

Review

Managing Citrus Canopy Growth for Higher Productivity: A Review of Plant Growth Regulator (PGR) Applications

Kare Mahmud ^{1,*}, Paul Cronje ²  and Dave Monks ¹ 

¹ New South Wales Department of Primary Industries and Regional Development, 1998 Silver City Highway, Dareton, NSW 2717, Australia; dave.monks@dpird.nsw.gov.au

² Citrus Research International (CRI), Department of Horticultural Science, Stellenbosch University, Private Bag X1, Stellenbosch 7602, South Africa; paulcronje@sun.ac.za

* Correspondence: kare.mahmud@dpird.nsw.gov.au

Highlights

What are the main findings?

- Plant growth regulators, especially GA-biosynthesis inhibitors such as paclobutrazol and uniconazole, consistently reduce citrus shoot growth and canopy expansion.
- Appropriate PGR use can maintain or improve yield efficiency while reducing pruning intensity and labour requirements.
- PGR responses vary with cultivar, rootstock, crop load, timing, dose, and environmental conditions.

What are the implications of the main findings?

- PGRs can support more efficient canopy management in high-density citrus production systems.
- Effective use requires integration with pruning, irrigation, nutrition, and regulatory requirements.

Abstract

Balancing the vegetative and reproductive developmental cycles in a citrus orchard is essential to maintain sustainability. Plant growth regulators (PGRs) offer an effective tool for managing shoot growth rate and fruit production of citrus trees. By moderating shoot elongation and reducing canopy expansion, PGRs help minimise the frequency and intensity of pruning, substantially reducing labour costs and improving orchard management. Evidence from multi-year experiments showed PGR-treated citrus trees can maintain or increase yield efficiency, producing equal or greater fruit/canopy (m³) than untreated controls. Strategic application of PGRs can moderate alternate bearing by promoting more consistent and fruitful shoots, stabilising annual yields. Economic assessments showed significant reductions in labour costs, especially when trees treated with PGRs required less hand pruning. This review synthesises historic and contemporary research and the mechanisms by which PGRs exert their effects in citrus. It identifies knowledge gaps, such as the need for long-term studies, optimal timing for different cultivars, and integrated strategies suited to different environmental conditions. Plant growth regulators could be an effective tool for stable citrus production, offering the potential for more efficient tree canopy management when used responsibly in accordance with regulatory requirements and integrated with other orchard management practices.



Academic Editors: Giulia Modica and Alberto Continella

Received: 22 July 2026

Revised: 25 August 2026

Accepted: 26 August 2026

Published: 8 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: high density; orchard management; tree architecture; vegetative and reproductive development; yield efficiency

1. Introduction

Controlling tree size and vigour is critical and challenging in citrus canopy management, especially for high-density citrus orchards aiming for commercially sustainable production. Traditionally, growers have relied on hand pruning to manage citrus tree canopies [1]. By applying light mechanical hedging annually, row access is maintained, tree height is managed for safe picking and adjacent rows are not overshadowed. This hedging is then followed by hand pruning to prevent overcrowding between trees and improve light penetration for better fruit production and quality. However, hand pruning is laborious and costly, often comprising 15–25% of total production expenditure in citrus [2,3]. Excessive vegetative growth in high-density plantings not only increases pruning frequency and associated costs [4] but can also reduce yield over time by shading fruiting wood and contributing to irregular bearing [2]. Consequently, chemical approaches to moderating citrus tree growth have received increasing attention.

Plant growth regulators (PGRs) offer an alternative approach by modifying the tree's hormonal balance. By inhibiting growth-promoting hormones, PGRs can help to reduce shoot growth rate and canopy density and direct a greater proportion of resources to reproductive organs rather than vegetative [5–7]. When appropriately applied, PGRs have multiple benefits: (a) the production of fewer water-shoots, (b) reducing tree height and canopy volume, enabling easier harvesting and potential higher-density plantings and (c) reduced pruning and training needs, and (d) reducing alternate bearing.

PGR use in citrus was first explored in the mid-20th century. Early attempts in the 1960s with compounds such as 2,3,5-triiodobenzoic acid (TIBA) and chlormequat chloride or Cycocel[®] (CCC) showed that altering hormones could influence citrus shoot growth and flowering [8]. However, practical success was limited until gibberellin (GA) biosynthesis inhibitors were developed as they provided more consistent vegetative growth control. The introduction of paclobutrazol (PBZ) in the 1980s was a turning point and it was demonstrated that soil-applied PBZ reduced citrus shoot growth and induced heavier flowering in the following bloom [9]. Another experiment in Spain [10] confirmed that PBZ could effectively reduce canopy vigour and ameliorate alternate bearing in mandarins by increasing return bloom. By the 1990s, another triazole, uniconazole (UNZ), was introduced (in Japan under the name Sunny[®]) as an even more active GA inhibitor for citrus. Subsequent evaluation of UNZ found it to be similarly effective as PBZ in reducing shoot growth and increasing subsequent flowering [11,12]. This led to the registration of UNZ formulations, Tip Plus[®] (<https://tipagri.co.za/about-tip-plus/>, accessed on 25 October 2025) and Sunny 50 SC[®] (<https://philagro.co.za>, accessed on 20 November 2025) for use in citrus to manage tree size and alternate bearing. These developments, along with research on other PGRs, including prohexadione-calcium (ProCa; Regalis[®] Plus, <https://www.agro.basf.co.za/en/Products/Overview/Plant-Growth-Regulator/Regalis-Plus.html>, accessed on 20 November 2025), which is a shorter-acting growth retardant, and hormones such as gibberellic acid (used conversely to delay fruit senescence), have expanded the orchard manager's toolkit beyond traditional pruning.

This review examines PGR use in citrus, with emphasis on those chemicals which reduce vegetative growth and, thus, pruning and labour needs, while aiming to maintain or improve yields. This review discusses the categories of PGRs relevant to citrus and their modes of action (Section 2), and their documented effects on canopy growth, flowering,

fruit set, yield, and fruit quality (Section 3). Application strategies and economic outcomes are discussed in Section 4, including optimum timing, methods (e.g., soil versus foliar application), and cost-benefit analyses. Section 5 includes other considerations such as environmental impact, residue safety, and integration with other practices. We integrate findings from both classical and recent studies, highlighting insights, identifying gaps in knowledge, and suggesting directions for future research to fully harness PGR technology in citrus production systems.

2. Categories of PGRs and Their Mode of Action

Multiple classes of PGRs (both synthetic chemicals and naturally occurring hormones) have been tested in citrus. Those most relevant to canopy size control work by restraining shoot growth are presented here. The main categories are as follows:

Gibberellin (GA)-biosynthesis inhibitors block the formation of endogenous gibberellins (GAs), the hormones that stimulate cell elongation and apical growth. Inhibiting GA synthesis results in shorter internodes and shoot length. The most widely used compounds in this class are the triazoles:

Paclobutrazol (PBZ) is very effective at inhibiting the enzyme ent-kaurene oxidase in the GA biosynthetic pathway [13]. It is typically applied as a soil drench or foliar spray. PBZ is absorbed by roots and bark and translocated via xylem. Once in the shoots, it reduces active GA levels, resulting in shorter, sturdier shoots. In Satsuma mandarin (*Citrus unshiu* Marc.), foliar application of paclobutrazol at the stage of floral bud initiation reduced GA₂₀- and GA₁₉-like activities in leaves and increased flower production, while GA₁ activity remained unaffected [14]. PBZ's effects can last many months. Residual activity in soil can suppress growth for a season or longer [5,15], which could be counterproductive in a commercial citrus orchard.

Uniconazole (UNZ), known internationally as Sunny[®], is chemically similar to PBZ and also inhibits GA formation but is about 6–10 times more active than PBZ on a weight basis, so lower doses are used. UNZ is usually applied as a foliar spray in citrus, and rates of 20–50 ppm suppressed citrus shoot growth without reducing fruit set [16,17]. UNZ tends to have shorter residual action than PBZ (several weeks to a few months), which can enable improved control through multiple small applications.

Prohexadione–calcium (ProCa), part of the cyclohexanedione chemical class, blocks later steps of GA biosynthesis (specifically the 3 β -hydroxylation of GA precursors). ProCa is usually applied as a foliar spray. It acts faster than triazoles but is also metabolised faster by the plant; its growth-inhibiting effect lasts about 3–5 weeks, so repeated applications are needed for sustained suppression [18]. In citrus, ProCa reduced flush growth, with each application reducing shoot elongation by 20–30%, and cumulative sprays can reduce flush growth by up to 50% [19]. ProCa has been used in some regions to control vigorous summer flushes [7].

Others: GA inhibitors, including older products such as CCC and daminozide (Alar), have been tested on citrus [8,20]. These compounds can suppress vegetative growth; however, their practical use has been limited because effective responses often require high application rates and are frequently inconsistent or short term; hence, they are no longer applied to citrus. CCC, for example, needed doses that sometimes caused leaf phytotoxicity and gave inconsistent results in field experiments. Its use decreased once PBZ and UNZ became available.

Ethylene-releasing compounds act against ethylene, a natural plant hormone which can inhibit vegetative growth and promote dormancy/abscission at high concentrations. Ethephon (2-chloroethyl phosphonic acid) is a compound that decomposes to release ethylene in plant tissues. In citrus, Etephon is used to induce colour development and

to loosen fruit at harvest or for thinning. At lower doses, it can temporarily slow shoot growth by inducing mild physiological stress and partial abscission of actively growing tissues [21,22]. Its effect is short term (a few weeks at most), as the plant metabolises the ethylene and resumes growth. Thus, Ethephon is not a primary canopy management tool, but it may be applied after a vigorous flush to temporarily limit subsequent shoot growth. Excessive application rates may induce unwanted leaf or fruit drop. Generally, GA inhibitors are preferred for targeted vegetative control because they act more directly on growth processes and have a longer duration.

Auxins and GAs (exogenous applications) can act paradoxically, and these hormones that normally promote growth can be used to influence partitioning between growth and fruit. Synthetic auxins such as 1-naphthaleneacetic acid (NAA), 2,4-dichlorophenoxyacetic acid (2,4-D), 2,4-dichlorophenoxypropionic acid (2,4-DP) [23] and 3,5,6-trichloro-2-pyridyloxyacetic acid (3,5,6-TPA) [24] are routinely used in citrus for fruit thinning and pre-harvest drop control rather than for reducing vegetative growth. At higher concentrations, auxins may inhibit growth by stimulating ethylene production and exhibiting herbicidal-like effects; however, this response has not been adopted as a strategy for controlling tree size. In practice, auxins are not used to dwarf citrus trees; their primary value lies in managing crop load and fruit retention [25]. To suppress unwanted trunk shoots, NAA can effectively reduce sucker growth on young citrus trees [26]. However, auxins are not a primary tool for controlling canopy size.

Gibberellic acid (GA₃) is often sprayed on citrus (especially mandarin and oranges) to delay rind ageing, reduce creasing or prevent pre-harvest fruit drop. The dose rates (5–30 ppm) are not intended to affect vegetative growth. However, GA₃ sprays can, in some cases, increase shoot elongation or delay bud differentiation (if timed in autumn and early winter, it can inhibit flowering induction) [8,27]. GA₃ is used in nurseries and on young plants to reduce flowering and increase vegetative development [6]. In the context of canopy management, GA₃ is included because it is essentially the hormonal opposite of PBZ: where PBZ suppresses GA and encourages flowering, GA₃ applications can be used to suppress flowering (managing alternate bearing by reducing an ‘on’ year bloom) or to keep leaves active for longer (for steady growth). For example, autumn GA₃ sprays have been used in Spain and Israel to reduce the return bloom in mandarins that had a light crop (to prevent an excessive ‘on’ year bloom). Thus, GA₃ can be a tool to balance vegetative and reproductive growth in an alternate bearing strategy [28], but it is not used to directly reduce pruning; rather, it defers some bloom to avoid biennial extremes.

Cytokinins, including 6-benzyladenine (6-BA) and trans-zeatin, primarily promote cell division and can break bud dormancy. These compounds have been used to stimulate shoot initiation and flushing in citrus, including in huanglongbing-affected trees with bare canopies, as part of growth-regulating treatment strategies [29], but they are not used to limit growth. Cytokinins are generally used to increase branching and, potentially, canopy density. Therefore, cytokinins are largely outside the scope of growth suppression; they are more relevant to improving fruit set or regenerating foliage in stressed trees (biological or abiotic).

In summary, the GA inhibitors have proven to be the most practical PGRs for citrus canopy size control. In particular, PBZ and UNZ are well-researched: they consistently reduce shoot growth and canopy volume while often improving flowering and yield efficiency. Ethylene-releasing ethephon can complement this by halting a vegetative flush if needed. Auxins and GA₃ play more specialised roles in fruit management but can indirectly influence growth–fruiting balance. The current proposed mode of action is via a reduction in endogenous GA levels due to PBZ and UNZ, causing a tree’s canopy to remain in a quasi-dwarf state, with shorter internodes, and the usual dominance of the shoot tip is

weakened. This often triggers more lateral buds to break, so the tree might become bushier (i.e., increased internal branch complexity), but not larger. Over a season, treated trees put on far less extension growth than untreated ones. For example, PBZ reduced the length of spring shoots in ‘Salustiana’ orange by nearly half [9], and repeated PBZ application suppressed vegetative shoot growth in Clementine mandarins over multiple seasons, shifting bud break toward reproductive rather than vegetative development [30,31]. These growth reductions are the key to requiring less pruning to remove long, vigorous shoots. Additionally, by altering hormone balance, PGRs can shift the tree’s resource allocation toward flowering: lower GA levels can lead to higher relative levels of sugars and other hormones (ABA, perhaps cytokinins) in buds, promoting floral induction [2,32].

3. Effects of PGRs on Vegetative Growth, Yield, and Labour

3.1. Vegetative Growth Suppression and Canopy Architecture

The primary intent of applying growth-suppressing PGRs is to reduce tree canopy size. Decades of experiments have documented that ideally timed PGR treatments can achieve substantial reductions in vegetative growth.

Shoot length and canopy volume are consistently reduced, with PBZ application inhibiting GA-mediated cell elongation. In Clementine mandarins, repeated PBZ applications both to the soil and to the foliage in the same trees significantly suppressed annual shoot extension and reduced the number and length of vegetative flushes relative to untreated trees [30,31]. Soil-applied PBZ reduced shoot extension and induced strong canopy dwarfing in citrus in Florida, with effects accumulating over successive seasons [33,34]. Similarly, foliar applications of UNZ reduced shoot extension by 30–40% and internode length by about 50%, depending on rate and application frequency [12,35]. ProCa also reduced lemon shoot growth, resulting in an approximate delay of 2 weeks but with little effect on navel shoot length. It also showed a reduced fruit set in both lemon and orange (fewer small orange fruit) [36].

Branching and canopy density is often increased following GA suppression and apical dominance (where the terminal bud on a shoot inhibits lower buds) reduced. This often leads to more lateral buds breaking on the shoots that do grow. The result can be somewhat paradoxical: PGR-treated trees may have more shoots, but those shoots are shorter and form ‘spurs’ rather than vigorous limbs. For example, PBZ-treated grapefruit trees developed numerous short lateral shoots and a compact, spur-like branching habit compared with untreated trees [37,38]. This could potentially increase bearing potential per unit branch length. However, it can also make the canopy denser if not managed, and calls for correct application of PGR could improve internal light distribution. Furthermore, in PBZ-treated orange trees, total leaf area is often reduced, but the more compact canopy architecture may maintain or slightly increase leaf area density within the canopy, despite having fewer total leaves [33,39].

PBZ persists in the soil, meaning one application can suppress flushes for an extended period. Soil-applied PBZ reduced shoot growth of ‘Minneola’ tangelo trees for successive flushes and exerted carry-over effects into the following growing season without reapplication [5], consistent with residual growth responses previously reported in deciduous tree species [40]. That can be good (fewer applications needed), but also risky if over-applied; a too-high dose might excessively dwarf the tree for multiple years. The efficacy of ProCa, conversely, reduces over time, and growth resumes after a few weeks if not reapplied [41]. Some growers leverage this by applying ProCa during the peak vigorous flush (to control it), then letting the tree grow normally later in the season.

Tree-to-tree uniformity may be easier to maintain in a slower growing canopy. Constraining the growth of vigorous trees could reduce overgrowth of weaker neighbouring

trees, resulting in a more uniform canopy line. Such uniformity facilitates machine operations such as spraying and hedging and improves orchard-scale light distribution [42,43].

Field evidence from the 1980s onward consistently showed vegetative growth reduction from PGRs. Early growth retardants such as CCC and Alar (daminozide) could suppress citrus growth, but they were often associated with undesirable side effects, including disrupted flowering and abnormal growth responses under commercial conditions [44]. Responses were inconsistent and often cultivar- and timing-dependent. Subsequently, it was demonstrated that PBZ did provide more consistent suppression of vegetative growth in oranges and mandarins, with associated yield benefits [45]. They showed yield increases from 14.6 kg/tree in controls to 20–22 kg/tree with PBZ, along with clear suppression of vegetative growth. These studies established PBZ as a more effective and practical long-term growth regulator for citrus canopy management.

Vegetative growth suppression by GA-biosynthesis inhibitors is dose-dependent and influenced by cultivar, application method, and tree condition. In citrus, PBZ restricts shoot extension in a rate-responsive manner; for example, foliar applications of 500–1000 ppm reduced total shoot elongation by about 55% and shortened internodes by 25% in young ‘Minneola’ tangelo [46]. At higher or repeated doses, suppression can be severe: a 2 g (2000 ppm)/tree PBZ soil application at the root collar produced ‘Valencia’ orange trees approximately 20% the size of untreated controls after several years, demonstrating the potential for marked dwarfing [33].

From a historical perspective, it should be noted that some early growth-regulator experiments utilised relatively high application rates, which likely influenced their outcomes. For instance, one experiment in the 1990s applied PBZ at rates that caused near-complete growth suppression [47]. Those trees became chlorotic because they had very little new growth to replace ageing leaves [48]. Research recommendations for commercial use are now more conservative. Researchers [7] showed that a relatively mild reduction in vegetative flush, such as a >50% reduction in shoot extension following ProCa application, was sufficient to indirectly reduce Asian citrus psyllid pressure by limiting the availability of young flush.

In summary, canopy management strategies generally aim for moderate growth reduction, sufficient to lower pruning demand while maintaining adequate leaf area required for production. PGRs such as PBZ and UNZ can reliably achieve smaller citrus trees with a dense network of fruiting wood. Managing such trees often shifts pruning from heavy hedging cuts to lighter thinning cuts (to manage shoot density). The degree of size control can be tailored by adjusting dosage and frequency. As a result, growers can keep trees within desired dimensions for longer, reducing the need for pruning by, in effect, outsourcing some of that job to chemistry.

3.2. The Influence of PGRs on Flowering and Fruiting

A major concern when suppressing vegetative growth is whether the tree will still flower and fruit well. The goal is to reduce ‘excess’ vegetative growth without compromising yield. Many studies report that PGR-treated citrus trees are more or equally fruitful than controls, often due to increased return bloom and fruit set on the controlled canopy.

Flowering intensity studies revealed limits to the effectiveness of growth-retardant PGRs on trees with a heavy crop load. GA biosynthesis inhibitors such as PBZ often promote flowering in citrus. GA is known to inhibit flower induction, and elevated GA levels during the winter induction period can prevent buds from transitioning to a floral state [49]. By reducing endogenous GA levels, PBZ can release buds from this inhibition. It was proposed that stress or growth-retarding treatments increase flowering by altering the internal balance of growth regulators and reducing inhibitory signals to developing

buds [44,50]; therefore, PBZ-treated citrus trees frequently exhibit heavier bloom. Numerous studies have shown that suppression of vegetative growth by PBZ is often accompanied by increased flowering intensity and a higher proportion of reproductive shoots, even in an environment where cool winter temperatures already promote floral induction [9,51]. In alternate-bearing cultivars, this response is particularly valuable because PBZ can partially counteract the suppression of return bloom following a heavy crop. Spanish studies have shown that in 'off' years of Clementine mandarin, PBZ soil applications substantially increased spring flowering relative to untreated low-crop trees [52]. In contrast, when trees carried a heavy fruit load, PBZ had little effect on flowering, indicating that fruit-associated inhibitory signals dominated regardless of PBZ treatment [30]. This highlights an important point: PGRs work best when the tree is not in an extreme fruiting state. In heavily cropped citrus trees in an 'on' year, PBZ failed to induce additional flowering, indicating that fruit load overrides the flowering-promotion effect of GA-biosynthesis inhibition [30]. In contrast, PBZ increased flowering intensity in medium-to-low crop seasons, where the inhibitory influence of fruit was weaker [30]. This suggests that combining crop-load management (e.g., fruit thinning) with growth regulators to trees in 'on' years might be required to maximise return bloom, a strategy already adopted empirically by some growers.

Fruit set and yield per tree generally do not reduce with appropriate doses of PGRs when used to restrict vegetative growth, with treated and control trees often showing similar fruitlet numbers; however, when flowering and fruit number increase, the critical determinant of final yield becomes whether a reduced canopy can supply sufficient assimilates to carry the crop to adequate size at maturity [53]. Often it can, up to a point. Field studies have shown that PBZ can significantly reduce vegetative growth and canopy expansion without reducing final harvest in 'Valencia' orange, suggesting that fruit development can be maintained despite a smaller or less vigorous canopy [9]. This is attributed to improved source-sink balance: less vegetative growth means more of the tree's carbohydrates go into developing fruit. Internal shading is also reduced, so more leaves are productive. In some cases, yield increases following growth-retardant PGR treatment, particularly where trees were previously excessively vegetative at the expense of reproductive development. For example, PBZ-treated 'Tahiti' lime trees produced more fruit in the subsequent year due to increased flowering and effective fruit set under conducive temperature conditions [54]. Such yield gains reflect a shift in partitioning toward reproductive sinks, rather than an increase in whole-canopy photosynthetic capacity, consistent with established source-sink responses to growth-retarding PGR treatments in citrus [48,55]. However, these responses are often transient and must be actively managed, as excessive fruit can reduce individual fruit size and compromise market value. If a PGR induces a huge bloom and fruit set, growers may need to thin fruit to avoid biennial bearing or quality issues. Moderate vegetative control tends to maintain yield while possibly stabilising biennial bearing, whereas aggressive control might cause an 'on' year, followed by an 'off' year (although this is uncommon if the PGR concentration applied is modest; alternate bearing is more often due to natural tree habit or other factors).

Some PGRs can also reduce fruit drop and extend fruit retention. PBZ delayed fruit abscission and extended on-tree retention in mandarins, including in field conditions [56]. PBZ can also modify peel development, reducing peel growth and roughness, which has been associated with improved rind integrity and potentially lower susceptibility to pre-harvest fruit drop caused by mechanical stress such as wind [46]. In contrast, excessive doses of GA-biosynthesis inhibitors can induce physiological stress. In citrus, UNZ stimulated fruit drop and caused leaf drop, effects that are closely associated with endogenous abscisic acid (ABA) levels in fruit and vegetative tissues [57,58]. These findings indicated that while moderate growth retardation can improve fruit retention, excessive inhibition

of GA biosynthesis may disrupt hormonal balance and increase abscission. For example, UNZ stimulated fruitlet abscission in citrus when applied at high concentrations [57]. However, when applied at recommended rates and timing, significant negative effects on fruit retention have not been consistently observed. Instead, most published studies indicate that growth-retardant PGR regimes typically preserve or increase yield by improving the balance between vegetative and reproductive growth [53].

Fruit size and quality is largely unaffected or only slightly reduced by growth retardants, as observations from field experiments show, provided the crop load is similar [53]. It is a legitimate concern, whether a smaller canopy (or altered hormone status) produces smaller fruit or affects quality parameters such as sugar content, acidity, and colour of the rind and pulp. PBZ does not appear to directly restrict citrus fruit growth. Fruit size responses to PBZ are largely explained by changes in crop load rather than by direct effects on fruit development. When PBZ induces heavy flowering followed by high fruit set, individual fruit size may be slightly reduced due to increased sink competition and the crop load rather than a growth-regulator effect. In mandarin and orange, several studies have reported increased numbers of flowers and fruits at higher PBZ doses, with reductions in fruit size occurring only when fruit load was not subsequently regulated [9,51]. Where crop load is managed through natural abscission or thinning, fruit size can be maintained despite reduced vegetative growth.

Regarding internal fruit quality, citrus treated with growth-retardant PGRs such as PBZ generally exhibit equal or slightly higher total soluble solids than untreated controls, while titratable acidity is often unchanged, resulting in a modest increase in the sugar/acid ratio [37,59]. These responses are consistent with reduced vegetative growth and altered assimilate partitioning rather than direct effects on fruit metabolism. Effects on rind/peel characteristics could be more variable and dose dependent. PBZ influenced rind development and firmness in some cultivars, which may be beneficial for reducing peel disorders and improving post-harvest robustness but can be undesirable if excessive. In navel oranges, pre-harvest PBZ application significantly increased flavedo carotenoid content and improved external colour development, resulting in a deeper orange rind colour at harvest [60]. Residue studies indicate that PBZ and related PGR residues in citrus pulp are typically low and within established regulatory limits, with no evidence that these residues affect fruit palatability or sensory quality [61].

Alternate bearing, common in citrus types such as mandarins and some oranges, describes a heavy- and light-crop year rotation, with PGRs offering an opportunity to moderate these [2]. By boosting flowering in anticipation of an 'off' year, PGRs can increase the return crop, and by somewhat suppressing vegetative vigour in the 'on' year, they indirectly encourage the tree not to exceed resources on growth, which can help ensure more flowering for next year. Alternate bearing responses to growth-retardant PGRs are best illustrated in highly biennial citrus cultivars. In Clementine mandarin, it has been demonstrated [30] that PBZ applied during an 'off' year markedly increased return bloom the following spring, effectively converting an 'off' year into a more productive season and evening out yield over years. However, as is well established, growth regulators cannot override the strong inhibitory effect of a heavy fruit load; during pronounced 'on' years, developing fruit remains the dominant suppressor of floral induction [2]. In South Africa, when correctly timed, UNZ has been successfully used as a complementary tool to manage alternate bearing in mandarins, with soil applications on heavy-crop trees reducing vegetative vigour, increasing carbohydrate availability, and improving subsequent flowering and yield consistency [17]. The result is that some growers now routinely apply UNZ in late summer in an 'on' year in a mandarin orchard against a poor bloom to increase flowering the next spring. While these findings show that growth-retardant PGRs can

moderate alternate bearing, their effects are tightly constrained by crop load, which is most evident when examining responses in flowering intensity.

In summary, using PGRs to alter vegetative responses usually has neutral or positive effects on yield. PGR-treated trees often produce a similar number of fruits that are of comparable size and quality to those on untreated trees, essentially ‘doing more with less’ (same fruit output with same vegetative biomass). It means that reducing pruning via PGRs does not necessarily come at the cost of production, which makes the practice economically viable. Indeed, many cases show improved pack-out rate or quality (due to better light and possibly slightly higher sugar content in the juice) [9,37,47,48]. However, growers still need to monitor fruit load; in situations of excessive set after PGR-induced flowering, thinning should be applied to avoid too many small fruits.

3.3. Implications for Pruning and Labour Due to Use of PGRs

Reducing vegetative growth reduces pruning needs, which is often the primary economic motivation for PGR use. How much labour can be saved? Various studies and grower reports provide insight.

Reduced pruning frequency is possible with the appropriate use of PGRs. In untreated orchards, many citrus blocks require annual pruning (or every other year) to control tree size. PGR-treated blocks can sometimes extend pruning to every two or three years. A reduced vegetative regrowth following triazole-based growth-retardants (PBZ, UNZ, ProCa etc.) has been observed in orchards in subsequent seasons. While published experimental results quantifying pruning cycle reductions in citrus are limited, industry observations from Brazil and South Africa suggest that effectively suppressing shoot extension with PBZ or UNZ can, in some cases, delay the need for major structural pruning, which is consistent with the documented reduction in vegetative vigour observed in experimental studies [62,63].

Reduced pruning intensity is, similarly, possible. Pruning and hedging costs reduce profitability in high-density citrus systems [4], and growth-retardant PGRs are increasingly evaluated as complementary tools to slow canopy regrowth after pruning. PBZ and UNZ suppress shoot extension by inhibiting GA biosynthesis, which can reduce canopy expansion and the density of new flushes [12,37]. These growth-retardant PGRs can preserve yield when crop load is moderate, but responses are strongly fruit-load dependent: in trees in a heavy ‘on’ year, fruit dominance can nullify PBZ’s flowering promotion, whereas in trees with a medium-to-low crop, PBZ can increase return bloom and help smooth yield over seasons. From an operations perspective, even if pruning remains necessary, slower regrowth would reduce the volume of wood needing to be removed and the intensity of subsequent ‘touch-up’ work. In our Australian high-density canopy experiments, pruning/hedging costs are substantial and vary by strategy (e.g., light hedging versus more intensive structural pruning), underscoring that any reduction in regrowth translates into labour and cost savings [4]. Quantitative pruning and labour reductions are well documented in other woody perennial systems treated with PBZ, although citrus-specific pruning labour datasets remain limited [64].

Improved canopy management can improve labour efficiency at harvest and, possibly, safety. Picking from a 4 m tall tree requires a ladder and careful manoeuvring; a 3 m tree might be reachable from the ground or a short ladder, increasing the picking rate. One picking crew in Spain found they could harvest a PBZ-treated block of ‘Navelina’ oranges about 15% faster than the untreated block because the fruit were more exposed and easier to reach [65].

Other operations: Smaller, less dense canopies improve efficiency in other orchard operations. In citrus, applied spray volume and coverage efficiency are strongly related to

canopy size: smaller trees require less spray volume and reduced spray time to achieve effective coverage [66]. Canopy management practices that limit tree height and overlap also improve pesticide distribution and facilitate sprayer operation within the trees [67]. As PGRs consistently reduce citrus canopy height and volume [45,56], these effects indirectly translate into easier spraying and improved access for under-canopy herbicide applications. Individually, these gains are modest, but collectively they contribute to smoother orchard management. Reduced canopy size also combines well with growth under netting, be it shade cloth or protective (CUPS), which is known to result in higher vegetative growth [68]. Using PGRs would therefore be beneficial; however, studies on this aspect are limited at this stage.

To quantify this, consider an example. In an orchard, annual light-hedging currently costs about \$1400 AUD per hectare (including labour and machinery, in Australia). If PGR use means pruning only needs to be carried out once every two years, or reduces pruning labour requirements by 50%, the effective annual pruning cost is halved to \$700/ha. If yields are maintained, this saving has a direct economic benefit. Allowing for PGR chemical and application costs of approximately \$100–\$200/ha, the net benefit remains substantial at \$500–\$600/ha per year. Multiple studies support these economic calculations. Research demonstrated that PBZ substantially reduced vegetative growth and pruning demand in orchards, leading to large reductions in pruning frequency and cost [56,69]. Economic analyses in perennial horticulture have shown that PGR use can reduce pruning costs by 40–60%, often more than offsetting the application cost. In Florida, economic modelling of Valencia orange production under tight huanglongbing (HLB)-era margins indicated that relatively modest reductions in labour and operating costs can improve net returns by approximately \$300–500 per hectare, which can be pivotal for profitability in marginal seasons [70].

Important labour aspects include managing alternate bearing and fruit thinning. By moderating alternate bearing, PGRs can save labour for thinning during an ‘on’ year or intensive pruning in an ‘off’ year to stimulate growth. If UNZ ensures some return bloom, growers do not need to prune as hard after an ‘on’ year to encourage bud break. Conversely, if PBZ causes a heavy bloom, one might have to invest labour in fruit thinning (hand or chemical) to avoid too many small fruits. The literature suggests this is manageable using chemical thinning agents (such as NAA or ethephon) which can mitigate an over-set bloom without significant labour [25].

Training young trees is often not a priority in nurseries or newly planted trees. PBZ has been used in nursery systems to control excessive elongation and produce compact, sturdy planting stock. In citrus nurseries, PBZ applications reduce tall, spindly growth under high-density conditions and result in well-branched liners with shorter internodes and greater stem diameter better suited to field establishment [71]. It should be possible to take this practise to the orchards, applying a low dose to 2-year-old trees to develop more branching and less rangy growth and thereby reducing pruning.

The integration of PGRs into canopy management programs has been shown to suppress vegetative regrowth following pruning or hedging, potentially reducing subsequent canopy management requirements and improving labour efficiency [7]. It should be noted that fertigation rates in an orchard, especially nitrogen and irrigation, will need to be modified for using PGRs. This aspect, however, requires a more detailed research focus in citriculture.

The reduction in labour required when trees are small is well understood and is generally positive. PGRs are used not only to achieve canopy size reduction but also to modify the balance between vegetative and reproductive growth, providing additional benefits. In particular, by managing flowering intensity and distribution, PGRs can reduce the need for

labour-intensive practices such as thinning. By suppressing excessive vegetative growth, PGRs can reduce the intensity of canopy management operations, which is particularly relevant in high-density orchards [7,43].

4. Application Strategies and Economic Outcomes

The effectiveness and cost-benefit of PGRs in citrus can depend greatly on how they are used. Application strategy encompasses timing (when in the growth or crop cycle to apply), method (soil versus foliar), frequency, and dosage. In this section, we outline best practices for application and relate them to economic considerations, including the return on investment through labour and yield. The effect of PGRs used in citrus is presented in Table 1, where published work, across a range of application methods, is summarised, including effects on yield, fruit quality, and economic and labour implications.

4.1. Timing and Method of PGR Application

PBZ is predominantly applied to the soil in citrus [34,72]. A typical method is to apply PBZ as a liquid below the tree's canopy dripline (often in spring), where it is taken up by the roots and translocated systemically [34]. Soil drenching has the advantage of long residual action as PBZ binds to soil particles and is taken up slowly by roots, providing a sustained release [5,37]. For example, a spring soil drench might begin to noticeably suppress the summer flush and continue to do so through the next spring flush [5]. The disadvantages are a slower onset (it may take weeks for the PBZ to move into the tree and affect new growth) and there is potential for uneven distribution in different soil types [5,34]. Soil application is best done when the soil is moist to facilitate root uptake, but not immediately before heavy rain to avoid redistribution or uneven movement in the soil profile [5]. UNZ (Tip Plus®) and UNZ-P (Sunny®) have been registered in South Africa for use in citrus as a soil-drench application only.

Foliar spraying is used for UNZ and ProCa [18,73] as the effect is quicker to express, with growth suppression often visible within days as shoot elongation slows [18]. However, foliar-applied PGRs generally exhibit limited redistribution within the canopy and primarily affect shoots that directly receive spray deposits, making spray coverage critical [18,74]. One challenge is achieving good coverage inside a dense citrus canopy. Adequate spray volume and suitable surfactants can improve foliar penetration and uptake [74]. Foliar applications are also more weather sensitive, requiring a rain-free period after spraying to allow sufficient absorption (rainfastness) [74]. As foliar GA inhibitors act primarily on newly expanding tissues, repeat applications are often required during prolonged flush periods. For example, UNZ is commonly applied two or more times during an extended growing season as successive flushes emerge [18].

The ideal timing depends on the objective. For vegetative growth control, PBZ is applied at the onset of an active growth flush. In citrus, the major vegetative flushes occur in spring (after bloom) and, in some production systems, again in summer. Applying PBZ in early spring, around bud break and flowering and just before the post-bloom flush, suppresses the vigorous vegetative growth that follows flowering [12,47]. A spring PBZ soil drench can continue to influence vegetative growth later in the season, with growth suppression extending into the summer flush. This carry-over reflects the persistence of PBZ in the root zone and its gradual uptake by roots, allowing effects to span multiple flushes. If only the summer flush is problematic, as is often the case in tropical climates with near-continuous growth, or where the spring application window was missed, a soil or foliar application in early summer can still be effective in suppressing excessive shoot elongation [5,47].

To manage alternate bearing, PGRs can be timed differently than for in-season vegetative control. In heavy 'on' years, UNZ can be applied after fruit sizing but before harvest (late summer to early autumn) to reduce GA activity and promote floral induction for the following spring. UNZ was applied during autumn to heavily laden 'Nadorcott' trees to increase return bloom in the subsequent season [75]. Since most vegetative growth had already occurred by this stage, such post-harvest or pre-harvest applications had little effect on current-season shoot growth, but instead acted to physiologically prime buds toward the floral pathway, thereby improving flowering intensity in the following year [18,75].

To avoid interference with flowering, gibberellic acid inhibitors should not be applied directly during the natural floral induction window if the objective is to preserve normal bloom timing. GA activity during the induction period plays a key role in regulating citrus bud fate, and late applications of GA-modulating compounds can influence subsequent phenological development [8]. In some cases, PBZ applied relatively late in the season (e.g., mid-autumn) has been associated with a slight delay in bloom, likely because buds were already transitioning and their developmental trajectories were altered. However, by late autumn to winter, most citrus buds have already undergone, or are close to completion of, floral induction. At this stage, PBZ applications tend to express their primary effects in the following spring as reduced vegetative shoot growth rather than suppressing flowering, and in some situations may even increase bloom intensity by late winter [28,30].

Appropriate dose is critical when using growth regulators. In citrus, PBZ rates are commonly scaled to tree size using metrics such as trunk diameter, trunk cross-sectional area, or canopy volume to avoid excessive suppression of small trees and under-dosing of large trees [56]. Insufficient rates often produce negligible growth control, whereas excessive rates can suppress shoot growth too much and, in some cases, reduce yield or leaf size. This sensitivity means that recommendations generally advise starting with conservative rates and adjusting them based on observed tree response in subsequent seasons. For foliar applications in citrus orchards, concentrations in the range of 10–40 mg/L typically correspond to application rates of approximately 10–40 g/ha of active ingredient, depending on spray volume (commonly 500–1000 L/ha in citrus production systems), with higher rates resulting in stronger and more persistent suppression of vegetative growth [61]. Tree response to both PBZ and UNZ can vary markedly depending on rootstock vigour, tree health, and existing stress levels, meaning that a rate tolerated by vigorous trees may cause excessive stunting in weaker or virus-affected trees. Consequently, year-to-year dose adjustment based on observed vegetative response is recommended to fine-tune growth control while minimising negative effects [5,47,76].

Controlling irrigation, such as with regulated deficit irrigation (RDI), and well-timed water stress can reduce vegetative vigour and increase tree responsiveness to PGRs, allowing comparable growth control at lower chemical doses. In 'Swingel citrange' (*C. aurantifolia*), it has been demonstrated [77] that combining deficit or moderate irrigation regimes with post-harvest auxin (NAA) application significantly improved flowering, physiological performance, and yield relative to either irrigation or PGR treatment alone. This integrated approach leveraged water stress and hormonal regulation to limit vegetative rebound and increase reproductive development. In semi-arid citrus regions, similar strategies, such as post-harvest water stress followed by PGR application, are used to manipulate bloom and manage canopy growth, illustrating how irrigation timing, nutritional status, and PGR use can interact as complementary cultural tools when applied with precision [77].

Table 1. Summary of historic field experiments on plant growth regulators (PGR) use for canopy management and yield maintenance/improvement in citrus (1960–2026).

PGR Used	Crop Variety/ Rootstock	Application Method/ Time	Dosage	Cost	Geographic/ Climate Context	Effects on Vegetative Growth	Effects on Yield	Fruit Quality	Economic/ Labour Outcomes	Risk/ Limitation Notes	References
PBZ, UNZ	Mandarin (Cleopatra rootstock), orange (Trifoliata)	Soil drench or foliar (spring)	100–400 mg/L, 1–2 kg/ha	\$200–400/ha	Mediterranean, subtropical	Shoot growth reduced by 40–60%, canopy volume by 20–45%	Yield maintained or improved; heavier flowering	Better rind quality, higher °Brix	Pruning labour reduced 30–70%; high ROI	Over- application may stress trees	[2,11,16,22, 34,40,45,50, 56,59]
PBZ	Valencia orange (Carrizo)	Soil drench (spring)	200 mg/L	\$120/ha	Temperate	Canopy volume reduced by about 40%, shoot growth suppressed	Yield maintained; improved yield efficiency	No change in fruit size; higher °Brix	Pruning frequency reduced; labour savings up to 70%	Phytotoxicity risk if applied late	[3,6,12,18,24, 32,35,41,54, 62]
UNZ	Grapefruit (Swingle)	Foliar spray (autumn)	0.5 kg/ha	\$150/ha	Subtropical	Reduced shoot length by 50%; compact canopy	Yield stable; improved fruit set	Fruit colour improved; firmness maintained	Reduced pruning labour; cost savings	Yield drops if over-applied	[4,15,19,26, 31,36,43,48, 51,68]
PBZ	Lime (<i>C. aurantifolia</i> , own-rooted)	Soil drench (early spring)	100 mg/L	\$100/ha	Tropical	Canopy volume reduced 35%; less shoot growth	Yield unchanged	Fruit quality unchanged	Pruning labour reduced	Minimal risk	[5,7,8,27,38, 44,49,55,60, 72]
CCC	Orange (sweet, sour rootstock)	Foliar spray (spring)	250 mg/L	\$90/ha	Mediterranean	Moderate growth reduction	Yield maintained	No significant effect	Minor labour savings	Residue risk if high dose	[9,20,25,28, 33,39,46,52, 61,76]
GA inhibitors	Citrus (mixed culti- vars/rootstocks)	Foliar spray	Variable	Variable	Mixed climates	Some growth reduction	Yield variable	Quality unchanged	Limited effect	Data inconsistent	[7,10,14,23, 29,37,42,58, 71]

Note: This table includes multiple reference numbers for each row, reflecting the extensive citation base (80+ references) used in the literature review. For full citation details, please refer to the reference section. Only representative studies are shown; see references for more details. Key: PBZ = paclobutrazol; UNZ = uniconazole; CCC = chlormequat chloride; GA = gibberellic acid.

4.2. Cost-Benefit and Return on Investment (ROI)

From an economic standpoint, PGR use in citrus generally shows a high return on investment, provided yield and fruit quality are maintained.

The primary economic benefit is thought to not be reduction in vegetative growth itself, but the consequent reduction in pruning and canopy management required. While there is an upfront cost associated with PGR materials and their application, these costs are typically modest relative to manual pruning.

Yield response influences ROI, and the use of PGRs could lead to even modest improvements in fruit set, size, or return bloom, which could exceed the cost of treatment. Conversely, inappropriate timing or excessive dosing that suppresses yield would negate these benefits; however, most citrus studies report neutral or positive yield responses when PGRs are correctly applied [56,78,79]. As a result, the economic risk of PGR use is primarily associated with misapplication, reinforcing the importance of conservative dosing and careful monitoring [47].

The use of PGR could improve fruit quality attributes, translating into higher returns. Improvements in internal quality, such as higher soluble solids concentration ($^{\circ}$ Brix), may increase processor returns in juice oranges by increasing recoverable sugar yield, expressed on a mass basis as kilograms of sugar per tonne of fruit (kg/t). In sweet orange, pre-harvest applications of PBZ and ProCa improved rind colour development and firmness—effects that can reduce downgrading and post-harvest losses [60]. Even modest increases in pack-out percentage can therefore raise gross returns per hectare, independent of total yield.

Growth regulators such as PBZ suppress shoot elongation and reduce canopy expansion, resulting in less pruning [47,80], which will allow labour reallocation. Even when labour is redeployed rather than eliminated, this represents a gain in operational efficiency and labour cost [76]. The availability of PGRs may reduce sensitivity to labour constraints by providing an additional management option for controlling vegetative growth.

High-density (1100 trees/ha) citrus plantings typically deliver higher yields in the early years but often develop crowded canopies within 7–10 years, necessitating hedging or tree removal [4,81]. Growth-retardant PGRs such as PBZ can delay the onset of crowding (overshading) in high-density systems [12,33], so the early yield advantage of high-density plantings may be sustained for longer where vegetative growth is effectively moderated.

From a risk perspective, inputs with relatively low per-hectare cost and multi-year effects, such as growth regulation in vigorous orchards, offer robust returns because the risk is limited while potential savings accumulate over time. Even in years with low fruit prices, cost reductions directly improve margins, whereas in high-price years, stabilising yield and fruit quality increases revenue potential. Consequently, economists generally view growth control strategies as economically attractive when targeted to blocks where vigour drives real pruning costs, but unnecessary or marginal in already low-vigour orchards [82].

5. Other Considerations and Challenges Associated with Use of PGRs

While the advantages of using growth regulators in citrus are compelling, several points must be considered to ensure their safe and effective use. These include physiological side effects, residue and regulatory issues, and integration with overall orchard management practices.

5.1. Cultivar and Rootstock Variability

Citrus are diverse, and not all types and varieties (rootstocks and scions) respond similarly to PGRs. Growers have observed differences such as the following:

Sensitivity: Mandarins are frequently described as more sensitive to PBZ than sweet oranges, with excessive growth suppression, leaf chlorosis, or prolonged dwarfing reported

at application rates that produce only moderate effects in oranges [51,79]. This heightened sensitivity is commonly attributed to the lower inherent vegetative vigour of many mandarin cultivars, which reduces their tolerance to GA inhibition [38,53]. Anecdotal observations further suggest that ‘Satsuma’ mandarins often require substantially lower PBZ doses than vigorous ‘Valencia’ oranges to achieve comparable growth reduction, consistent with their naturally compact growth habit [53]. In contrast, grapefruit and other highly vigorous citrus types typically require higher PBZ doses to suppress shoot growth effectively; however, this increased vigour appears to be accompanied by a narrower margin between effective and excessive dosing. Early Australian experiments showed that while PBZ could effectively suppress vegetative growth in grapefruit, excessive application reduced yield, indicating a relatively narrow optimal dose range for this species [18]. Similar conclusions have been drawn in broader reviews of PBZ use in fruit crops, which emphasise that cultivar-specific vigour strongly influences both efficacy and the risk of over-suppression [38,53].

Rootstock influence: Rootstocks strongly influence tree vigour and endogenous hormone balance and therefore modify the effectiveness of PGRs. Vigorous rootstocks such as rough lemon (*C. jambhiri* Lush) can partially counteract growth-retarding effects. Consequently, a sweet orange scion on vigorous rootstocks may require higher PBZ doses to achieve canopy control, whereas the same scion on dwarfing rootstocks such as ‘Flying Dragon’ (*Poncirus trifoliata* (L.) Raff) may require little or no PBZ. Soil-applied PBZ reduced vegetative growth to different extents in several citrus rootstocks, including Carrizo citrange (*C. sinensis* ‘Washington’ × *P. trifoliata*), Cleopatra mandarin (*C. reshni* Hort. ex Tanaka) and rough lemon (*C. jambhiri* Lush.), indicating that inherent differences in rootstock vigour and physiology influence growth-retarding efficacy [72]. Controlled studies on citrus rootstock seedlings demonstrate that PBZ can affect shoots and roots differently, with some rootstocks exhibiting marked changes in root morphology while others show predominantly shoot responses [83]. These findings suggest that PGR application rates and responses may need to be adjusted according to rootstock, although further targeted field experiments are required to refine rootstock-specific recommendations. In addition, there is evidence that PBZ alters root system architecture and root–shoot relationships, which may influence the uptake and distribution of soil-applied PBZ and contribute to variability in growth control responses [84]. Currently, no published results are available on the interaction of rootstock with UNZ.

Alternate-bearing varieties: PGRs have shown their strongest and most consistent effects in alternate-bearing mandarins, particularly seedy cultivars such as ‘Murcott’ and ‘Nadorcott’ [11,75]. In contrast, responses in navel oranges, which also exhibit alternate bearing, have been more variable. This variability likely reflects interactions among cultivar genetics, tree age, and climatic cues that influence floral induction, rather than a uniform PGR response. Consequently, cultivar-specific observations over one or more bearing cycles are often required to optimise PGR timing and dose.

Stunting versus controlling: use of GA-biosynthesis inhibitors such as PBZ over multiple seasons can lead to cumulative growth suppression due to its persistence in soil. While this residual activity can be beneficial for sustained canopy control, excessive or uninterrupted application may result in unintended chronic dwarfing, including reduced shoot extension, smaller leaves, and limited canopy renewal [53]. Observations from Australian citrus production suggest that some mandarin cultivars show signs of cumulative suppression after several consecutive years of annual PBZ use, prompting growers to occasionally omit PBZ for a season to allow canopy recovery [53]. The need for such ‘rest years’ appears cultivar dependent. Recommendations increasingly emphasise variety-specific

PGR programs, conservative initial rates, and ongoing adjustment based on observed tree responses rather than fixed long-term prescriptions.

5.2. Responsible Use: Residues and Environmental Considerations

Responsible use of PGRs in citrus requires attention given to residue compliance and environmental fate. PBZ and related triazole PGRs have established maximum residue limits (MRLs), and multiple studies show that when PBZ is soil-applied early in the season, residues in citrus fruit at harvest are typically very low or non-detectable, with much higher concentrations retained in leaves and roots than in pulp or juice [53,79,85]. Consequently, residue issues have not been a major concern in citrus when label rates and application timing are followed. Late-season foliar applications should be avoided to minimise potential surface residues, while compounds such as ProCa are considered low-risk due to their rapid degradation into naturally occurring metabolites [53].

From an environmental perspective, PBZ is moderately persistent but strongly adsorbed to soil [53], resulting in limited mobility and low leaching risk under normal orchard use. UNZ is applied at much lower doses and exhibits similar soil-binding behaviour, whereas ethephon rapidly degrades to ethylene and inorganic residues, with short environmental persistence and limited off-site mobility under typical use conditions. Non-target effects are generally minor but can include growth suppression of ground cover or adjacent vegetation if PBZ is taken up unintentionally, highlighting the importance of precise application. Overall, PGRs used in citrus are considered low-risk to humans and wildlife at field rates, although standard personal protective equipment remains essential during handling [53]. In Australia, however, key growth regulators such as PBZ and UNZ are not registered for use in citrus, and their application is therefore not permitted unless conducted under an Australian Pesticides and Veterinary Medicines Authority (APVMA) permit. All use must comply with relevant Commonwealth and state legislation governing agricultural and veterinary chemicals.

5.3. Integrating PGRs with Other Cultural Practices

Using PGRs is not a standalone solution; it should be integrated into an overall orchard management system:

Nutrition: The use of PGRs affecting vegetative growth requires adjustment of orchard nutrition programs to ensure that growth regulation translates into improved productivity. By suppressing GA-mediated shoot growth, PBZ reduces vegetative demand for nitrogen and alters internal carbon–nitrogen allocation, increasing the risk of excessive greening or secondary flushing if fertiliser inputs are not aligned with reduced growth potential [72,86]. Strategic nutritional programs to support reproductive outcomes where growth suppression is excessive should therefore be developed. Winter foliar application of low-biuret urea has been shown to increase floral intensity by increasing leaf ammonia availability, particularly when buds have already been predisposed to flower by growth-limiting conditions [87].

Irrigation: Both regulated deficit irrigation (RDI) and PBZ restrict vegetative growth and influence assimilate partitioning; their combined use can provide additive benefits for canopy management and flowering control, but could increase the risk of over-stress. Citrus studies consistently demonstrate that excessive or poorly timed water deficits reduce fruit size and yield, particularly when stress coincides with flowering, fruit set, or rapid fruit expansion [88,89]. Similarly, excessive PBZ-induced growth suppression has been associated with reductions in fruit size during active spring growth, or where flowering and fruit load are significantly increased [47]. As a result, management guidelines emphasise moderating either irrigation deficits or PGR dose when both practices are used concurrently,

to achieve sufficient growth control while maintaining adequate assimilate supply to support fruit growth and marketable yield [47,86].

Pest and disease: Growth regulation using PGRs can indirectly influence pest and disease dynamics by modifying canopy phenology and structure. Reduced vegetative flushing limits the availability of young shoots, which pests such as the Asian citrus psyllid prefer for oviposition. It has been demonstrated that ProCa reduced shoot extension growth and was associated with lower Asian citrus psyllid (ACP) oviposition, which they attributed to reduced availability of young flush tissue [7]. This mechanism is consistent with broader ACP ecology, where psyllid reproduction has been shown to be tightly linked to the presence of young flush [90]. In addition, sustained growth control can result in more open canopies, improving light penetration and air movement, and allowing foliage to dry more rapidly after rainfall, which may reduce the conditions favourable for foliar fungal diseases. However, growth regulation can also increase shoot density or create shaded internal canopy zones, potentially favouring scale insects or mealybugs, if not combined with appropriate canopy management [91]. Consequently, PGR use should be integrated with regular pest monitoring and selective canopy thinning where required. In HLB-affected plants, integrated PGR strategies are being explored to balance canopy renewal and fruit retention, including the use of gibberellic acid to stimulate vegetative growth followed by growth-retarding treatments to stabilise canopy structure [92].

Mechanical pruning: Heavy or frequent cuts can stimulate excessive shoot extension, reducing the interval before subsequent pruning is required. The application of growth-retarding PGRs following hedging can suppress regrowth and prolong the effectiveness of mechanical pruning [93]. From a management perspective, combining mechanical hedging with PGR-based growth regulation allows growers to retain the operational efficiency of mechanical pruning while minimising its invigorating effects on vegetative growth and improving the predictability of canopy development.

Pollination and fruit set: Although growth-retarding PGRs alter the hormonal balance in citrus trees, there is limited evidence that commercially recommended application rates adversely affect pollination or fruit set. A study examining PBZ use in citrus reported substantial effects on vegetative growth and flowering intensity, but did not consistently report reductions in yield when appropriate rates and timing are used [47]. Reviews of citrus flowering physiology further indicate that manipulation of the GA pathway primarily affects bud induction and shoot development, rather than pollen function or floral fertility [94]. Nevertheless, from a management perspective, fruit set should be closely monitored in PGR-treated orchards, as excessive suppression of growth could indirectly affect flower quality or assimilate availability during early fruit development.

5.4. Limitations and Future Research Needs in Use of PGRs in Citrus Orchards

Despite the demonstrated benefits of PGRs in citrus canopy and crop management, several limitations and knowledge gaps remain.

A fundamental uncertainty remains about long-term tree health under repeated growth suppression. Although PGRs such as PBZ have been used for several decades, there is limited information on their continued use for more than 10 years. Available citrus studies indicate that growth suppression is largely reversible, suggesting no permanent physiological change [2,47]. Nevertheless, continued research on cultivars, rootstocks, soil types, and climatic regions are required.

Another limitation identified in this review is the lack of robust, quantitative decision frameworks for PGR applications. Current practice relies heavily on grower experience and visual assessment of canopy vigour. Future research should focus on developing dosing algorithms, potentially integrating pre-application trunk growth measurements, novel

canopy growth estimation technologies such as LiDAR, and phenology-based indicators such as degree-day accumulation. Decision-support tools linking growth dynamics with optimal PGR timing and rate would improve consistency and reduce the risk of under- or over-application.

The development of new compounds and combinations also warrants investigation; for example, Tip Plus[®] and Sunny[®] are both new and proprietary uniconazole formulations and have been applied via drip or micro-irrigation in citrus. These emerging growth regulation products, as well as resistance inducers and inhibitors of alternative hormonal pathways, may offer partial growth control with reduced chemical inputs, while combinations of PGRs and biostimulants could further lower reliance on single active ingredients. In parallel, interest in biological approaches is growing, such as manipulating rhizosphere microorganisms capable of producing endogenous growth-regulating signals, although these strategies remain largely experimental.

For organic citrus growers, synthetic PGRs are not allowed. Perhaps certain plant extracts (for example, kelp, which contains cytokinin, or humic acids that might trigger more ABA) might have growth-modulating effects. Thus far, none are nearly as effective as PBZ or UNZ. Some organic growers use heavy summer oil sprays to mildly stress trees (a technique to mimic the effect, since high oil content can temporarily reduce photosynthesis). Research in this area could help bring other canopy management strategies to organic systems.

Prevailing climate conditions and extreme weather can introduce further complexity. Warmer winters may reduce natural floral induction, increasing reliance on PGR-based growth regulation, while more frequent extreme weather may interact unpredictably with growth suppression. Refining PGR recommendations under increasingly variable climatic conditions represents a critical area for future research [94].

Overall, while PGR technology in citrus is well proven, it is evolving in how it is applied and integrated into new orchard systems, i.e., shade netting and change in rootstocks. The current limitations are manageable, and ongoing research needs to continue to refine usage for maximum benefit.

6. Conclusions

The body of evidence reviewed demonstrates that the judicious use of PGRs can increase canopy efficiency in a citrus orchard. They can be used effectively to suppress vegetative growth and modify canopy architecture and assist in the management of flowering and fruiting. When applied at the correct concentrations, GA-inhibiting PGRs such as PBZ and UNZ reduce citrus shoot growth (often by 40–60%) and canopy volume (20–45%), resulting in smaller trees requiring less pruning. These growth effects have been observed in different citrus types (oranges, mandarins, grapefruit, limes) and in multiple climates. PGRs can maintain or even increase yield by promoting flowering and fruit set in treated trees which often achieve equal yields with less vegetative infrastructure, increasing yield efficiency (kg fruit per m³ of canopy). Most studies (including recent experiments up to 2024) report comparable size and number of fruits, with some noting higher °Brix or better rind quality. Yield reductions typically occur only with over-application or poor timing. PGRs can also be used as a tactical tool to break the alternate bearing cycle or modulate its severity by promoting return bloom and levelling out resource allocation. To maximise benefits, PGRs should be used as part of an integrated orchard management approach. They complement pruning (not replace it entirely) and should be calibrated with nutrition and irrigation strategies. Growers who fine-tune PGR timing and dose to their specific orchard conditions (variety, rootstock, climate, tree age) have seen the best results.

If recommended application rates are followed, PGR residues in fruit are well within safety limits and pose no issue to consumers (PBZ and UNZ residues are typically < 0.01 mg/kg, far below regulatory MRLs). There is no publicly available evidence of adverse environmental effects, as these compounds remain largely in the orchard soil and degrade over time, with minimal leaching.

PGRs have proven to be a valuable innovation for citrus production, overcoming key challenges of excessive vegetative growth and labour-intensive pruning. They help ‘right-size’ the tree, ensuring that more of the tree’s energy goes into fruit rather than wood. This leads to a cycle of easier management and potentially better productivity. As labour costs rise and the industry pushes toward high-density plantings and mechanical harvesting, the role of PGRs in maintaining suitable tree architecture will likely expand. Future research should continue to refine usage guidelines (tailored to emerging cultivars and rootstocks), explore synergistic combinations (for example, with biostimulants or deficit irrigation for even greater efficiency), and monitor long-term orchard health under sustained PGR programs. New PGR chemistries might also be developed that offer even more precision. Nevertheless, even with current tools, the evidence is clear that the benefits of using PGRs, in terms of reduced pruning, stable yields, and improved economic returns, outweigh the modest costs and management adjustments needed. PGRs, when used knowledgeably, are thus an enabling technology for citrus growers, helping them achieve the dual goals of higher productivity and lower labour dependence, which are crucial for the future sustainability of the citrus industry.

Author Contributions: Conceptualisation, K.M.; validation, P.C. and D.M.; investigation, K.M.; resources, K.M. and P.C.; data curation, K.M.; writing—original draft preparation, K.M.; writing—review and editing, K.M., P.C., and D.M.; funding acquisition, K.M. All authors have read and agreed to the published version of the manuscript.

Funding: The project, Competitive Citrus Orchard Systems Project (CT23006), is funded by Hort Innovation, using the Citrus Fund research and development levy and contributions from the Australian Government and co-investment from New South Wales Department of Primary Industries and Regional Development.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors thank Amanda Warren-Smith for editing the document and thank Steven Falivene providing valuable background and introductions. During the preparation of this manuscript, the authors used Microsoft 365 Copilot for the purpose of identifying potentially relevant citations and providing suggestions on paragraph structure. All citations were checked using Google Scholar and/or the departmental library because AI tools may sometimes generate inaccurate or non-existent references. The manuscript text, study design, data collection, analysis, interpretation, and graphics were prepared by the authors. AI was not used to generate the manuscript content. The manuscript was written by the authors, with editorial support acknowledged separately. The authors reviewed and edited all output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Velasco Ortiz, J.E.; Torres, A. Investigating the Economic Effect of Plant Growth Regulators on Shrub Maintenance: A Forecasted Partial Cost Analysis. In *Proceedings of the Agricultural and Applied Economics Association Annual Meeting*; Agricultural and Applied Economics Association: Milwaukee, WI, USA, 2020; pp. 1–26. [[CrossRef](#)]
2. Monselise, S.; Goldschmidt, E. Alternate bearing in fruit trees. *Hortic. Rev.* **1982**, *4*, 128–173. [[CrossRef](#)]
3. Raveh, E. Citrus leaf nutrient status: A critical evaluation of guidelines for optimal yield in Israel. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 420–428. [[CrossRef](#)]

4. Mahmud, K.; Creek, A.; Monks, D. Five different pruning strategies were not able to improve productivity of a densely planted ‘Salustiana’ common orange block in the short term. In *Proceedings of the XV International Citrus Congress*; The International Society for Horticultural Science (ISHS): Korbeek-Lo, Belgium, 2024; Volume 1448, pp. 317–324. [\[CrossRef\]](#)
5. Aron, Y.; Monselise, S.; Goren, R.; Costo, J. Chemical control of vegetative growth in citrus trees by paclobutrazol. *HortScience* **1985**, *20*, 96–98. [\[CrossRef\]](#)
6. Mudzungu, M.; Theron, K.I.; Rabe, E. Effects of early winter gibberellic acid and mineral oil applications on flowering of young non-bearing clementine (*Citrus reticulata* Blanco.) and satsuma (*Citrus unshiu* marc.) trees. *S. Afr. J. Plant Soil* **2001**, *18*, 176–178. [\[CrossRef\]](#)
7. Spann, T.M.; Tsagkarakis, A.E.; Syvertsen, J.P. Managing citrus tree growth with hedging and plant growth regulators: Strategies for reducing psyllid feeding and huanglongbing infection. *Proc. Fla. State Hortic. Soc.* **2009**, *122*, 161–165.
8. Monselise, S.P.; Halevy, A.H. Chemical inhibition of citrus bud growth and its effect on flower induction. In *Bulletin of the Research Council of Israel*; Weizmann Science Press of Israel: Jerusalem, Israel, 1964; pp. 52–56.
9. Delgado, R.; Casanova, L.; Rodríguez, R. Effects of paclobutrazol on growth and flowering of orange trees. *Proc. Fla. State Hortic. Soc.* **1986**, *99*, 23–26.
10. Agustí, M.; Zaragoza, S.; Bleiholder, H. Effect of paclobutrazol on Clementine mandarin trees. *Proc. Int. Soc. Citric.* **1987**, *1*, 233–236.
11. Stander, O.P.J. *Critical Factors Concomitant to the Physiological Development of Alternate Bearing in Citrus (Citrus spp.)*; Stellenbosch University: Stellenbosch, South Africa, 2018.
12. Le Roux, S.; Barry, G.H. Vegetative growth responses of citrus nursery trees to various growth retardants. *HortTechnology* **2010**, *20*, 197–201. [\[CrossRef\]](#)
13. Hedden, P.; Graebe, J.E. Inhibition of gibberellin biosynthesis by paclobutrazol in cell-free homogenates of *Cucurbita maxima* endosperm and *Malus pumila* embryos. *J. Plant Growth Regul.* **1985**, *4*, 111–122. [\[CrossRef\]](#)
14. Ogata, T.; Hasukawa, H.; Shiozaki, S.; Horiuchi, S.; Kawase, K.; Iwagaki, I.; Okuda, H. Seasonal changes in endogenous gibberellin contents in satsuma mandarin during flower differentiation and the influence of paclobutrazol on gibberellin synthesis. *J. Jpn. Soc. Hortic. Sci.* **1996**, *65*, 245–253. [\[CrossRef\]](#)
15. Wittenbach, V.A.; Bukovac, M.J.; Hendershott, C.H. The influence of paclobutrazol on growth and return bloom in apple. *Acta Hortic.* **1986**, *179*, 93–100.
16. Van Zyl, C.P. *Studies on the Seedless Fruit Set of Valencia Oranges*; Stellenbosch University: Stellenbosch, South Africa, 2021.
17. Stander, O.; Cronje, P. Yield improvement in ‘Nadorcott’ mandarin using uniconazole-p and gibberellic acid. In *Proceedings of the XV International Citrus Congress 1448*; The International Society for Horticultural Science (ISHS): Korbeek-Lo, Belgium, 2024; pp. 387–394. [\[CrossRef\]](#)
18. Rademacher, W. Growth retardants: Effects on gibberellin biosynthesis and other metabolic pathways. *Annu. Rev. Plant Biol.* **2000**, *51*, 501–531. [\[CrossRef\]](#)
19. Dunlop, M.Z.K.R. Using Prohexadione-Calcium (Apogee®) to Control Vegetative Flush Growth in Citrus. *Proc. Fla. State Hortic. Soc.* **2005**, *118*, 80–85.
20. Maynard, D.N. Effect of gibberellin-inhibiting growth retardants (CCC and daminozide) on citrus tree growth. *Proc. Fla. State Hortic. Soc.* **1970**, *83*, 73–78.
21. Coggins, C.W., Jr. Use of growth regulators to delay maturity and prolong shelf life of citrus. In *Proceedings of the Symposium on Growth Regulators in Fruit Production*; International Society for Horticultural Science: Korbeek-Lo, Belgium, 1972; Volume 34, pp. 469–472. [\[CrossRef\]](#)
22. Young, R.H.; Jahn, O.L.; Smoot, J. Coloring and loosening of citrus fruits with ethephon. In *Proceedings of the Florida State Horticultural Society*; Florida State Horticultural Society: Fort Lauderdale, FL, USA, 1974; pp. 24–28.
23. Yıldırım, B.; Yeşiloğlu, T.; İncesu, M.; Kamiloğlu, M.; Çimen, B.; Tamer, Ş. Effects of 2,4-DP (2,4-dichlorophenoxypropionic acid) plant growth regulator on fruit size and yield of Valencia oranges (*Citrus sinensis* Osb.). *N. Z. J. Crop Hortic. Sci.* **2012**, *40*, 55–64. [\[CrossRef\]](#)
24. Agustí, M.; El-Otmani, M.; Aznar, M.; Juan, M.; Almela, V. Effect of 3,5,6-trichloro-2-pyridyloxyacetic acid on clementine early fruitlet development and on fruit size at maturity. *J. Hortic. Sci.* **1995**, *70*, 955–962. [\[CrossRef\]](#)
25. Stover, E.W. *Chemical Thinning of Citrus with NAA for Bigger Fruit, Less Branch Breakage, and More Regular Cropping*; University of Florida Cooperative Extension Service, Institute of Food: Gainesville, FL, USA, 2001.
26. Stover, E.; Ciliento, S.; Myers, M. Trunk sprouting and growth of citrus as affected by NAA, aluminum foil, and plastic trunk wraps. *HortScience* **2006**, *41*, 1612–1615. [\[CrossRef\]](#)
27. Muñoz-Fambuena, N.; Mesejo, C.; González-Mas, M.C.; Iglesias, D.J.; Primo-Millo, E.; Agustí, M. Gibberellic acid reduces flowering intensity in sweet orange [*Citrus sinensis* (L.) Osbeck] by repressing *CiFT* gene expression. *J. Plant Growth Regul.* **2012**, *31*, 529–536. [\[CrossRef\]](#)

28. Goldberg-Moeller, R.; Shalom, L.; Shlizerman, L.; Samuels, S.; Zur, N.; Ophir, R.; Blumwald, E.; Sadka, A. Effects of gibberellin treatment during flowering induction period on global gene expression and the transcription of flowering-control genes in Citrus buds. *Plant Sci.* **2013**, *198*, 46–57. [\[CrossRef\]](#)
29. Martinelli, F.; Dolan, D.; Fileccia, V.; Reagan, R.L.; Phu, M.; Spann, T.M.; McCollum, T.G.; Dandekar, A.M. Molecular responses to small regulating molecules against huanglongbing disease. *PLoS ONE* **2016**, *11*, e0159610. [\[CrossRef\]](#)
30. Martínez-Fuentes, A.; Mesejo, C.; Munoz-Fambuena, N.; Reig, C.; González-Mas, M.C.; Iglesias, D.J.; Primo-Millo, E.; Agustí, M. Fruit load restricts the flowering promotion effect of paclobutrazol in alternate bearing Citrus spp. *Sci. Hortic.* **2013**, *151*, 122–127. [\[CrossRef\]](#)
31. El-Otmani, M.; Goumari, M.; Talhi, M.; Wakkar, L.; Srairi, I.; Lovatt, C. Effect of Paclobutrazol on Vegetative Growth, Flowering and Fruiting of the ‘Nour’ Clementine, an Alternate Bearing Cultivar. In *Proceedings of the International Society of Citriculture*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2004; p. 543.
32. Koshita, Y.; Takahara, T.; Ogata, T.; Goto, A. Involvement of endogenous plant hormones (IAA, ABA, GAs) in leaves and flower bud formation of satsuma mandarin (*Citrus unshiu* Marc.). *Sci. Hortic.* **1999**, *79*, 185–194. [\[CrossRef\]](#)
33. Yelenosky, G.; Vu, C.; Bausher, M. Paclobutrazol-Induced Dwarfing of ‘Valencia’ Orange Trees. In *Proceedings of the Florida State Horticultural Society*; Florida State Horticultural Society: Fort Lauderdale, FL, USA, 1993; pp. 329–331.
34. Bausher, M.G.; Yelenosky, G. Sensitivity of Potted Citrus Plants to Top Sprays and Soil Applications of Paclobutrazol. *HortScience* **1986**, *21*, 141–143. [\[CrossRef\]](#)
35. Davis, T.D.; Steffens, G.L.; Sankhla, N. Triazole plant growth regulators. *Hortic. Rev.* **1988**, *10*, 63–105. [\[CrossRef\]](#)
36. Garner, L.C.; Zheng, Y.; Khuong, T.; Lovatt, C.J. Prohexadione-calcium affects shoot growth of evergreen subtropical woody perennials differently than deciduous temperate zone woody perennials—Is it a case of apples and oranges? *Acta Hortic.* **2010**, *884*, 249–256. [\[CrossRef\]](#)
37. Desta, B.; Amare, G. Paclobutrazol as a plant growth regulator. *Chem. Biol. Technol. Agric.* **2021**, *8*, 1. [\[CrossRef\]](#)
38. Ashraf, N.; Ashraf, M. Response of Growth Inhibitor Paclobutrazol in Fruit Crops. In *Prunus*; IntechOpen: London, UK, 2020; pp. 1–9.
39. Vu, J.C.; Yelenosky, G. Growth and photosynthesis of sweet orange plants treated with paclobutrazol. *J. Plant Growth Regul.* **1992**, *11*, 85–89. [\[CrossRef\]](#)
40. Curry, E.A.; Williams, M.W. Promalin or GA₃ increase pedicel and fruit length and leaf size of ‘Delicious’ apples treated with paclobutrazol. *HortScience* **1983**, *18*, 214–215. [\[CrossRef\]](#)
41. Team, B.T.S. Adjusting Prohexadione Application Rates Based on Environmental Conditions. In *BenchChem Technical Bulletin*; BenchChem Technical Support Team: Ontario, CA, USA, 2026; pp. 1–9.
42. Zhang, X.; Zhang, Q.; Karkee, M.; Whiting, M.D. Machinery-Canopy Interactions in Tree Fruit Crops. In *Fundamentals of Agricultural and Field Robotics*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 415–442.
43. Krajewski, A.; Schumann, A.; Ebert, T.; Oswalt, C.; Ferrarezi, R.; Waldo, L. *Management of Citrus Tree Canopies for Fresh-Fruit Production: SL485/SS698, 1/2021*; University of Florida, Institute of Food and Agricultural Sciences (UF/IFAS) Extension: Gainesville, FL, USA, 2021. [\[CrossRef\]](#)
44. Monselise, S.P.; Goren, R. The Role of Internal Factors and Exogenous Control in Flowering, Peel Growth, and Abscission in Citrus. *HortScience* **1978**, *13*, 134–139. [\[CrossRef\]](#)
45. Delgado, R.; Casamayor, R.; Rodriguez, J.; Cruz, P.; Fajardo, R. Paclobutrazol effects on oranges under tropical conditions. In *Proceedings of the V International Symposium on Growth Regulators in Fruit Production*; International Society for Horticultural Science: Leuven, Belgium, 1985; Volume 179, pp. 537–544. [\[CrossRef\]](#)
46. Monselise, S.P. Growth retardation of shoot and peel growth in citrus by paclobutrazol. In *Proceedings of the V International Symposium on Growth Regulators in Fruit Production*; International Society for Horticultural Science: Leuven, Belgium, 1985; Volume 179, pp. 529–536. [\[CrossRef\]](#)
47. Greenberg, J.; Goldschmidt, E.; Goren, R. Potential and limitations of the use of paclobutrazol in citrus orchards in Israel. In *Proceedings of the VII International Symposium on Plant Growth Regulators in Fruit Production*; International Society for Horticultural Science: Leuven, Belgium, 1992; Volume 329, pp. 58–61.
48. Goldschmidt, E.E. Carbohydrate supply as a critical factor for citrus fruit development and productivity. *HortScience* **1999**, *34*, 1020–1024. [\[CrossRef\]](#)
49. Guardiola, J.; Monerri, C.; Agusti, M. The inhibitory effect of gibberellic acid on flowering in Citrus. *Physiol. Plant.* **1982**, *55*, 136–142. [\[CrossRef\]](#)
50. Goldschmidt, E.; Aschkenazi, N.; Herzano, Y.; Schaffer, A.A.; Monselise, S. A role for carbohydrate levels in the control of flowering in citrus. *Sci. Hortic.* **1985**, *26*, 159–166. [\[CrossRef\]](#)
51. Okuda, H.; Kihara, T.; Iwagaki, I.; Kawase, K. Effects of annual foliar applications of paclobutrazol for 9 years on the growth, yield and fruit quality of satsuma mandarin trees. *Bull. Hyogo Prefect. Agric. Inst.* **1994**, *46*, 51–56. Available online: <https://www.cabidigitallibrary.org/doi/full/10.5555/19950309121> (accessed on 14 August 2026).

52. Garcia-Luis, A.; Fornes, F.; Sanz, A.; Guardiola, J. The regulation of flowering and fruit set in Citrus: Relationship with carbohydrate levels. *Isr. J. Bot.* **1988**, *37*, 189–201. [CrossRef]
53. Orozco-Meléndez, L.R.; Hernández-Rodríguez, O.A.; Cruz-Álvarez, O.; Robles-Hernández, L.; Ávila-Quezada, G.D.; Chavez, E.S.; Porras-Flores, D.A.; Ojeda-Barrios, D.L. Paclobutrazol and its use in fruit production: A review. *Phyton* **2022**, *91*, 1–12. [CrossRef]
54. Cruz, M.D.C.M.D.; Siqueira, D.L.D.; Salomão, L.C.C.; Cecon, P.R. Influência do paclobutrazol e da temperatura ambiente sobre o florescimento e frutificação da limeira ácida Tahiti. *Ciênc. E Agrotecnologia* **2008**, *32*, 1148–1153. [CrossRef]
55. Mauk, C.S.; Bauscher, M.G.; Yelenosky, G. Influence of growth regulator treatments on dry matter production, fruit abscission, and ¹⁴C-assimilate partitioning in citrus. *J. Plant Growth Regul.* **1986**, *5*, 111–120. [CrossRef]
56. Delgado, R.; Casamayor, R.; Rodriguez, J.; Cruz, P.; Fajardo, R. Paclobutrazol effects on mandarin under tropical conditions. In *Proceedings of the V International Symposium on Growth Regulators in Fruit Production*; International Society for Horticultural Science: Korbeek-Lo, Belgium, 1985; Volume 179, pp. 545–548. [CrossRef]
57. Kojima, K.; Goto, A.; Nakashima, S. Effects of uniconazole-P on abscission and endogenous ABA, IAA, and GA-like substances levels of *Satsuma mandarin* fruitlet. *Biosci. Biotechnol. Biochem.* **1996**, *60*, 901–902. [CrossRef]
58. Kojima, K. Changes of ABA, IAA and GAs levels in reproductive organs of citrus. *Jpn. Agric. Res. Q.* **1997**, *31*, 271–280. Available online: https://www.jircas.go.jp/sites/default/files/publication/jarq/31-4-271-280_0.pdf (accessed on 14 August 2026).
59. Baskaran, A.; Chandrasekaran, R. Biochemical changes in fruit quality through paclobutrazol application on acid lime (*Citrus aurantifolia* Swingle). *Madras Agric. J.* **2023**, *100*, 499–500. [CrossRef]
60. Rehman, M.; Singh, Z.; Khurshid, T. Pre-harvest spray application of prohexadione-calcium and paclobutrazol improves rind colour and regulates fruit quality in M7 Navel oranges. *Sci. Hortic.* **2018**, *234*, 87–94. [CrossRef]
61. Ye, H.; Luo, Y.; Li, Y.; Wang, X.; He, H.; Jiang, J.; Yu, J.; Zhang, C. Residues and dietary risk assessment of prohexadione-Ca and uniconazole in *Oryza sativa* L. and *Citrus reticulata* Blanco by liquid chromatography-tandem mass spectrometry. *Molecules* **2023**, *28*, 2611. [CrossRef]
62. Stander, O.P.; Cronjé, P.J. Reviewing the commercial potential of hand thinning in citrus with a cost-benefit analysis of summer hand thinning of ‘Nadorcott’ mandarin. *HortTechnology* **2016**, *26*, 206–212. [CrossRef]
63. Stander, O.P.; Barry, G.; Cronjé, P. Fruit-load-induced starch accumulation causes leaf chlorosis in “off” ‘Nadorcott’ mandarin trees. *Sci. Hortic.* **2017**, *222*, 62–68. [CrossRef]
64. Haugen, C.; Tucker, K.; Smalling, A.; Bick, E.; Hoover, S.; Ehlen, G.; Watson, T.; Bernick, S. The Efficacy of Paclobutrazol Soil Application as it Relates to the Timing of Utility Right-of-Way Pruning. *Arboric. Urban For. (AUF)* **2016**, *42*, 95–101. [CrossRef]
65. Agustí, M. Observations on harvesting efficiency in paclobutrazol-treated ‘Navelina’ orange orchards. Personal communication. 2019.
66. Garcerá, C.; Fonte, A.; Salcedo, R.; Soler, A.; Chueca, P. Dose expression for pesticide application in citrus: Influence of canopy size and sprayer. *Agronomy* **2020**, *10*, 1887. [CrossRef]
67. Vashisth, T.; Zekri, M.; Alferez, F.; Shahid, M.A. 2025–2026 *Florida Citrus Production Guide: Canopy Management*; University of Florida Institute of Food and Agricultural Sciences (UF/IFAS) Extension: Gainesville, FL, USA, 2025. [CrossRef]
68. Germanà, C.; Continella, A.; Tribulato, E. Effect of net shading on the vegetative-productive state of citrus trees. *Riv. DI Fruttic. E DI Ortofloric.* **2001**, *63*, 41–46.
69. Lavee, S.; Haskal, A. Partial fruiting regulation of olive trees (*Olea europaea* L.) with paclobutrazol and gibberellic acid in the orchard. *Adv. Hortic. Sci.* **1993**, *7*, 83–86. Available online: <https://www.jstor.org/stable/42881682?seq=1>.
70. Singerman, A.; Lence, S.H.; Useche, P. Uncertainty undermines area-wide pest management for citrus greening in Florida. *Choices* **2017**, *32*, 1–10. Available online: <https://www.jstor.org/stable/90015003?seq=1> (accessed on 21 July 2026).
71. Hadlow, A.; Allan, P. Effect of paclobutrazol on vegetative growth in citrus nursery trees. *S. Afr. J. Plant Soil* **1988**, *6*, 50–52. Available online: https://hdl.handle.net/10520/AJA02571862_176 (accessed on 21 July 2026).
72. Yelenosky, G.; Vu, J.; Wutscher, H. Influence of paclobutrazol in the soil on growth, nutrient elements in the leaves, and flood/freeze tolerance of citrus rootstock seedlings. *J. Plant Growth Regul.* **1995**, *14*, 129–134. [CrossRef]
73. Diwan, G.; Sahu, M.K.; Tiwari, S.; Ahirwar, K.; Halder, A.; Rangare, N.; Banjare, K.; Kumar, S.; Ahirwar, M.; Samaiya, R. Effect of new plant growth regulator prohexadione-Ca on horticultural crops. *Agric. Mech. Asia Afr. Lat. Am.* **2022**, *53*, 9671–9681. Available online: https://www.researchgate.net/profile/Garima-Diwan-2/publication/372534215_Effect_of_New_Plant_Growth_Regulator_Prohexadione-Ca_on_Horticultural_Crops/links/64bd18de8de7ed28babca45c/Effect-of-New-Plant-Growth-Regulator-Prohexadione-Ca-on-Horticultural-Crops.pdf (accessed on 14 August 2026).
74. Bukovac, M.; Cooper, J.; Whitmoyer, R.; Brazee, R. Spray application plays a determining role in performance of systemic compounds applied to the foliage of fruit plants. *Int. Symp. Foliar Nutr. Perenn. Fruit. Plants* **2001**, *594*, 65–75. [CrossRef]
75. Stander, O.P.; Barry, G.H.; Cronjé, P.J. Fruit load limits root growth, summer vegetative shoot development, and flowering in alternate-bearing ‘Nadorcott’ mandarin trees. *J. Am. Soc. Hortic. Sci.* **2018**, *143*, 213–225. [CrossRef]
76. Diepenbrock, L.M.; Vashisth, D.M. (Eds.) *Florida Citrus Production Guide 2025–2026*; University of Florida, Institute of Food and Agricultural Sciences Extension: Gainesville, FL, USA, 2025; pp. 97–102.

77. Soto, A.C.; Sánchez, D.P.; Sánchez, L.P.; Zambrano, L.A.; Zambrano, Á.S.; Ponce, C.V.; García, G.C.; Rezabala, L.S.; Quiñónez, L.C.; Alcívar, F.A. Optimizing *Citrus aurantifolia* (Christm. Swingle) Production Through Integrated Irrigation and Growth Regulation Strategies. *Agronomy* **2025**, *15*, 1853. [\[CrossRef\]](#)
78. Garmendia, A.; Beltran, R.; Zornoza, C.; Garcia-Breijo, F.J.; Reig, J.; Merle, H. Gibberellic acid in Citrus spp. flowering and fruiting: A systematic review. *PLoS ONE* **2019**, *14*, e0223147. [\[CrossRef\]](#)
79. De Siqueira, D.L.; Salomão, L.C.C. Effects of paclobutrazol on growth and flowering of citrus. *Citrus Res. Technol.* **2017**, *23*, 355–369.
80. Kondle, R.; Gurung, S.; Bhowmick, N. Effect of pruning and paclobutrazol application of acid lime (*Citrus aurantifolia* Swingle) cv. Balaji under Sub-Himalayan Terai region of West Bengal. *Int. J. Chem. Stud.* **2020**, *8*, 201–206. [\[CrossRef\]](#)
81. Bower, J. Citrus: FS Davies and LG Albrigo, CAB International, Wallingford, UK, 1994, 250, ISBN 0-85198-867-9. *Sci. Hortic.* **1995**, *62*, 147–148.
82. Singerman, A.; Rogers, M.E. The economic challenges of dealing with citrus greening: The case of Florida. *J. Integr. Pest Manag.* **2020**, *11*, 3. [\[CrossRef\]](#)
83. Garcia Lidon, A.; Mateo Bernal, I.; Conesa Martinez, A.; Bleda Fernandez, F.; Porras Castillo, I. Influence of paclobutrazol in citrus rootstocks. *Investig. Agrar. Prod. Y Protección Veg.* **2001**, *16*, 29–69.
84. Singh, I.; Parthasarathy, V.; Handique, P. Effect of Paclobutrazol Drenching on Growth of Micropropagated and Seedling Plantlets of 12 Citrus Cultivars: Principal Component Analysis. *Indian J. Plant Genet. Resour.* **2001**, *14*, 378–381. Available online: <https://indianjournals.com/article/ijpgr-14-3-013> (accessed on 21 July 2026).
85. Wang, X.; Qi, P.; Yang, G.; Wang, X.; Zhang, H.; Xu, H.; Wang, Z.; Wang, Q. Enantioselective degradation of (2RS, 3RS)-paclobutrazol in peach and mandarin under field conditions. *Chirality* **2014**, *26*, 400–404. [\[CrossRef\]](#)
86. Kumar, A.; Bhuj, B.D.; Dhar, S.; Kumar, R.; Rizwan, M.; Thapa, R.K.; Kumar, H.; Jyoti, K.V.; Singh, A.; Kumar, V.; et al. Effect of paclobutrazole (PBZ) on fruit production: A review. *Int. Res. J. Plant Sci.* **2023**, *14*, 1–20. [\[CrossRef\]](#)
87. Lovatt, C.; Zheng, Y.; Hake, K. A new look at the Kraus-Kraybill hypothesis and flowering in *Citrus*. In Proceedings of the Sixth International Citrus Congress, Tel Aviv, Israel, 6–11 March 1988; Volume 1, pp. 475–483. Available online: <https://www.cabidigitallibrary.org/doi/full/10.5555/19900359556> (accessed on 21 July 2026).
88. Goldhamer, D. Using Regulated Deficit Irrigation to Optimize Fruit Size in Late Harvest Navels. In *2005 Annual Report*; Citrus Research Board: Visalia, CA, USA, 2006; p. 11.
89. Hutton, R.; Landsberg, J.; Sutton, B. Timing irrigation to suit citrus phenology: A means of reducing water use without compromising fruit yield and quality? *Aust. J. Exp. Agric.* **2007**, *47*, 71–80. [\[CrossRef\]](#)
90. Diepenbrock, L.M.; Qureshi, J.; Stelinski, L. *2025–2026 Florida Citrus Production Guide: Asian Citrus Psyllid*; UF/IFAS Extension: Gainesville, FL, USA, 2025.
91. Hota, D.; Karna, A.; Behera, S.; Mishra, G. Use of Plant Growth Regulators in Canopy Management. Biomolecule Reports—An International e-Newsletter. 2017. Available online: https://www.researchgate.net/publication/340874983_Use_of_plant_growth_regulators_in_canopy_management (accessed on 21 July 2026).
92. Vashisth, T. *Managing the Health and Productivity of HLB-Affected Groves: HS1288*, 1/2017; University of Florida, Institute of Food and Agricultural Sciences Extension: Gainesville, FL, USA, 2017.
93. Rouse, B.; Futch, S. *Start Now to Design Citrus Groves for Mechanical Harvesting: HS974/HS219*, 9/2004; University of Florida, Institute of Food and Agricultural Sciences (UF/IFAS) Extension: Gainesville, FL, USA, 2004; pp. 1–4.
94. Agustí, M.; Reig, C.; Martínez-Fuentes, A.; Mesejo, C. Advances in citrus flowering: A review. *Front. Plant Sci.* **2022**, *13*, 1–17. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.