2021).

High-wire and other vertical training systems in greenhouse cucumbers highlight additional efficiency dimensions. A high-wire system produced more consistent weekly yields than a modified-umbrella system, even though the latter doubled fruit number per plant and increased total yield, suggesting that vertically oriented canopies can stabilize harvest rhythm at the expense of some productivity. In another high-wire study, training cucumbers on a single main stem per slab achieved the same yield per area as multi-stem configurations while improving water use, simplifying work, and stabilizing weekly production, underscoring that simple vertical architectures can enhance input efficiency and labor organization without sacrificing output.

7.3 Comprehensive evaluation of representative regional cultivation cases

Regional Luffa and cucurbit case studies show that trellis choice interacts strongly with local climate, infrastructure and market conditions. In Sri Lanka, sponge gourd grown under horizontal trellising achieved average yields of 8.4 t ha⁻¹ with improved fruit number compared with prostrate vines, indicating clear agronomic benefits of overhead support under tropical field conditions. In subtropical Mexico, direct-sown sponge gourd on live-stake trellis systems produced 5-20 fruits per plant and fruit weights up to 660 g at the best site, with production costs per fruit about one-third lower than at less favorable sites, demonstrating that simple wire-and-stake frameworks can support profitable small-scale production in diversified landscapes (Fernández-Lambert et al., 2025).

Beyond Luffa, other cucurbits underline how trellising adapts to regional constraints. In North Florida, A-frame and wire-trellis cucumbers showed no significant yield advantage over conventional ground culture, suggesting that in humid subtropical climates with certain cultivars and management, trellising may primarily improve handling and fruit cleanliness rather than yield. In Israel, winter-grown acorn squash under protected cultivation yielded 56% more when trellised, with fruits that were firmer, better colored and richer in dry matter, soluble solids, carotenoids and antioxidants, illustrating that in high-value, protected systems, vertical trellising can simultaneously raise productivity and quality to meet premium markets (Adeeko et al., 2024).

8 Trellising Systems, Production Efficiency, and Sustainable Development

8.1 Effects on labor requirements and production costs

Trellis design strongly influences both variable and fixed production costs in cucurbit systems. In organically grown ridge gourd, the T-trellis produced the highest marketable yield while using simpler materials than the locally common pandal, resulting in the highest benefit-to-cost (B:C) ratio across varieties and demonstrating that trellis choice can improve profitability even when yield differences are modest. Off-season trellis-based bottle gourd cultivation likewise showed only small differences in cultivation cost between seasons, yet off-season crops achieved substantially higher net returns and B:C ratio due to better prices, underlining how trellis systems can support profitable timing strategies (Singh et al., 2024).

Labor requirements are also shaped by trellis structure and associated training operations. In highbush blueberry, adding a V-trellis increased pruning time in some years without compensating yield gains, raising total pruning and harvest costs per kilogram relative to a standard T-trellis and highlighting the risk that more complex trellises can raise labor costs (Strik and Davis, 2022). Conversely, improved training concepts in cucumber, such as lowering-type systems, have simplified repetitive tasks like old leaf removal and harvesting, pointing to the potential for trellis designs that facilitate partial or full automation of key operations.

8.2 Effects on disease and pest management as well as field operations

Raising cucurbit canopies on trellises can indirectly aid disease and pest management through improved aeration and reduced soil contact. In sponge gourd, horizontal trellising increased yield and fruit quality compared with prostrate vines, and pest and disease observations showed only mild leaf miner and low fruit fly damage, supporting the view that Luffa can be grown with minimal external inputs and low production costs when properly supported (Silva et al., 2012). Field studies with trellised cucumbers in open ground report that air exchange between plants improves, soil moisture is better managed, fruit quality improves, and soil-borne diseases decrease, illustrating multiple sanitary and operational benefits of the trellis method over conventional culture.

Interactions between trellising and targeted pest-management tools are also important. In slicing cucumber, trellising reduced downy mildew necrosis slightly and increased total fruit yield by about 15%, but trellising alone did not raise marketable yield; fungicide applications remained the main driver of disease suppression and marketable production, indicating that support structures must be integrated with chemical or biological controls (Keinath, 2019). More generally, trellis-based vegetable systems are recognized as a component of sustainable production that can lower overall production costs, improve food quality, and support organic methods by enhancing sunlight interception, aeration, and reducing pest and disease contact, thereby easing field operations like harvesting and crop inspections (Singh et al., 2024).

8.3 Prospects for trellising cultivation in sustainable and high-efficiency production

Trellis systems are increasingly framed as a cornerstone of sustainable intensification, enabling higher yields per unit ground area and more efficient use of vertical space. A recent agrivoltaic design study noted that using trellises can double or triple yield per acre while reducing diseases and pests, easing harvest, and producing cleaner crop products, and proposed low-cost wood-based PV racking that simultaneously functions as trellis support and irrigation/fertigation infrastructure. For small and marginal farmers, multilayer trellis farming and off-season trellis-based production have repeatedly outperformed traditional systems in net returns and profit, suggesting a pathway to livelihood improvement and more resilient production systems (Singh et al., 2024).

Within *Luffa* specifically, sponge gourd has been identified as a high-potential underutilized cucurbit whose yield and fruit quality are strongly enhanced by trellising, and which can be grown with low external inputs and minimal pesticide use, aligning well with organic and low-input strategies. Broader reviews of dioecious cucurbits emphasize that integrating trellising with mulching, biofertilizers and growth regulators holds “immense potential” for future vegetable production and markets, particularly for minor cucurbits cultivated by smallholders, indicating that optimized trellis systems can be central to high-efficiency, resource-conserving production chains (Nayak et al., 2024).

9 Future Perspectives and Conclusions

Existing studies on *Luffa* and related cucurbits show that trellising can clearly increase yield and improve fruit quality, but the evidence base is still narrow and fragmented. Most work focuses on short-term comparisons of a few trellis designs at single sites and seasons, often without detailed characterization of plant physiology, microclimate, or fruit quality beyond basic traits. For sponge gourd, for example, horizontal systems were identified as promising, yet evaluations were confined to limited environments and short time frames, with explicit calls to repeat experiments across more seasons and to expand trait coverage. Another major limitation is that trellis research on *Luffa* is largely decoupled from other technological advances in crop management. Studies rarely integrate trellising with rootstock use, controlled environments, or detailed monitoring of water and nutrient dynamics, even though grafting and soilless culture have proved effective for improving yield and quality in closely related cucurbits. Economic and labor aspects are also underexplored: while some work on ridge gourd has compared benefit-cost ratios among trellises, there is little quantitative analysis of labor ergonomics, long-term structural costs, or adoption barriers among smallholders who still rely on fences or trees for support.

Rapid progress in precision agriculture and IoT provides a rich toolbox that has scarcely been applied to *Luffa* trellis systems. Cloud-based platforms and wireless sensor networks have already been used to monitor greenhouse microclimate, automate control, and increase cucumber yield and quality in soilless systems, demonstrating the potential of data-driven management. Similar sensor architectures, combined with simple actuators, could be adapted to trellised *Luffa* to control irrigation, fertigation, and possibly shading or ventilation based on real-time canopy and weather data. Beyond basic monitoring, next-generation “smart trellises” could embed low-cost sensors and edge computing into the support structure itself. Reviews of smart sensors and IoT in agriculture emphasize the value of continuous measurements of plant stress, soil moisture, and microclimate, coupled with artificial intelligence for predictive decision-making. Integrating these capabilities with modular, adjustable trellis designs would allow dynamic management of canopy density, pruning, and harvest timing in response to incoming light, temperature, and plant status, linking structural design with automation and making intensive *Luffa* systems more resilient and resource-efficient.

Overall, research to date indicates that lifting *Luffa* vines from the ground onto engineered trellises reliably increases total yield, mainly by raising fruit number without compromising basic external quality. However, the optimal trellis configuration clearly depends on cultivar, environment, and production goals, and current evidence is insufficient to define robust design principles across regions. Experience from ridge gourd and other cucurbits suggests that relatively simple, moderately elevated systems can offer a favorable balance of yield, fruit quality, and cost, but systematic comparisons with horizontal pergolas, vertical walls, and three-dimensional designs remain scarce. Future studies on *Luffa* trellising should therefore be multi-season and multi-site, combining

detailed measurements of growth, canopy light distribution, and fruit nutritional quality with rigorous economic and labor analyses. There is particular need to test trellis systems under stress conditions such as heat, salinity, and water deficit, where grafting onto tolerant *Luffa* rootstocks, IoT-based greenhouse or field control, and soilless cultivation are already showing promise in other cucurbits. Integrating these technologies into comprehensive, sensor-informed trellis packages, and co-designing them with farmers for different ecological and market contexts, will be essential to fully exploit the yield and quality potential of *Luffa* as an emerging high-value crop.

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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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