Plant Gene and Trait 2026, Vol.17, No.5, 408-420
http://genbreedpublisher.com/index.php/pgt

Case Study Open Access

Canopy Management and Fruiting Regulation for High-Quality Mandarin Production

Jie Xu [1,2]

1 Huangcunqiao Village Committee, Jiangjia Town, Chun'an County, Chun'an, 311722, Zhejiang, China
2 Zhejiang Agronomist College, Hangzhou, 310021, Zhejiang, China
Corresponding email: 734746965@qq.com

Plant Gene and Trait, 2026, Vol.17, No.5 doi: 10.5376/pgt.2026.17.0029
Received: 17 Sep., 2026
Accepted: 20 Oct., 2026
Published: 27 Oct., 2026

Copyright © 2026 Xu, This is an open access article published under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Preferred citation for this article:
Xu J., 2026, Canopy management and fruiting regulation for high-quality mandarin production, Plant Gene and Trait, 17(5): 408-420 (doi: 10.5376/pgt.2026.17.0029)

Abstract This study examines recent English-language research on canopy architecture, pruning, flowering, fruit thinning, fruit quality, and orchard sensing. Mandarin studies provide the principal evidence; findings from other citrus crops are used with explicit attention to their transferability. The analysis distinguishes light interception from light distribution, carbohydrate availability from developmental signaling, and total yield from marketable production. Pruning can improve canopy renewal, but its effects depend on tree age, treatment timing, retained foliage, and subsequent crop load. Thinning can improve fruit growth, yet very low loads do not necessarily improve soluble solids or peel condition. A literature-based Satsuma case compares a greenhouse canopy-training investigation with a separate delayed-harvest crop-load experiment. Both studies support an integrated approach to canopy management and fruiting regulation. This study aims to clarify the relationships among canopy architecture, crop load, and fruit quality, provide a theoretical basis for the appropriate combination of pruning and thinning practices in mandarin production, and offer management guidance for increasing marketable fruit yield, improving fruit quality, and maintaining stable production over successive seasons.

Keywords Mandarin; Canopy management; Fruiting regulation; Light distribution; Crop load; Fruit quality; Sustainable production

1 Introduction

Mandarin production plays an important role in the global citrus industry, where growers must balance fruit yield, market quality, and the long-term productivity of their orchards. A successful harvest is not measured only by the total weight of fruit collected. Fruit size, peel color, flavor, texture, and the proportion meeting commercial standards are equally important. These characteristics vary among cultivars and growing environments, making it difficult to define fruit quality through a single measurement. Maslov Bandić et al. (2023) reported differences in fruit quality and flavonoid and carotenoid composition among Satsuma mandarin cultivars grown in the Neretva Valley. Their findings indicate that quality evaluation should consider both external appearance and internal composition. Consumer acceptance also depends on eating characteristics that may not be immediately visible. Lian et al. (2022) found that differences in the physiological and ultrastructural properties of Satsuma mandarin segment membranes were associated with inferior mastication characteristics. Such findings suggest that larger or more attractive fruit do not necessarily provide better eating quality. Orchard productivity must also be assessed over several growing seasons. Cronje et al. (2021) observed that different canopy training systems influenced yield, fruit size, and production efficiency in young 'Nadorcott' mandarin trees, with responses changing as the trees developed. Since mandarins are perennial evergreen trees, management decisions made during one production cycle may influence flowering and fruiting in the following year (Agustí et al., 2022). Sustainable production therefore requires attention to both current fruit quality and future tree performance.

Canopy management is an important component of mandarin cultivation because the arrangement of branches and leaves determines how sunlight enters the tree and how effectively the canopy supports fruit development. Dense canopies may restrict light penetration, leaving interior leaves and fruits under shaded conditions. Excessive pruning, however, can reduce the leaf area available for photosynthesis and encourage vigorous vegetative

regrowth. The objective is not simply to create an open canopy but to maintain a productive structure with suitable light distribution and sufficient foliage. Light conditions also influence fruit appearance. Lado et al. (2019) demonstrated that light regulates carotenoid biosynthesis in mandarin and sweet orange peels, although the effects of shading on chlorophyll degradation and carotenoid accumulation differ. This indicates that greater light exposure does not always produce the same improvement in peel coloration. Pruning intensity, branch distribution, and canopy renewal should therefore be adjusted according to tree vigor, developmental stage, and production conditions. Fruiting regulation is closely related to these practices because the number of developing fruits determines how strongly reproductive growth competes for available resources. A canopy with abundant foliage may support a larger crop than a weak or heavily pruned tree, but excessive fruit load can still restrict individual fruit growth and influence subsequent flowering. Coordinating canopy structure with reproductive demand is essential for maintaining stable production.

The relationship between vegetative growth and fruiting is more complex than competition for carbohydrates alone. Developing fruits require assimilates and nutrients, while shoots, roots, and developing buds also depend on resources produced or stored within the tree. Heavy fruiting may reduce the resources available for vegetative renewal and influence flowering in the following season. However, recent physiological research indicates that fruit presence can regulate reproductive development through molecular signaling mechanisms. Agustí et al. (2020) identified an association between fruit-dependent flowering inhibition and epigenetic regulation involving the floral repressor *CcMADS19* and an FT-like floral promoter. These findings suggest that reduced return flowering cannot be explained entirely by carbohydrate depletion. Tree management must account for the interaction of resource availability, shoot development, and flowering regulation. Fruit thinning can reduce competition among developing fruits and improve fruit size under suitable conditions, but excessive thinning may not consistently improve sweetness, peel condition, or overall commercial value. Similarly, pruning can improve canopy structure while reducing current photosynthetic capacity if too much productive foliage is removed. These responses depend on cultivar characteristics, tree age, environmental conditions, and treatment timing. Effective management therefore requires a coordinated approach that considers both immediate fruit development and the physiological processes supporting future production.

This study aims to examine the physiological basis and practical applications of canopy management and fruiting regulation for high-quality mandarin production. It focuses on canopy architecture, light distribution, pruning, vegetative renewal, flower bud differentiation, fruit set, crop load, and fruit quality formation, while analyzing the relationships among these processes and their effects on marketable fruit yield and production stability. Satsuma mandarin cultivation is used as a case study to examine research evidence related to canopy training and crop load management. This study seeks to further clarify how canopy structure can be coordinated with reproductive growth demands without relying on fixed pruning intensities or universal crop load targets.

2 Canopy Management in Mandarin Production

2.1 Canopy architecture and light distribution

A canopy has at least three relevant properties: its external dimensions, its amount of foliage, and the arrangement of that foliage. These should not be treated as equivalent. Tree height and crown width describe occupied space, but they cannot show whether leaves form a thin productive shell or occur throughout the crown. In greenhouse Satsuma, direct leaf area measurements were more informative for yield assessment than crown cover or indirectly estimated plant area (Yano et al., 2022). This supports measuring canopy function rather than relying exclusively on its outline.

The distinction also matters when interpreting digital measurements. Liu et al. (2021) estimated canopy parameters of ‘Longanyou’ pummelo from LiDAR point clouds. Their work demonstrates the availability of geometric descriptions, but pummelo canopy reconstruction does not itself establish the productive capacity of a mandarin tree. A dense cloud of measured points can include woody surfaces and repeatedly sampled outer foliage. Before a geometric index guides pruning, it should be calibrated against the biological variable that the decision actually requires.

For orchard assessment, a useful protocol would combine canopy dimensions with sampled leaf area, relative light availability at several depths, and the location of fruiting shoots. Repeated observations would distinguish an immediate opening effect from subsequent canopy closure. Measurements taken only above and beneath the tree would miss redistribution among intermediate layers. Similarly, one midday observation would describe conditions at that moment, not the radiation environment experienced throughout fruit development. These are measurement requirements, not an argument for maximizing every light-related index.

A more defensible objective is to reduce persistently unproductive shading while retaining enough effective foliage. The desirable arrangement should be established separately for young and mature trees, exposed and protected orchards, and contrasting scion-rootstock combinations. Canopy openness becomes useful when it improves a specified biological or operational outcome; by itself, it is neither a quality measurement nor proof of efficient production.

Interception and distribution can favor different assessments of the same canopy. A crown may capture much of the incoming radiation while concentrating it in relatively few outer leaves. Increasing the illuminated surface of interior foliage could then be more useful than increasing interception further. Conversely, extensive openings may leave radiation unused by the tree. This reasoning suggests evaluating both the fraction intercepted and its internal distribution, together with retained leaf area. The management objective is a productive arrangement, not the maximum reading from a single sensor.

2.2 Pruning practices and canopy renewal

Formative pruning establishes a manageable framework, maintenance pruning controls crowding and access, and renewal pruning replaces aging or poorly positioned bearing structures. Although these purposes overlap, they should remain explicit in experimental descriptions. Removing a competing leader is not physiologically equivalent to clipping every shoot tip, even when both operations are called moderate pruning. Treatment reports should identify the organs removed, their developmental stage, and the amount of retained canopy.

Evidence from young ‘Nadorcott’ trees illustrates the importance of this detail. Cronje et al. (2021) compared pyramid-shaped, open-center, and minimally pruned trees; shaped trees initially carried less yield but produced larger fruit, and responses changed as the orchard aged. In another ‘Nadorcott’ investigation, mechanical pruning moderated alternate bearing over multiple seasons (Mesejo et al., 2020). These results are compatible rather than contradictory: one concerns early canopy construction, whereas the other concerns repeated intervention in an established reproductive cycle.

Commercial feasibility introduces another layer. Fonte et al. (2022) evaluated mechanical pruning of ‘Clemenules’ over four years and incorporated economic analysis. Their findings show why pruning expenditure cannot be considered independently of fruit value. A faster operation may be useful, but lower labor cost does not guarantee the highest net return when yield and commercial grades also change. Mechanical and selective manual operations should therefore be compared as production strategies rather than merely as alternative cutting tools.

The practical interpretation is conditional. A pruning plan should state whether it seeks to restore access, renew bearing wood, or moderate reproductive demand. It should also specify how success will be assessed after regrowth and at harvest. Recording removed leaf area or biomass alongside retained bearing shoots would make pruning intensity more comparable across orchards. Such reporting would prevent a percentage reduction in shoot length from being mistaken for the same percentage reduction in whole-tree photosynthetic capacity.

The multiyear ‘Nadorcott’ result also helps separate regulation from restoration. Mesejo et al. (2020) reported a cumulative yield advantage under their repeated mechanical-pruning treatment, showing that removal of reproductive structures need not translate into a lasting production loss. The result should not be generalized to severe crown reduction. Its relevance is that an intervention can be evaluated over the complete response period, including the following crop, rather than judged from the immediately removed material. This temporal accounting is especially important when comparing systems intended to moderate alternate bearing.

2.3 Vegetative growth and canopy productivity

Canopy renewal has a developmental role beyond replacing lost leaves. Mesejo et al. (2022) demonstrated that reversal of fruit-dependent flowering inhibition involved the emergence of shoots from buds carrying an epigenetically silenced *CcMADS19* state. The new shoot was therefore not simply additional photosynthetic surface; it formed part of the pathway through which subsequent flowering competence was restored. This finding provides a mechanistic reason to preserve appropriate renewal growth while regulating excessive crop demand.

It does not follow that all vigorous shoots should be retained. The useful distinction is between growth that can contribute to the intended bearing framework and growth that compromises that framework. A proposed assessment would record shoot origin, age, position, and later reproductive fate rather than classify vigor from shoot length alone. Where seasonal flushes overlap, sampling should follow identified shoot cohorts. Otherwise, an apparent treatment effect on leaf chemistry may reflect different leaf ages rather than altered whole-tree nutritional status.

Leaf measurements also require careful scaling. Keeley et al. (2022), working with huanglongbing-affected citrus, examined acclimation at leaf and shoot levels. Their study illustrates why physiological performance per unit leaf area and performance of the entire shoot are different quantities. A healthy-looking or highly active sampled leaf cannot establish that a diminished canopy supplies sufficient carbon. Disease-affected trees additionally require separate interpretation; pruning evidence from healthy trees should not be transferred to them without assessing canopy loss and tree condition.

For productive canopy management, retained foliage and renewal shoots should be assessed together. The former supports current function, whereas the latter represents potential future structure. An intervention that improves access today but leaves little suitable renewal growth should not be judged successful solely from harvest convenience. Conversely, abundant new shoots are not sufficient evidence of improved productivity until their contribution to flowering, fruit retention, and marketable production has been established.

Reserve measurements need equally careful interpretation. In the disease context examined by Keeley et al. (2022), starch accumulation accompanied impaired carbohydrate export; high leaf starch was therefore not a simple sign of abundant usable reserves. For management studies, the implication is to measure reserve status alongside tissue age, growth, and transport-related symptoms. One measurement from a selected leaf cannot distinguish successful replenishment from restricted utilization. Repeated sampling of defined tissues would provide a more informative picture of whether postharvest management is restoring capacity or merely changing where carbohydrates accumulate.

3 Fruiting Regulation and Fruit Development

3.1 Flower bud differentiation and flowering regulation

Flower induction, floral differentiation, bud emergence, and anthesis describe different stages and should not be used interchangeably. Induction concerns the acquisition of reproductive competence; differentiation concerns the development of recognizable floral structures. Environmental conditions and endogenous signals influence these stages, but the relevant timing differs among production systems. The recent synthesis by Agustí et al. (2022) emphasizes the interaction of temperature, water status, fruit presence, and flowering-gene activity in citrus. A calendar date is therefore less informative than the developmental stage at which a treatment acts.

Rootstock identity adds a genetic component. Bennici et al. (2021) found differences in floral induction and *CiFT* expression between rootstocks supporting ‘Tarocco Scirè’ sweet orange. This is not a direct demonstration of equivalent responses in mandarins, but it establishes that flowering cannot always be interpreted from the scion or orchard weather alone. In breeding-oriented trials, rootstock should be treated as an experimental factor rather than an incidental description, especially where tree vigor and flowering intensity are major outcomes.

Water status and growth regulators can alter flowering through stage-specific responses. Tang and Lovatt (2022) found that water deficit followed by re-irrigation increased inflorescence production in ‘Washington’ navel orange.

Gibberellic acid inhibited floral development and prevented the increase in *AP1*, *AP2*, and downstream floral-organ-identity transcripts, without suppressing the measured bud expression of *FT*, *SOC1*, or *LFY*. This result cautions against assuming that every inhibition of flowering operates through the same upstream gene. It also distinguishes induction from later developmental commitment. The experiment informs physiological interpretation, but does not establish a drought or chemical-treatment program for mandarin orchards.

Management should consequently begin by diagnosing whether the problem is insufficient inductive conditions, limited suitable shoots, excessive flowering, or fruit-associated inhibition. These conditions demand different responses. A proposed monitoring scheme would combine previous crop history with shoot maturity and observed bud development. Treatments could then be evaluated against the identified limitation instead of being described broadly as flower promotion or flower control.

For alternate-bearing trees, return flowering is a developmental outcome rather than a direct assay of stored sugar. The epigenetic evidence of Agustí et al. (2020) links fruit presence with activation of a floral repressor in nearby leaves. This local relationship helps explain why apparently similar branches may differ in later reproductive behavior. A useful extension would compare the flowering fate of identified fruiting and nonfruiting shoots within each treatment. Whole-tree flower totals alone could conceal that spatial pattern and encourage an overly uniform prescription for branches with different histories.

3.2 Fruit set and crop load regulation

Fruit set establishes the initial reproductive population, but a useful load estimate must describe the number of fruit retained at a stated developmental stage. Initial flower counts, recently set fruit, and the population remaining after natural drop answer different questions. For management comparisons, the starting population and subsequent losses should therefore be reported separately. Without that information, a nominal thinning percentage does not reveal the final demand imposed on the tree.

There is direct evidence that thinning can improve commercial outcomes. Khurshid and Sanderson (2023) reported improved fruit size, yield, and return flowering following thinning in ‘Washington Navel’ orange. The results support the broader importance of load regulation but should not supply a numerical target for Satsuma, because crop identity and production conditions differ. A transferable principle is to evaluate the retained crop and the following bloom together, not to copy an absolute fruit count across trees of different capacities.

The method of removal also matters. In ‘Clemenrubi’ mandarin, Ortiz et al. (2020) tested a branch shaker over three years. Mechanical thinning increased work rate and produced a fruit-size response comparable to manual thinning, but it did not selectively remove fruit according to size. This distinction changes the management question: mechanical removal can reduce a population efficiently, whereas selective hand thinning can also reshape its quality distribution. Their labor requirements and objectives are therefore not identical.

A defensible local thinning program would record fruit number relative to canopy capacity and retain information about branch-level clustering. The same total population may be concentrated on a few shoots or distributed widely. Sampling both scales would help distinguish whole-tree overload from local crowding. The decision should then be checked after thinning, rather than inferred from time spent or fruit collected on the ground. Such verification makes the intervention reproducible and permits its costs to be compared with the commercial response.

Timing also needs an explicit developmental interpretation. The thinning study of Khurshid and Sanderson (2023) discusses fruit growth in relation to early cell division and subsequent enlargement. An early removal changes competition over a longer remaining growth period than a late removal, but this alone does not establish the best commercial timing. The decision must also account for the uncertainty of subsequent retention and the cost of removing fruit that might otherwise be lost naturally. Trials comparing dates should therefore assess both final crop response and the work required to achieve it.

3.3 Crop load and fruit quality formation

Quality responses to load are not necessarily monotonic. In protected, delayed-harvest Satsuma, Xu et al. (2021) found that very low whole-tree loads were not favorable for soluble-solids accumulation and were associated with greater puffiness. This result cautions against describing heavy thinning as an automatic route to sweeter, better fruit. The crop must be interpreted in relation to harvest timing and peel condition, not through fruit number alone.

Management outside thinning can also modify the apparent relationship. Hofman et al. (2024) examined irrigation and winter nitrogen in 'Imperial' mandarin and found that granulation responses depended on seasonal conditions. Elmenofy et al. (2023) studied deficit irrigation together with anti-stressor treatments in 'Murcott'. These studies show that water and nutrient context belong in the interpretation of quality outcomes. They do not justify assuming that any observed difference in soluble solids was caused solely by crop load or that water restriction is universally beneficial.

Peel integrity deserves separate attention. Li et al. (2025) investigated Satsuma cracking through developmental, anatomical, and management observations. Pervaiz et al. (2023) compared metabolic characteristics associated with preharvest rind disorder in 'Owari' Satsuma. Neither study establishes a general pruning treatment for preventing all peel disorders. Together, they support a broader quality assessment in which sugar measurements are accompanied by clearly diagnosed defects rather than a single category of unmarketable fruit.

For evaluating load treatments, soluble solids and titratable acidity should be retained as separate measurements alongside their ratio. A ratio alone cannot identify which component changed. Fruit mass, size distribution, peel condition, and harvest maturity should also be reported. These distinctions allow a treatment that increases average fruit size but worsens another commercial trait to be recognized as a trade-off rather than classified unconditionally as quality improvement.

Another interpretive problem is the difference between concentration and amount. A higher concentration of soluble solids may reflect altered water content as well as additional accumulation of dissolved material. Where the objective is to explain carbon allocation, paired measurements of fruit mass, dry matter, and relevant compounds would be more informative than concentration alone. The same logic applies to apparent nutritional dilution in larger fruit. These are analytical distinctions: they do not assume that any particular thinning or irrigation treatment caused the effect, but identify what would need to be measured to establish it.

4 Integrated Effects of Canopy Management and Fruiting Regulation

4.1 Interactions between canopy structure and fruit distribution

Within-tree position creates a useful link between canopy structure and fruit quality. Adhikari et al. (2020) compared canopy positions and harvest dates in 'Imperial' mandarin and found differences in color and quality characteristics. The evidence supports spatially stratified sampling: fruit collected only from accessible outer branches cannot adequately characterize the whole crop. It does not establish that position itself is the causal treatment, since position also represents differences in light exposure and local growth conditions.

A proposed sampling design would divide trees into consistent height and depth zones, record the fruit population in each, and weight quality measurements by that population. This would separate a change within a zone from a change in the proportion of fruit occupying favorable zones. For example, an improved whole-tree mean after pruning could arise from redistribution rather than improved performance of every retained fruit. Both outcomes may be useful, but they imply different mechanisms and different expectations for subsequent seasons.

Image-based methods offer ways to describe fruit distribution. Hou et al. (2022) combined improved object detection with binocular vision to localize citrus fruit. Such information could be aligned with canopy structure to identify concentrations of visible fruit. However, a spatial map of detected fruit should be validated against field counts before it is interpreted as a complete map of crop demand. Hidden fruit and overlapping branches remain biological features that an algorithm must handle, not quantities that can simply be assumed absent.

The integration proposed here is measurement-led: establish where productive foliage and fruit occur, identify the zones that limit quality or access, and select the least disruptive intervention consistent with that diagnosis.

Blanket opening of the crown is not the only possible response. Redistribution of bearing shoots, selective removal of clustered fruit, or a revised harvest sequence may address different parts of the same spatial problem.

Exposure also has a protective dimension. The Satsuma sunburn study provides evidence that peel injury involves more than superficial discoloration, including damage to rind structures (Kim et al., 2022). On that basis, a proposed opening treatment should include inspection of newly exposed fruit rather than assess only the improvement in canopy light readings. Where excessive exposure becomes the limiting factor, retaining strategic foliage may be preferable to further opening. Such conditional retention is consistent with quality-oriented management and should not be mistaken for failure to prune sufficiently.

4.2 Coordination of vegetative and reproductive growth

Source-sink coordination is often reduced to competition between leaves and fruit, but roots and growing shoots must remain within the analysis. Silva et al. (2021), using carbon tracing in citrus under water deficit, showed that rootstock identity influenced sink strength and carbon allocation. Their work involved sweet orange-rootstock combinations rather than a mature mandarin thinning trial. Nevertheless, it demonstrates why belowground demand cannot be represented adequately by a fixed residual share after fruit requirements are satisfied.

Developmental signaling provides another connection. Haim et al. (2021) linked fruit presence with polar auxin transport in citrus and olive stems and restricted auxin release from buds. Together with the flowering studies discussed earlier, this evidence supports a model in which reproductive demand and shoot behavior are connected through both resource allocation and signaling. An adequate leaf count does not, by itself, reveal whether buds are able to grow or respond to inductive conditions.

Integrated treatments can also create competing outcomes. Ahmadpoor et al. (2022) examined pruning and girdling in ‘Kinnow’ and reported increased fruit number with reduced individual fruit weight. Their results illustrate why stronger reproduction is not synonymous with better fruit quality. Girdling should not be treated as a routine substitute for a balanced canopy, and this review does not derive an application protocol from that experiment. The relevant point is that changing allocation can alter several yield components in opposing directions.

A working management model should therefore track three quantities separately: functional foliage, the current fruit population, and the condition of renewal shoots. These are proposed decision variables rather than a validated universal index. Their joint use would help reveal whether an intervention relieves reproductive pressure while preserving future capacity, or merely shifts the limitation elsewhere. The aim is not to eliminate competition, which is intrinsic to a growing tree, but to prevent one seasonal demand from undermining the production objectives of another.

From an orchard management perspective, this framework suggests evaluating production stability rather than focusing solely on maximum vegetative vigor or fruit number. Trees that maintain productive canopy structures with fewer corrective pruning operations may offer practical advantages in terms of labor efficiency and long-term productivity. Similarly, responses to fruit thinning should be evaluated within specific cultivar–rootstock combinations. These considerations emphasize the importance of developing management strategies that balance vegetative growth, reproductive demand, and production stability over successive seasons.

4.3 Integrated management for yield and quality improvement

Integration requires a sequence of decisions rather than simultaneous application of every available practice. A useful proposed sequence begins with structural assessment and crop history, continues with selective canopy adjustment, and then revises fruit load after the retained framework is known. This avoids setting a load target against foliage that will subsequently be removed. The sequence should remain flexible where local phenology or harvest timing requires a different order.

Digital counting could support the reassessment stage. Lyu et al. (2022) developed detection and counting methods for green citrus using an edge-computing system. Zhang et al. (2022) combined in-field citrus detection

with tracking, addressing repeated observations of fruit in image sequences. These contributions are relevant to measurement, not direct proof that algorithm-guided thinning improves marketable yield. A production decision additionally requires information about the relationship between visible counts, total load, tree capacity, and the intended commercial grade.

Operational evaluation should combine measured fruit outcomes with a transparent budget. Pruning, thinning, repeated inspection, and additional harvest passes all require labor. The economic analysis by Fonte et al. (2022) reinforces the need to judge management through returns rather than cutting cost alone. For integrated programs, the proposed comparison should include cumulative saleable production and treatment expenditure over successive seasons. A one-year improvement could otherwise obscure a delayed production penalty or an establishment cost that changes the ranking of systems.

The appropriate claim for present practice is therefore conditional coordination. Canopy and load decisions should share a common assessment of tree condition, but the benefit of their interaction must still be tested. A combined treatment that outperforms an untreated control does not demonstrate synergy unless its component treatments are also included. This distinction is essential for identifying whether additional complexity provides a genuine advantage or whether a simpler intervention would achieve the same result.

Economic reporting should preserve the distribution of fruit among saleable grades. Total revenue is the sum of the quantity sold in each grade multiplied by its realized price; management cost must then be deducted on a comparable area and time basis. An increase in mean fruit weight can raise or lower that revenue depending on where fruit move within the grading schedule. A transparent analysis would therefore present the observed grade distribution and evaluate alternative price assumptions, rather than insert one favorable price that makes the preferred treatment appear superior.

5 Case Analysis: Integrated Canopy and Crop Load Management in Satsuma Mandarin Orchards

5.1 Case background and production challenges

This case is a comparative analysis of independent publications, not an account of one orchard receiving a complete integrated treatment. Yano et al. (2022) investigated ‘Miyagawa wase’ Satsuma on trifoliate orange in Japanese greenhouses, comparing canopy characteristics and training systems. Xu et al. (2021) studied four-year-old ‘Oita wase’ on trifoliate orange under protected delayed-harvest cultivation in Shanghai during 2019–2020. Both concern Satsuma mandarin (*Citrus unshiu*), but their cultivars, management calendars, and experimental questions differ.

The comparison is useful precisely because it connects questions that are often separated. The canopy study asks how a productive structure can be described and maintained. The load study asks how the fruit population influences late-season quality. A grower ultimately needs both answers, yet neither answer can replace the other. Evidence for a productive training system does not determine the appropriate fruit population for a different cultivar or harvest schedule.

For analytical consistency, the case treats yield formation and quality preservation as distinct objectives. The first requires information about productive canopy capacity; the second requires information about the condition and maturity of retained fruit. Environmental conditions, cultivation history, and harvest timing limit the direct comparability of their findings. No numerical results are pooled across the two studies. Their findings instead define testable management questions: whether canopy capacity can help set a local load range, and whether that range remains suitable when fruit are retained beyond the usual commercial harvest.

Harvest timing is a particularly important boundary. The Japanese system produced an early, summer-harvested crop, whereas the Shanghai experiment deliberately extended fruit retention into late maturity. Protected cultivation therefore does not make their seasonal demands equivalent (Xu et al., 2021; Yano et al., 2022). For an integrated comparison, management should be indexed relative to flowering, major fruit drop, harvest, and

renewal growth. This would allow the biological timing of interventions to be compared without treating dates from unlike cropping calendars as interchangeable. It would also clarify whether a proposed intervention acts during fruit growth or after crop removal.

5.2 Canopy and fruiting management practices

The Japanese investigation compared modified-open-center and multi-leader trellis training and included long-term observations of the experimental plantings (Yano et al., 2022). The Shanghai experiment contrasted 120 fruit per tree with low loads of 20 or 30 fruit and also examined differences among fruit-bearing branches (Xu et al., 2021). These numbers describe the original experiment; they are not recommended loads for other orchards.

The treatments act at different scales. Training changes the arrangement of bearing structures over years, whereas fruit removal changes the reproductive population within a season. Their integration would require reassessing the retained crop after structural changes, rather than applying a thinning level independently of the canopy. This is a proposed extension of the evidence, not a treatment combination tested in either publication.

A suitable follow-up design would compare locally relevant canopy treatments at several crop loads within the same cultivar-rootstock system. Initial tree condition and previous yield should be balanced among treatments, with untreated or conventional management retained as a reference. Measurements should distinguish the immediate loss of foliage from later canopy recovery. Fruit number should be checked repeatedly because the imposed treatment and the eventual harvest population may differ.

The experimental unit should also remain explicit. Multiple sampled fruit improve description of a tree, but do not create additional independent trees. Quality sampling should cover canopy positions and use a predefined maturity criterion. These design safeguards would make a future integrated comparison more informative than merely collecting additional fruit from a small number of contrasting trees.

5.3 Effects on fruit yield and quality

In the canopy study, trellis-trained trees had greater productivity during the earlier production period, and direct leaf area index was the strongest of the evaluated canopy indices for explaining yield (Yano et al., 2022). In the delayed-harvest study, very low whole-tree loads did not consistently favor soluble-solids accumulation and increased puffiness risk (Xu et al., 2021). The shared implication is not that high load is always preferable, but that canopy capacity and fruit quality require separate measurements.

Peel color needs particularly careful interpretation. Mitalo et al. (2022) examined low-temperature-associated degreening in Satsuma through physiological and transcriptomic analyses. Their findings mean that color changes near harvest cannot simply be attributed to canopy exposure or load. Conversely, Kim et al. (2022) documented anatomical damage and altered physiological characteristics in sunburned Satsuma fruit. An exposed fruit can therefore differ in color because of desirable development or injury, and visual scoring should distinguish these outcomes.

For assessing the integrated proposition, average fruit mass would be insufficient. A complete evaluation would need the size distribution, soluble solids, acidity, peel defects, saleable proportion, and harvest timing, together with the subsequent flowering response. Neither selected study supplies every part of this combined assessment. The missing measurements should be identified as gaps rather than filled by assumptions from a different cultivar.

The case consequently supports a restrained interpretation of quality improvement. It is possible for an intervention to improve one component while leaving another unchanged or reducing commercial acceptability. Reporting those components separately would allow growers to choose according to their market, rather than accepting a single composite label whose biological and economic meaning remains unclear.

5.4 Case implications and practical applications

The most useful inference is that thinning targets should follow a diagnosis of productive canopy capacity, while their success should be judged against the intended harvest conditions. This is more informative than applying a

fixed number to trees that differ in foliage, age, or structural development. It also avoids using the largest fruit as the sole indicator that the intervention worked.

For an orchard considering change, a limited comparison with current practice would provide a safer learning process than immediate whole-orchard conversion. The proposed comparison should preserve cultivar, rootstock, and harvest criteria while changing a clearly defined management factor. Observations should include labor time and fruit rejected for named defects. Continuing into the following season would reveal whether an apparent gain depended on sacrificing return bloom or renewal growth (Figure 1).

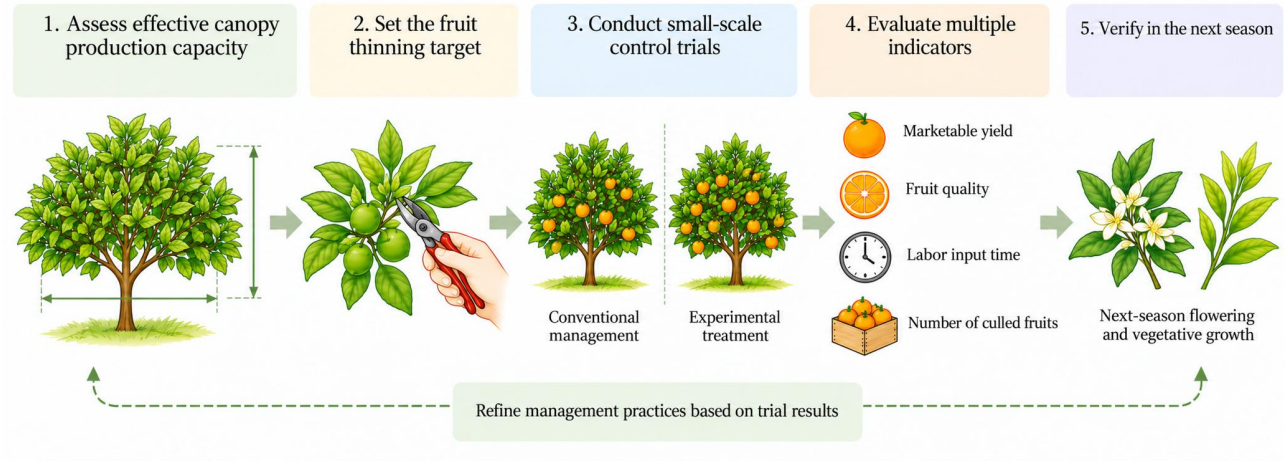


Figure 1 Schematic framework for evaluating canopy management and fruit thinning strategies in mandarin orchards
Image caption: The proposed framework consists of five steps: (1) Assessing effective canopy production capacity to determine the tree's ability to support fruit development; (2) Setting fruit thinning targets based on canopy condition and production requirements; (3) Conducting small-scale controlled trials to compare conventional management with experimental treatments; (4) Evaluating multiple indicators, including marketable yield, fruit quality, labor input time, and the number of culled fruits; and (5) Assessing flowering and vegetative growth in the following production season to identify potential carryover effects. Trial results can inform further adjustments to management practices. This framework represents a proposed evaluation approach rather than a universally validated management protocol.

The separate physiological studies also suggest where additional measurements could be useful. Pervaiz et al. (2023) linked Satsuma rind disorder with metabolic differences, while Lian et al. (2022) investigated segment-membrane properties relevant to mastication. These findings do not prove that canopy or load adjustment corrects those problems. They identify quality dimensions that a future integrated experiment could measure rather than presume to improve.

Transfer to other mandarins should retain this experimental discipline. A canopy form is not portable independently of tree vigor and orchard access, and a load target is not portable independently of maturity and the commercial size requirement. The case offers a framework for adaptation, not a finished universal package. Its main contribution is to make the missing link explicit: the interaction between canopy treatment and crop load still needs direct testing under shared conditions.

6 Challenges and Future Perspectives

6.1 Limitations of current management practices

A persistent difficulty is the mismatch between treatment descriptions and biological effects. Terms such as light pruning or moderate thinning are easy to communicate but difficult to compare when retained foliage, starting crop, and tree size are omitted. Future studies should describe interventions in operational and biological terms, allowing another orchard to reproduce the treatment rather than merely its name.

Another limitation is the narrow evaluation period. One harvest can reveal an immediate response but cannot establish stable production. Trials should retain information on previous crop history and continue long enough to assess carryover effects. Economic outcomes deserve the same continuity. An intervention should not be

recommended from improved fruit size without determining whether saleable production and net returns improved. Reporting labor constraints would also help distinguish a biologically promising treatment from one that cannot be implemented reliably at commercial scale.

Common reporting templates would make this evidence easier to reuse. At minimum, they should connect tree identity, treatment history, sampling position, and harvest outcomes. Clear definitions would be more valuable than adding numerous measurements whose biological relationship to the management decision is unspecified.

6.2 Precision technologies for canopy and fruiting management

Precision management should be organized around the decision it supports. A grower deciding which trees need thinning requires a trustworthy load estimate and an interpretable threshold, not simply a visually impressive reconstruction. Systems should report uncertainty, identify poorly observed canopy regions, and allow field checks where predictions are least reliable.

Development priorities should include combining canopy geometry with functional measurements and connecting fruit counts with size distributions. Calibration must extend across cultivars, growth stages, and contrasting orchard conditions. A practical system should also tolerate missing observations and remain useful when imaging conditions are imperfect. The relevant test is whether sensor-assisted decisions outperform a feasible conventional assessment after equipment, labor, and correction costs are included. Automation should simplify a justified management decision rather than make an uncertain recommendation appear more precise than it is.

6.3 Future research priorities

The central experimental priority is a multiyear factorial comparison of canopy management and crop load. Such studies should distinguish component effects from interactions and include enough independent trees or plots to support the intended inference. Quality assessment should combine commercial grading with eating characteristics and clearly classified physiological disorders. Publication of unsuccessful or neutral treatments would improve interpretation of the conditions under which intervention is unnecessary.

Breeding programs could complement this work by evaluating architecture, renewal behavior, and fruit-quality stability under contrasting loads. Scion and rootstock selection should be examined together rather than assuming that a desirable genotype performs similarly under every management system. Environmental evaluation should accompany this effort, including water use, input requirements, and the resources consumed per unit of saleable fruit. The desired outcome is a locally adaptable production strategy whose benefits remain visible beyond the single season in which it was developed.

A coordinated research network could use shared core measurements while retaining locally appropriate treatments. This would preserve regional relevance without sacrificing comparability. Rather than seeking one global optimum, the network could identify which decision rules remain reliable across environments and which require recalibration. Such distinctions would help translate experimental results into transparent recommendations with stated limits of application.

7 Conclusions

High-quality mandarin production requires coordination of canopy capacity, fruit demand, and future bearing potential. These elements are connected, but they should not be collapsed into a single proxy. Canopy volume cannot fully describe productive foliage, fruit number cannot fully describe reproductive demand, and soluble solids cannot fully describe eating or commercial quality. Keeping these distinctions visible improves both research interpretation and orchard decision-making.

Pruning and thinning are useful because they alter different parts of the production system. Their benefits depend on what is removed, what remains, and when the intervention occurs. The evidence does not support the assumption that greater canopy openness or lower fruit load is always preferable. Nor does success of the component practices prove that their combination produces an additional benefit.

The Satsuma case illustrates a productive way to use incomplete but complementary evidence. Canopy research informs assessment of productive structure, while crop-load research identifies quality responses that may otherwise be overlooked. Their integration is a plausible management proposition requiring direct testing, not an already demonstrated universal protocol. Future progress should therefore prioritize cultivar-specific, multiyear experiments and measurement systems that connect tree condition with commercial outcomes. The practical objective is a crop that meets quality requirements repeatedly, at an acceptable cost, while maintaining the tree's capacity to produce it again.

For immediate interpretation, the most defensible rule is to diagnose before intervening and verify after intervening. The retained canopy, the adjusted fruit population, and the harvested quality distribution should tell a consistent story. When they do not, the discrepancy is useful evidence: it identifies an unmeasured constraint or an incorrect assumption. Management improves when such discrepancies guide the next comparison, rather than being hidden by a favorable average or a general claim of better tree balance.

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.

References

Adhikari P., Singh Z., Tokala V.Y., Kyaw P.N., and Walsh B., 2020, Fruit canopy position and harvest date influence on colour and quality of Imperial mandarin (*Citrus reticulata* Blanco), Australian Journal of Crop Science, 14(4): 660-666.
https://doi.org/10.21475/ajcs.20.14.04.p2304

Agustí M., Mesejo C., Muñoz-Fambuena N., Vera-Sirera F., de Lucas M., Martínez-Fuentes A., Reig C., Iglesias D.J., Primo-Millo E., and Blázquez M.A., 2020, Fruit-dependent epigenetic regulation of flowering in *Citrus*, New Phytologist, 225(1): 376-384.
https://doi.org/10.1111/nph.16044

Agustí M., Reig C., Martínez-Fuentes A., and Mesejo C., 2022, Advances in citrus flowering: A review, Frontiers in Plant Science, 13: 868831.
https://doi.org/10.3389/fpls.2022.868831

Ahmadpoor A., Salari M., and Miri S.M., 2022, Pruning and girdling influence alternative bearing of 'Kinnow' mandarin (*Citrus reticulate* Blanco), Journal of Horticulture and Postharvest Research, 5(1): 13-20.

Bennici S., Las Casas G., Distefano G., Gentile A., Lana G., Di Guardo M., Nicolosi E., La Malfa S., and Continella A., 2021, Rootstock affects floral induction in *Citrus* engaging the expression of the *FLOWERING LOCUS T* (*CiFT*), Agriculture, 11(2): 140.
https://doi.org/10.3390/agriculture11020140

Cronje R., Human C., and Ratlapane I., 2021, Pruning strategies for young 'Nadorcott' mandarin trees planted in high density orchards in South Africa, International Journal of Fruit Science, 21(1): 921-931.
https://doi.org/10.1080/15538362.2021.1940418

Elmenofy H.M., Hatterman-Valenti H.M., Hassan I.F., and Mahmoud M.M.A., 2023, Effects of deficit irrigation and anti-stressors on water productivity, and fruit quality at harvest and stored 'Murcott' mandarin, Horticulturae, 9(7): 787.
https://doi.org/10.3390/horticulturae9070787

Fonte A., Torregrosa A., Garcerá C., Mateu G., and Chueca P., 2022, Mechanical pruning of 'Clemenules' mandarins in Spain: Yield effects and economic analysis, Agronomy, 12(4): 761.
https://doi.org/10.3390/agronomy12040761

Haim D., Shalom L., Simhon Y., Shlizerman L., Kamara I., Morozov M., Albacete A., Rivero R.M., and Sadka A., 2021, Alternate bearing in fruit trees: fruit presence induces polar auxin transport in citrus and olive stem and represses IAA release from the bud, Journal of Experimental Botany, 72(7): 2450-2462.
https://doi.org/10.1093/jxb/eraa590

Hofman H.J., Toegel H., Parfitt S.C., and Smith M.W., 2024, Reduced irrigation in high rainfall years and winter application of nitrogen reduce granulation in Imperial mandarin (*Citrus reticulata* cv. Imperial), Crop & Pasture Science, 75(10): CP24019.
https://doi.org/10.1071/CP24019

Hou C., Zhang X., Tang Y., Zhuang J., Tan Z., Huang H., Chen W., Wei S., He Y., and Luo S., 2022, Detection and localization of citrus fruit based on improved You Only Look Once v5s and binocular vision in the orchard, Frontiers in Plant Science, 13: 972445.
https://doi.org/10.3389/fpls.2022.972445

Keeley M., Rowland D., and Vincent C., 2022, Citrus photosynthesis and morphology acclimate to phloem-affecting huanglongbing disease at the leaf and shoot levels, Physiologia Plantarum, 174(2): e13662.
https://doi.org/10.1111/ppl.13662

Khurshid T., and Sanderson G.P., 2023, Fruit thinning improves fruit size, yield and return flowering in 'Washington Navel' orange (*Citrus sinensis* L. Osbeck), International Journal of Fruit Science, 23(1): 246-255.
https://doi.org/10.1080/15538362.2023.2284760

Kim M., Park Y., Yun S.K., Kim S.S., Joa J., Moon Y.E., and Do G.R., 2022, The anatomical differences and physiological responses of sunburned Satsuma mandarin (*Citrus unshiu* Marc.) fruits, Plants, 11(14): 1801.
https://doi.org/10.3390/plants11141801

Lado J., Alós E., Manzi M., Cronje P.J.R., Gómez-Cadenas A., Rodrigo M.J., and Zacarías L., 2019, Light regulation of carotenoid biosynthesis in the peel of mandarin and sweet orange fruits, Frontiers in Plant Science, 10: 1288.
https://doi.org/10.3389/fpls.2019.01288

Li Y., Jin G., Wen M., Zhu X., and Zheng Y., 2025, Mechanisms and management strategies for Satsuma mandarin fruit cracking, Agronomy, 15(3): 698.
https://doi.org/10.3390/agronomy15030698

Lian X., Li F., Chang Y., Zhou T., Chen Y., Yin T., Li Y., Ye L., Jin Y., and Lu X., 2022, Physiological and ultrastructural alterations linked to intrinsic mastication inferiority of segment membranes in Satsuma mandarin (*Citrus unshiu* Marc.) fruits, Plants, 11(1): 39.
https://doi.org/10.3390/plants11010039

Liu X., Wang Y., Kang F., Yue Y., and Zheng Y., 2021, Canopy parameter estimation of *Citrus grandis* var. Longanyou based on LiDAR 3D point clouds, Remote Sensing, 13(9): 1859.
https://doi.org/10.3390/rs13091859

Lyu S., Li R., Zhao Y., Li Z., Fan R., and Liu S., 2022, Green citrus detection and counting in orchards based on YOLOv5-CS and AI edge system, Sensors, 22(2): 576.
https://doi.org/10.3390/s22020576

Maslov Bandić L., Vlahoviček-Kahlina K., Sigurnjak Bureš M., Sopko Stracenski K., Jalšenjak N., Fruk G., Antolković A.M., and Jurić S., 2023, Fruit quality of Satsuma mandarins from neretva valley and their flavonoid and carotenoid content, Horticulturae, 9(3): 383.
https://doi.org/10.3390/horticulturae9030383

Mesejo C., Martínez-Fuentes A., Reig C., Balasch S., Primo-Millo E., and Agustí M., 2020, Mechanical pruning attenuates alternate bearing in 'Nadorcott' mandarin, Scientia Horticulturae, 261: 108993.
https://doi.org/10.1016/j.scienta.2019.108993

Mesejo C., Marzal A., Martínez-Fuentes A., Reig C., de Lucas M., Iglesias D.J., Primo-Millo E., Blázquez M.A., and Agustí M., 2022, Reversion of fruit-dependent inhibition of flowering in *Citrus* requires sprouting of buds with epigenetically silenced *CcMADS19*, New Phytologist, 233(1): 526-533.
https://doi.org/10.1111/nph.17681

Mitalo O.W., Asiche W.O., Kang S.W., Ezura H., Akagi T., Kubo Y., and Ushijima K., 2022, Examining the role of low temperature in Satsuma mandarin fruit peel degreening via comparative physiological and transcriptomic analysis, Frontiers in Plant Science, 13: 918226.
https://doi.org/10.3389/fpls.2022.918226

Ortiz C., Torregrosa A., Ortí E., and Balasch S., 2020, Mechanical thinning of mandarins with a branch shaker, HortTechnology, 30(6): 745-750.
https://doi.org/10.21273/HORTTECH04451-20

Pervaiz T., Park S., Rezk A., Hur M., Obenland D., Arpaia M.L., and El-kereamy A., 2023, Metabolomic analyses provide insights into the preharvest rind disorder in Satsuma Owari Mandarin, Frontiers in Plant Science, 14: 1263354.
https://doi.org/10.3389/fpls.2023.1263354

Silva S.F., Miranda M.T., Costa V.E., Machado E.C., and Ribeiro R.V., 2021, Sink strength of citrus rootstocks under water deficit, Tree Physiology, 41(8): 1372-1383.
https://doi.org/10.1093/treephys/tpab008

Tang L., and Lovatt C.J., 2022, Effects of water-deficit stress and gibberellic acid on floral gene expression and floral determinacy in 'Washington' navel orange, Journal of the American Society for Horticultural Science, 147(4): 183-195.
https://doi.org/10.21273/JASHS05213-22

Xu F., An H., Zhang J., Xu Z., and Jiang F., 2021, Effects of fruit load on sugar/acid quality and puffiness of delayed-harvest citrus, Horticulturae, 7(7): 189.
https://doi.org/10.3390/horticulturae7070189

Yano T., Yasutake D., and Kiyosue Y., 2022, Characterization of canopy structure for high-yield performance of greenhouse-grown satsuma mandarins using direct measurements and indirect estimations, Journal of Agricultural Meteorology, 78(1): 19-30.
https://doi.org/10.2480/agrmet.D-21-00018

Zhang W., Wang J., Liu Y., Chen K., Li H., Duan Y., Wu W., Shi Y., and Guo W., 2022, Deep-learning-based in-field citrus fruit detection and tracking, Horticulture Research, 9: uhac003.
https://doi.org/10.1093/hr/uhac003

Disclaimer/Publisher's Note

The statements, opinions, and data contained in all publications are solely those of the individual authors and contributors and do not represent the views of the publishing house and/or its editors. The publisher and/or its editors disclaim all responsibility for any harm or damage to persons or property that may result from the application of ideas, methods, instructions, or products discussed in the content. Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.