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REVIEW ARTICLE

Impact of canopy architecture on phenology and production efficiency of flower crops: A review

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Abstract

Canopy architecture plays a crucial role in regulating plant growth, phenology and yield by influencing the microclimatic environment, light interception and resource use efficiency. This review systematically explores the interplay between canopy structure and plant phenological stages, particularly in flower crops. Structural traits such as leaf orientation, plant height, branching pattern and spatial distribution of foliage significantly determine the distribution of light within the canopy, affecting photosynthesis and developmental timing. Variations in canopy architecture have been shown to influence flowering induction, fruit set and yield potential by altering the temperature and light quality perceived by the plant. The review also highlights the hormonal control of canopy traits, with auxins, gibberellins and cytokinins modulating shoot elongation, leaf expansion and apical dominance. Furthermore, it examines practical approaches for canopy manipulation, including spacing, pruning and training systems, aimed at maximizing productivity and enhancing crop performance under varied environmental conditions. The integration of remote sensing tools and canopy modelling techniques is emphasized for real-time monitoring and optimization of canopy performance. Understanding the relationship between canopy design and phenology provides critical insights for breeding programs and precision agriculture strategies. This synthesis underscores the importance of tailored canopy management to achieve sustainable yield improvements and better adaptation to climate variability in flower crops.

Keywords: canopy structure; environment; flowering; light; management strategies

Introduction

Canopy architecture plays a critical role in determining plant performance, particularly in flowering crops, by regulating light interception, photosynthetic efficiency and overall biomass and floral yield (1). The layout of leaves, stems and flowers in the canopy influences important processes like water loss, nutrient flow and carbon intake (2). A well-organized canopy improves light access, decreases shading between plants and boosts air flow, which helps lower disease rates and increases flower quality. Different canopy structures in various flower species and types cause different growth patterns, affecting blooming times, bud growth and overall production efficiency (3). In commercial flower growing, managing canopy structure through trimming, spacing and training is important for achieving even growth and synchronized blooming, which ensures flowers are of marketable quality (4). Furthermore, improvements in plant breeding and biotechnology have made it possible to create flower types with beneficial structural features that improve production efficiency in different environmental conditions.

The link between how a plant's canopy is shaped and its growth timing is very important for making efficient use of resources, as it directly impacts the plant's ability to use sunlight, water and nutrients (5). Thick canopies may cause self-shading, which lowers photosynthesis in the lower leaves and changes hormone levels that control blooming and growth (6). Moreover, openly structured canopies can enhance light spread and air flow, resulting in healthier plants and longer blooming times (7). Additionally, environmental factors like temperature, humidity and light strength work with canopy shape to affect how well crops grow (8). Knowing these interactions is essential for applying precise horticultural methods that improve flower yield, quality and shelf life after harvest. This review underscore a comprehensive knowledge of canopy architecture influences phenology and production efficiency in flower crops, with emphasis on effective management strategies and recent research advancing sustainable floriculture.

Canopy architecture: concepts and components

Canopy architecture, defined as the spatial arrangement of leaves, branches and floral structures, plays a pivotal role in determining plant growth, resource utilization and productivity-particularly in flowering crops (9, 10). An optimized canopy structure enhances light interception, airflow and photosynthetic efficiency, thereby maintaining a balance between vegetative growth and floral development, leading to improved flower quality and yield (11). Canopy structure is influenced by important design and functional features that decide how well a plant uses light, water and nutrients (12). These features include leaf area index (LAI), light uptake, plant height, branching style and leaf arrangement - all of which affect growth and productivity. LAI measures the total leaf area for each unit of ground surface and influences how effectively sunlight is captured and how efficiently photosynthesis occurs (13).

Plant height and branching styles influence competition for light and the placement of flowers, with taller plants often showing stronger apical growth, which can restrict side branching and reduce flower numbers (*Gladiolus grandifloras* and *Helianthus annuus*). A well-branched canopy, however, ensures even flower placement, improving both appearance and market value. Leaf angle and leaf arrangement also regulate light penetration, with the optimal configuration reducing mutual shading and increasing photosynthetic efficiency (14). By manipulating these architectural traits, growers can strategically design canopies to optimize light distribution, enhance flower quality and improve resource-use efficiency-conceptually illustrated in Fig. 1.

Role of canopy structure in optimizing photosynthesis and resource allocation

The layout of a plant's leaves directly affects its ability to perform photosynthesis and utilise resources (15). Photosynthesis, the primary process driving plant growth, depends on efficient light capture and carbon uptake. A well-organized leaf structure helps to spread light evenly throughout the plant, avoiding too much shading and allowing the lower leaves to aid in overall photosynthesis (16). In flowering plants, this leads to better bud growth, consistent blooming and for longer-lasting blooms.

Beyond light interception, leaf structure also influence water and nutrient distribution. Plants with open, well-spaced leaf areas exhibit better transpiration efficiency, reducing excess moisture that can lead to fungal diseases (17). A well-maintained leaf structure further supports efficient transport through the xylem and phloem, ensuring effective mobility of essential nutrients such as nitrogen and potassium. Additionally, leaf arrangement plays a role in regulating hormone levels that govern both vegetative and reproductive growth (18). For instance, in *Rosa hybrida*, a well-distributed leaf arrangement that maximizes light interception promotes balanced auxin-cytokinin levels, enhancing lateral bud break and increasing the number of flowering shoots. In contrast, in *Chrysanthemum morifolium*, a denser canopy with overlapping leaves that shade lower foliage disrupts this hormonal balance, suppressing lateral growth and delaying floral initiation.

Influence of genetic and environmental factors on canopy development

The structure of a plant canopy is influenced by both genetic and environmental factors (19). Genetically, every species and variety has a set canopy structure, determining plant height, branching, stem length and leaf shape. Breeding programs aim to create types with desirable architectural traits like compact growth, high branching density and better light catching, as seen in roses bred for upright growth and chrysanthemums chosen for even flowering (20). Environmental conditions such as light levels, temperature, humidity and soil quality also influence canopy growth (21). Bright light conditions support compact, bushy canopies, while low light can cause stretched growth. Changes in temperature affect stem length and when plants flower, while the availability of nutrients and water impacts canopy density and overall plant health (22). High light promotes compact canopies, whereas, low light conditions often induce etiolation. Horticultural interventions such as pruning, training, pinching and spacing

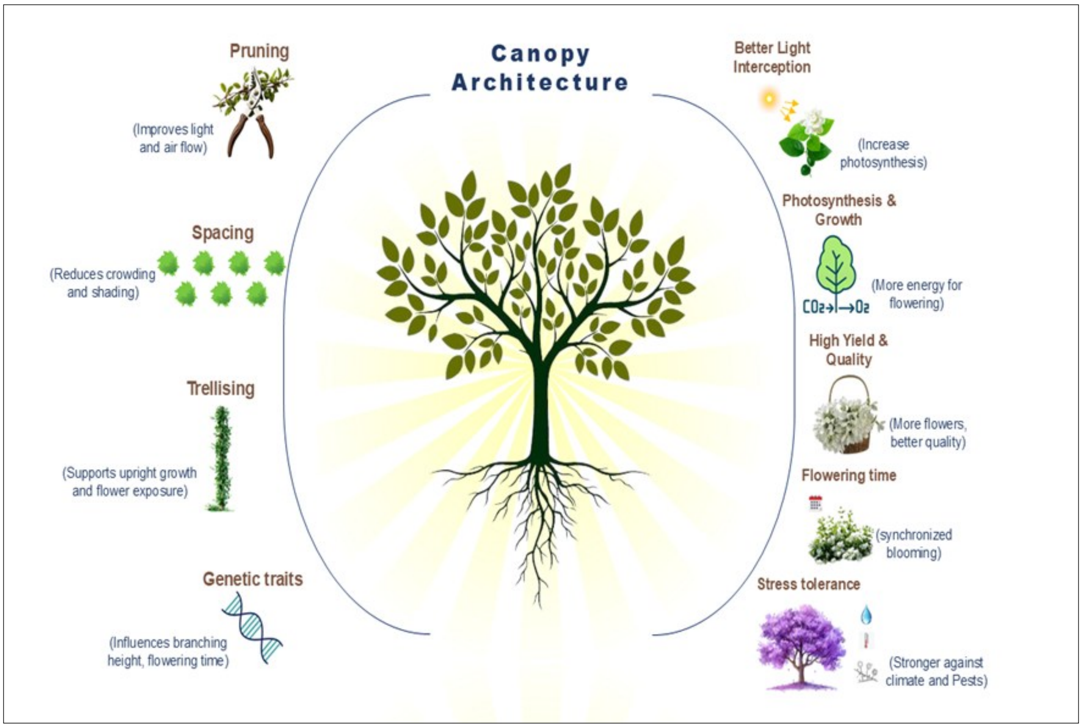

Fig. 1. Schematic representation of key factors influencing canopy architecture.

optimize canopy density and flower quality (23). Techniques like pinching and thinning encourage compact, flower-rich growth, while the use of trellises improves light exposure and air circulation. Integrating genetic insights with environmental management allows growers to optimize flowering time, enhance floral yield and improve stress resilience.

Canopy architecture and phenology of flower crops

Canopy design is very important in deciding the growth stages of flowering crops, affecting points like bud growth, flower opening and aging (24). The spatial arrangement of leaves and branches influences the internal distribution of light, airflow and resources-factors essential for coordinated floral development (25, 26). On the other hand, poor canopy management can cause uneven flowering, slow growth changes and lower flower quality.

The reproductive phases in flower plants-bud growth, flower opening and senescence are closely linked to canopy structure, as it influences light penetration, airflow and resources allocation within the plant (27). Successful bud growth requires sufficient light and carbohydrate reserves for initiation and development, but thick canopies can cause excessive shading, reducing photosynthesis and limiting the resources necessary for flower formation (28). Proper pruning and training make sure that growing buds get enough light and nutrients. During flower opening, factors like light strength, temperature and hormone control, all affected by the canopy structure, decide when and how well flowers open (29). A well-ventilated canopy reduces heat accumulation, lowering the chance of early blooming or deformities, while a balanced shape reduces mechanical strain on delicate flower parts (30). In aging, the last flowering phase, too much shade or a crowded canopy can speed up flower aging because of higher ethylene levels and lower photosynthesis. Managing canopy density helps to prolong the flowering period, ensuring enough light is available and reducing aging caused by ethylene (31). Understanding how canopy structure relates to flowering stages is important for improving production plans, ensuring consistent flower quality and minimizing losses from flowers blooming too early or too late (Table 1).

Influence of light distribution on floral induction and timing

Light is a critical environmental factor regulating floral induction and developmental timing (36). High light levels encourage the photosynthetic activity, providing energy for starting flower buds, while low light situations, often due to too much shading from the canopy, can delay or stop flowering due to lack of energy. Flowering plants like chrysanthemums and orchids are higly responsive to light intensity and require particular light levels to bloom (37). Photoperiod signals are also important for the structure of the canopy affects the leaves to acquire light duration signals, which control the flowering of short-day and long-day plants. In chrysanthemums (short-day plants), too much shading can interfere with their ability to sense the photoperiod, causing delays in blooming. In long-day plants like carnations, light distribution is crucial for flowers to bloom together (38). Additionally, the quality of light, especially the ratio of red to far-red light (R:FR), is essential in controlling flowering. Dense canopies increase far-red light exposure, promoting tall growth instead of flower bud initiation (39). Managing the canopy properly helps keep a good R:FR balance, ensuring flowers bloom evenly and reducing competition among floral shoots. By improving light distribution, growers can better control when flowers bloom and increase the overall flower yield, making light management a key part of how canopy and flowering times interact in flower farming.

Role of plant hormones in canopy-phenology interactions

Plant growth regulators play a vital role in managing the relationship between plant shape and flowers development, affecting key growth stages such as bud formation, flower change and flower longevity (40). Some of the main hormones involved are gibberellins (GAs), auxins and cytokinins, each influencing plant architecture and flower development in distinct ways. GAs promote stem elongation, flowering initiation and the breaking of dormancy; auxins regulate apical dominance, root initiation and directional growth responses such as phototropism, thereby influencing canopy form and cytokinins stimulate cell division, delay leaf senescence and promote lateral bud outgrowth, contributing to branching and increased flower-bearing sites. For example, GAs promote stem elongation and flowering, as seen in lilies and roses, where GA application can induce blooming even under low light conditions (41). However, excessive GA levels in dense canopies can encourage excessive vegetative growth, reducing flowering success. Auxins regulate branching by mainataing high concetration in apical shoot, which suppresses lateral bud growth and results in a straighter, denser plant structure (fig. 2) (42). In orchids and chrysanthemums, the application of cytokinins has been shown to to prolong flower longevity and enhance flower size (43). An in-depth understanding of hormonal regulation enables targeted manipulation and plant shape allows for careful adjustments in plant growth using specific hormone applications, enhancing even flowering and product quality in modern flower farming systems.

Canopy management and its role in production efficiency

Canopy management is a key agronomic strategy in floriculture, enhancing flower yield, quality, uniformity and resilience to biotic and abiotic stresses (44-46). Techniques such as pruning, training and trellising are used to modify canopy structure, improve light interception and reduce disease incidence (47). Pruning is a basic practice that involves the careful removal of parts of the plant, such as stems, branches or buds, to control

Table 1. Comparative overview of canopy architecture types

Flower Crop	Canopy Architecture	Management Practice	Reference
Rose (*Rosa hybrida*)	"Bent canopy": upright hedge plus bent shoots capture radiation deeper into canopy	Training system involving shoot bending to maintain multi-tier canopy	(32)
Gerbera (*Gerbera jamesonii*)	Basal rosette with vertical flower stalks; open structure optimized for supplemental LED lighting	Supplemental LED lighting (41-180 μmol m^{-2} s^{-1} PPFD) accelerates bud formation	(33)
Jasmine (*Jasminum sambac*)	Bushy, spreading canopy; influenced by planting density and pruning regime	Modified planting systems and pruning schedule to optimize canopy spread & yield	(34)
Chrysanthemum (*Chrysanthemum morifolium*)	Dense, multi-branch canopy affected by light quality; diffuse light enhances canopy photosynthesis compared to direct light	Pruning, strategic spacing, and manipulation of light conditions to improve light use	(35)

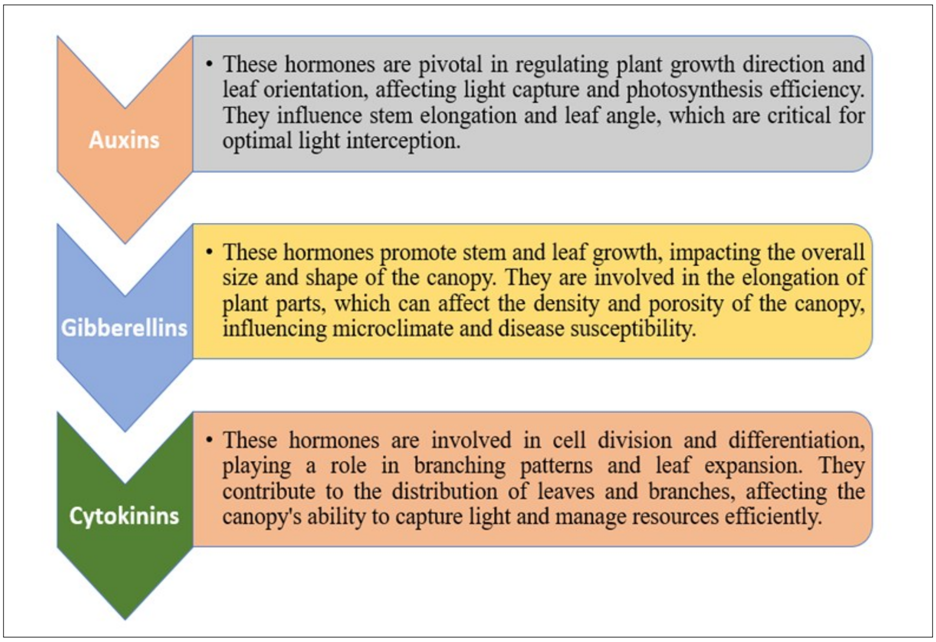

Fig. 2. Role of plant hormones-auxins, gibberellins, and cytokinins -in regulating canopy structure through influence on leaf orientation, shoot elongation, branching and leaf expansion. These hormones modulate microclimate and resource distribution within the canopy.

the size of the plant, promote branching and encourage flower bud growth (48). This is especially helpful for flowering plants like roses and chrysanthemums, where proper pruning helps create a well-organized canopy for timed blooming. Different pruning methods includes, such as heading back, which cuts the main shoot to encourage side branching and create a fuller canopy with more places for flowers to grow (49).

Thinning, which removes weak or extra shoots to improve light flow and air movement, reducing the risk of fungal diseases (50). Pinching, which is the removal of the top bud to stop the top growth from dominating, encouraging side branching and coordinated blooming (51). In addition to pruning, training is another important canopy manipulation method that shapes plant growth for better light absorption and less shading. Techniques like espalier training, often used in decorative plants, create a flat two-dimensional canopy to enhance light utilization. Fan training, which promotes side growth and ensures flowers are evenly spread and support-based training, useful for climbing plants like jasmine and clematis, where guiding stems onto structures makes better use of space and improves flower visibility. Complementing pruning and training, trellising is a useful method for supporting taller or vine-like flowering plants, such as orchids and lilies (52). These techniques enhance crop performance under diverse environmental conditions, as illustrated in Fig. 3. Using these canopy manipulation techniques wisely helps flower crops grow in the best possible way, boosting flower yield, improving resistance to diseases and enhancing their ability to adapt to different growing conditions.

Role of planting density and spatial arrangement in optimizing production

Planting density and spatial arrangement significantly influence canopy structure, light interception and the efficient use of resources in flower crop production systems (53). The optimal spacing varies depending on the growth habits of the crop and specific production objectives, as planting density, defined as the number of plants per unit area, directly impacts the competition for essential resources such as light, water and nutrients. High-density planting, commonly practiced in space-limited greenhouse

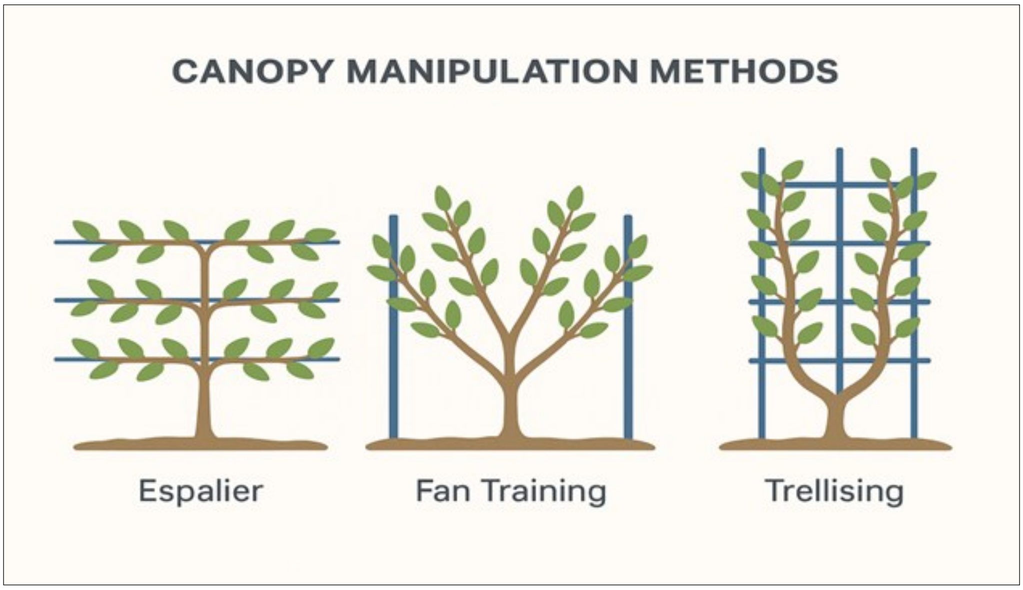

Fig. 3. Common canopy manipulation techniques used in horticulture: Espalier, fan training and trellising. These practices guide shoot orientation and enhance flower exposure, airflow and light distribution for improved plant productivity.

environments, maximizes land use but requires careful canopy management to prevent excessive shading and restricted airflow. This is particularly important for crops like chrysanthemums and marigolds, where overcrowding can lead to elongated stems (chrysanthemum) and smaller flowers (marigold) due to insufficient light exposure (54).

Conversely, low-density planting enhances light penetration and air circulation, reducing the risk of fungal diseases and promoting uniform flower growth, though it may result in underutilized land and lower total yield (55). In addition to density, plant arrangement also significantly influences canopy performance and resource distribution. Square planting, often seen in large-scale cut-flower production, ensures uniform spacing and balanced growth (56). Row planting, with adjustable spacing, facilitates easier access for pruning, watering and harvesting. Staggered planting offsets plant positions to minimize mutual shading and improve light access, supporting optimal canopy development. Ultimately, selecting the appropriate planting density and arrangement depends on factors such as crop type, cultivation environment (open field or greenhouse) and resource availability.

Water and nutrient management in relation to canopy architecture

Canopy structure plays a critical role in modulating water dynamics, nutrient transport and overall physiological balance in flower crops (57). Effective water management-especially in dense plantings-is essential for maintaining ideal canopy conditions while preventing stress and disease out breaks. Drip irrigation is especially beneficial in closely spaced flower crops, as it delivers water directly to the root zone, minimizing moisture on the foliage and reducing the risk of fungal infections (58). In contrast, sprinkler irrigation can ensure even water distribution but may increase humidity within the canopy, necessitating careful monitoring to prevent diseases such as powdery mildew and *Botrytis*. However, sprinklers are preferred in situations requiring uniform coverage over large planting areas, for seedling growth, during high-temperature periods for evaporative cooling and for the application of foliar nutrients or pesticides.

Nutrient management, plays a vital role in canopy development and sustained flowering. Nitrogen (N) encourages vigorous leafy growth and larger leaves but excessive application can result in overly dense foliage and reduce flower production, highlighting the need for balanced fertilization. Phosphorus (P) is crucial for root development and the initiation of flowering, ensuring robust bud formation. Potassium (K) regulates water movement, strengthens disease resistance and extends flower longevity by reinforcing cell walls and enhancing stress tolerance (59). In addition to soil fertilization, foliar spraying and the use of growth regulators can further enhance canopy formation and flowering responses. Integrating efficient water and nutrient management strategies with good canopy management practices enables growers to promote healthier plants, achieve enhanced flower yields and minimize environmental impacts, ultimately higher production for sustainability and efficiency.

Light interception and photosynthetic efficiency in flower crops

Light interception and photosynthetic efficiency are key determinants of growth, floral development and yield in flower crops (60). The arrangement of the plant's leaves controls the light absorbed and utilised, affects both the number and quality of flowers produced (61). In canopies with multiple layers, improving light access and spread is vital for consistent growth and flowering. For example, in *R. hybrida*, selective pruning of upper shoots enhances light penetration to lower leaves, promoting uniform bud development across the plant. Poor light management can cause shading problems that reduced photosynthesis, degrade flower quality and make plants more vulnerable to diseases as in *C. morifolium*, where dense, unthinned foliage reduces light to interior leaves, leading to smaller blooms and creating humid microclimates that favor *Botrytis* infection (62). To improve light use efficiency, several canopy modification methods like thinning, pruning and spacing changes are used to ensure even light spread and boost overall crop performance are mentioned on Fig. 4.

In flower crops, particularly those with dense foliage or complex branching patterns, efficient light penetration and uniform light distribution are critical for maximizing photosynthesis and promoting balanced growth (63). Maintaining a balanced LAI and employing targeted canopy manipulation techniques such as thinning, pruning or strategic spacing are essential to enhance light interception and ensure even physiological performance throughout the plant canopy. For instance, coffee (*Coffea arabica*) under optimal irrigation regimes exhibits LAI values ranging from approximately 3.5 to 5.3 m^2/m^2 depending on water availability, while dense, multi-layered crop canopies often reach LAI levels between 3 and 7 during peak growth stages (64). One of the key indicators of a plant's light capture efficiency is the LAI, which measures the total leaf surface area relative to ground area. While a moderate LAI enhances light interception, excessively high LAI can cause the upper leaves to overshadow lower foliage, leading to reduced photosynthetic activity in the lower canopy and resulting in uneven growth and poor flower quality. To address

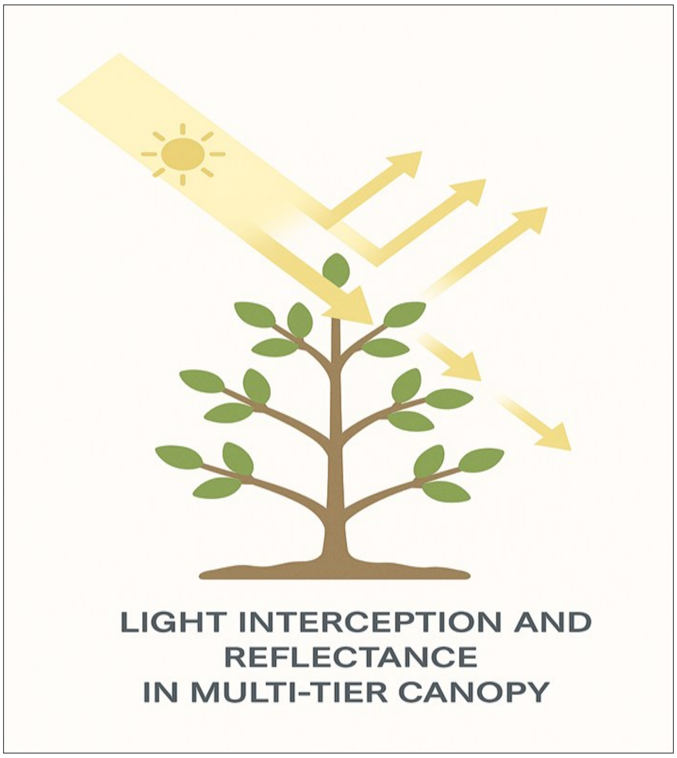

Fig. 4. Conceptual diagram showing light interception and reflectance in multi-tier canopies. Enhanced leaf layering enables deeper radiation penetration and light use efficiency, improving photosynthesis and plant development.

these challenges, maintaining a well-structured canopy through effective management practices is essential. Such strategies help to distribute light more evenly, minimize excessive shading and optimize photosynthetic efficiency across all canopy levels, ultimately leading to more uniform blooming, enhanced bud development and improved overall flower crop productivity.

Effects of shading and self-shading on flower quality and yield

Shading and self-shading significantly impact the productivity of flower crops by altering growth patterns, reducing flower quality and ultimately decreasing yield (65). Excessive shading occurs when dense foliage prevents sufficient light from reaching the lower parts of the plant, thereby limiting photosynthesis and hindering proper flower development. In light-sensitive crops such as gerberas and lilies, poor light conditions can reduce bloom size and color intensity, diminishing their market appeal (66). Additionally, shading can delay flowering by disrupting photoperiodic responses and the initiation of bloom cycles, leading to inconsistent flowering, an issue particularly problematic in crops like chrysanthemums, which require uniform light exposure for synchronized blooming. Beyond structural issues, heavy shading also creates a humid microenvironment within the canopy, which fosters the development of fungal and bacterial diseases. Compounded by poor air circulation, these environments foster pathogen outbreaks such as powdery mildew and *Botrytis*-ultimately degrading flower quality and commercial value (67).

Canopy modifications to maximize light-use efficiency

To enhance light capture and improve photosynthesis efficiency in flower crops, growers implement various canopy adjustment techniques aimed at maximizing light penetration and ensuring even distribution throughout the plant (68). One widely used method is thinning, which involves selectively removing excess branches, leaves or flower buds to reduce internal shading and allow more light to reach the lower canopy layers. This practice is particularly effective in crops such as roses and chrysanthemums, where thinning not only balances vegetative and reproductive growth but also enhances air circulation and lowers the risk of disease (69). In densely planted setups, overcrowding can lead to excessive shading and reduced photosynthetic activity. In addition, pruning and training methods are essential for shaping the canopy to optimize light distribution. For instance, strategic pruning in plants like orchids and *Hibiscus* helps prevent excessive shading and ensures that flowering sites receive adequate light. Training systems such as trellising and espalier are particularly beneficial for climbing and vining species like jasmine and passion flowers, as they enhance light exposure and flower visibility (70).

Innovative tools, including reflective mulches and LED lighting systems, further augment light distribution-especially in greenhouse setups. Reflective ground covers redirect sunlight into lower canopy zones, while LED grow lights offer customizable spectra and intensity, supporting consistent light exposure during critical phenological stages. These interventions, collectively improve photosynthetic efficiency, uniform flowering and flower quality under both field and controlled environments as illustrated in Fig. 5.

Role of canopy architecture in stress tolerance

Canopy architecture significantly contributes to the abiotic stress resilience of flower crops by influencing water use efficiency, temperature regulation and environmental adaptability (71). The way leaves, stems and branches are arranged affects how well plants save water, keep temperatures stable and handle extreme weather (72). The structure and arrangement of the plant canopy play a vital role in helping plants adapt to these challenges by regulating water use, temperature control and moisture management. For drought resistance, canopy architecture significantly affects a plant's ability to conserve water and minimize transpiration. A well-organized canopy with optimal leaf orientation reduces direct sun exposure and lowers water loss (73). Drought-tolerant species such as lavender and marigolds possess adaptive traits like smaller leaves, hairy surfaces and waxy cuticles, which help minimize moisture loss while maintaining photosynthetic activity. Deep-rooted species like roses can access subsoil moisture during prolonged dry spells. In addition, canopy thinning through selective pruning reduces leaf surface area and transpiration, further enhancing drought tolerance (74).

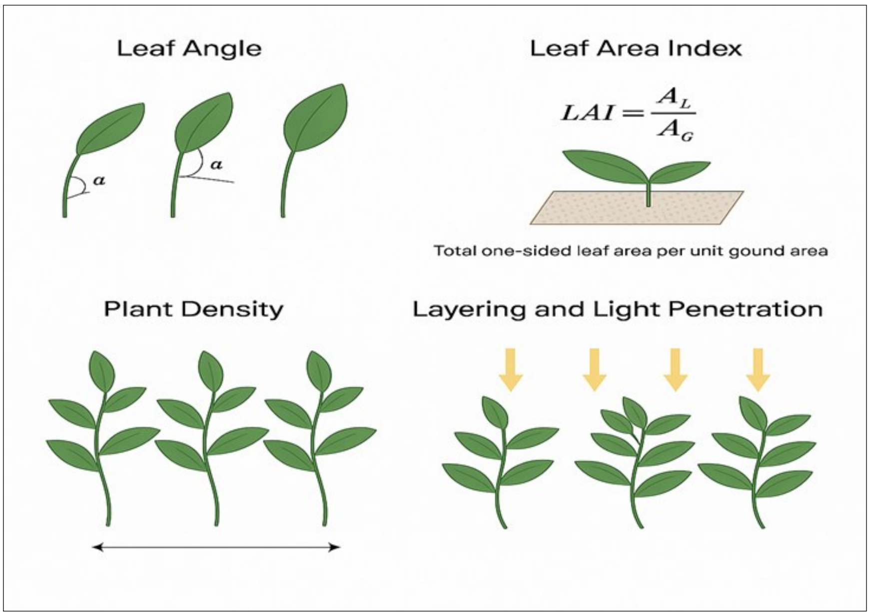

Fig. 5. Core canopy structural traits influencing light interception: leaf angle, leaf area index (LAI), plant density and layering pattern. These parameters determine the extent of photosynthetically active radiation (PAR) capture and overall canopy performance.

Canopy architecture also plays a critical role in alleviating heat stress by improving convective cooling and limiting thermal radiation absorption (75). In crops such as *Gerbera* daisies and lilies, upright leaf angles and well-spaced foliage facilitate heat dissipation, keeping canopy temperatures lower. Heat-tolerant flowers like orchids and *Hibiscus* can even reposition their leaves through nyctinastic movement to avoid intense sunlight, while species like dusty miller reflect sunlight with silvery, light-colored foliage, reducing heat absorption (76). These canopy traits enhance plant survival and aesthetic value under elevated temperature regimes.

In waterlogged or flooded conditions, plant adaptation is mediated by both canopy and root morphological traits. Aquatic ornamental species such as *Nelumbo nucifera* (lotus) and *Nymphaea* spp. (water lilies) are naturally adapted to submerged environments. Their floating leaves maintain contact with atmospheric CO_2, while internal aerenchyma tissues facilitate oxygen transport to roots under hypoxic conditions (77). By optimizing canopy structure through thoughtful design and management, growers can significantly improve flower crops' resilience to drought, heat and flooding, ensuring stable yields and high-quality blooms even under challenging environmental conditions. Thus, optimizing canopy structure through both genetic selection and cultural management is essential for enhancing flower crop resilience to abiotic stressors, securing yield stability and marketable quality under variable climatic conditions.

Adaptations of different flower crops to varying environmental conditions

Different flower crops have developed specific features and functions to handle various climate conditions, allowing them to grow well in tough environments (78). Drought-resistant flower crops like lavender (*Lavandula* spp.) have small, narrow leaves with a lot of essential oils, which decrease water loss. Marigold (*Tagetes* spp.) has a deep root system and thick outer layer to limit dehydration (79). *Bougainvillea* spp., known for its vibrant bracts, utilizes reduced leaf area and robust root architecture for enhanced drought resilience. In response to heat stress, crops like *Gerbera jamesonii* orient their leaves vertically to minimize heat interception, whereas *Helianthus annuus* (sunflower) adjusts floral orientation for optimal light capture without excessive thermal load.

Hibiscus rosa-sinensis has thick, shiny leaves that cut down on water loss and stay hydrated even when it's very hot (80). On the other hand, flood-resistant flower crops thrive in soggy conditions through special features. Lotus (*Nelumbo nucifera*) has leaves that float and a wide network of air-filled tissues, which help carry oxygen to the roots underwater. Water lily (*Nymphaea* spp.) also contains aerenchymatous tissue that facilitates oxygen transport to submerged roots. Iris (*Iris* spp.) adapts to episodic flooding through rhizomatous structures that enhance aeration and support nutrient uptake. These adaptations collectively support floral productivity and ornamental quality across varied environments.

Application of climate-resilient canopy designs in floriculture

To mitigate the effects of climate stress and enhance resilience in floriculture, climate-resilient canopy designs are increasingly being adopted (81). This includes careful changes in planting, adjustments to structures and protective growing methods. For climbing flowers, using trellises lifts plants above areas that might flood, which lowers the risk of waterlogging. Protective growing methods also help strengthen crops; shade nets protect sensitive flowers like orchids and *Anthuriums* from high temperatures, while rain shelters and raised beds safeguard moisture-sensitive plants from root damage in flood-prone spots. In arid zones, the use of drought-tolerant cultivars with deep rooting systems, such as heat-adapted *Gaillardia* or *Cosmos*, enhances water-use efficiency and ensures sustained flowering under limited irrigation (82). Through the integration of climate-smart canopy designs, floriculture systems can achieve higher resilience, sustained yields and improved ornamental quality under changing environmental conditions is illustrated in fig.6.

Role of canopy architecture in disease and pest control in flower crops

The spatial arrangement of leaves, stems and flowers shapes the canopy microclimate-affecting humidity, air movement and temperature which directly influences pest and pathogen development. The structure of a plant's canopy plays a critical

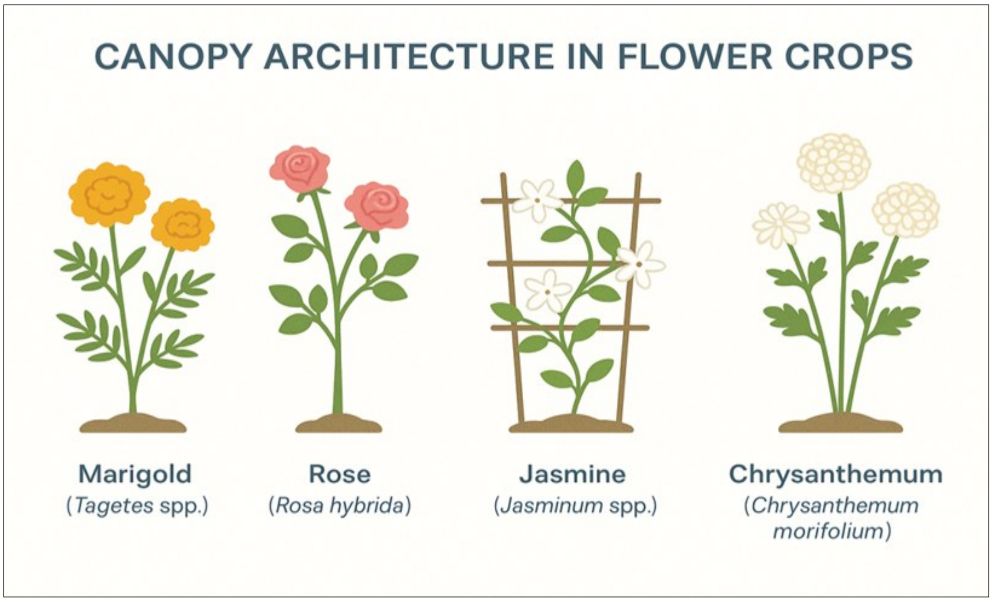

Fig. 6. Illustration of characteristic canopy architectures in ornamental flower crops such as marigold, rose, jasmine and chrysanthemum. These structural forms influence light interception, flower display and agronomic management.

role in disease and pest resistance, as it directly influences air circulation, light penetration and moisture retention. Poorly managed, dense canopies create ideal conditions for pathogens and insect pests, while well-maintained canopies help mitigate these risks (83). Adequate air flow is essential for disease prevention, as excess moisture trapped within dense foliage fosters the development of fungal and bacterial infections such as powdery mildew, *Botrytis* (gray mold) and downy mildew. For example, in crops like roses and chrysanthemums, maintaining an open canopy structure significantly lowers humidity levels, thereby reducing the incidence of fungal infections.

Light availability also plays a vital role in suppressing pathogens, since many fungal spores, such as those of *Botrytis cinerea*, thrive in shady, moist environments. Improved light exposure further suppresses spore germination. In petunias and gerberas, selective defoliation helps reduce internal humidity and fungal infection risk (84). Additionally, canopy density influences pest pressure, as crowded foliage offers shelter for insects like aphids, thrips and whiteflies, complicating pest management. Thick canopies can also obstruct insecticide coverage and interfere with the activity of natural predators. In marigolds and carnations, regular pruning minimizes pest hiding spots and helps control populations of aphids and thrips, ultimately contributing to more vigorous and resilient flower crops.

Adaptations of different flower crops to varying biotic stress conditions

Different flower species have evolved structural and physical adaptations that naturally enhance their resistance to diseases and pests, offering valuable traits for farmers seeking resilient varieties and sustainable cultivation practices. For instance, disease-resistant flowers such as roses (*Rosa* spp.) are often bred for fungal resistance and their upright growth habit combined with well-spaced leaves promotes better air circulation, reducing the likelihood of infections like black spot and powdery mildew. Chrysanthemums (*Chrysanthemum* spp.) possess thick, waxy leaves that prevent fungal spores from adhering, while certain hybrids of lilies (*Lilium* spp.) are less susceptible to *Botrytis* due to their vertical leaf arrangement, which discourages moisture accumulation. Similarly, pest-resistant flowers exhibit biochemical and physical traits that act as natural deterrents. Marigolds (*Tagetes* spp.) release allelopathic compounds that repel nematodes and insect pests, thereby reducing dependence on chemical treatments (85). Lavender (*Lavandula* spp.) contains essential oils that are toxic or repellent to aphids, spider mites and other sap-sucking insects. Petunias (*Petunia* spp.) have glandular hairs that trap small pests like thrips and whiteflies, serving as an effective physical barrier. Beyond individual species traits, overall canopy structure plays a key role in enhancing resistance. Compact or open canopies improve light penetration and air movement, which helps suppress disease development (86). These naturally occurring defense traits, supported by targeted breeding, enhance resilience and reduce dependence on chemical controls in commercial flower production.

Advances in canopy architecture research for flower crops

In the past few years, progress in canopy structure research has greatly helped in increasing the efficiency, durability and output of flower plants (87). The developments due to use of advanced technologies are transforming modern flower farming by allowing precise farming, improving genetics and supporting decision-making based on data for better canopy management. For instance, Advanced technologies such as remote sensing, which enables hyper spectral imaging for real-time mapping of canopy density and leaf area index in chrysanthemums to optimize pruning schedules; genetic modification, which accelerates the enhancement of structural traits such as leaf angle in *Gerbera* to achieve a more compact and light-efficient canopy and artificial intelligence, which integrates these datasets to predict canopy performance under varying climatic conditions and guide precision irrigation and nutrient delivery are collectively transforming canopy architecture management in floriculture.

Conclusion

Canopy design plays a crucial role in determining the growth, productivity and overall performance of flower crops. The spatial arrangement of leaves, stems and branches influences light interception, photosynthetic efficiency and the distribution of water and nutrients. These factors are key to enhancing flowering behavior and maximizing yields. An optimized canopy not only supports increased flower output but also helps regulate the microclimate around the plants and improves resilience to environmental stress, leading to higher-quality blooms and more sustainable cultivation systems. Technological advancements such as remote sensing for real-time monitoring, artificial intelligence (AI) for predictive modelling and genetic tools for structural trait optimization are revolutionizing how canopy structures are managed. Despite this progress, significant challenges remain, including the need for crop-specific canopy models, interdisciplinary research and the development of sustainable strategies tailored to various growing environments. Future research should focus on integrating technological innovations with practical horticultural methods to develop flower crops that are both high-yielding and climate-resilient. By refining canopy design, the floriculture industry can enhance production efficiency, environmental sustainability and economic viability, better meeting the demands of a rapidly evolving global market. Bridging research with field-level implementation remains essential to ensure these innovations benefit growers across diverse ecological and economic settings.

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Authors' contributions

AN took the lead in conceptualizing the review paper, identifying relevant literature, conducting critical analysis and drafting the manuscript. KI contributed to the literature search, data extraction and assisted in the preliminary interpretation of findings. RA provided overall guidance, helped refine the research framework, reviewed the manuscript critically and supported in identifying potential funding sources. RC played a key role in organizing the manuscript, summarizing core findings and revising the content to ensure academic clarity and coherence. MS contributed to the thematic structuring of the review, enhancing scientific presentation and ensuring consistency throughout the manuscript. HN contributed the overall analysis and summarizing the manuscript. All authors read and approved the manuscript.

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