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# Impacts of gibberellin application on citrus: an overview from seed germination to fruit quality enhancement

**Abstract.** Gibberellins are key plant hormones, and their application in citrus plants is frequently reported. This review aims to provide an overview of the application of gibberellic acid (GA3) in citrus cultivation, emphasizing their effects on growth, flowering, fruit quality, and ripening. Citrus fruits often face challenges like irregular fruit set, size inconsistency, and environmental stress, impacting yield and profitability, with exogenous gibberellin application as a potential solution. Applying gibberellins can accelerate citrus seed germination and seedling growth, enhance vegetative growth, inhibit flowering, delay fruit ripening, and improve fruit quality. However, the efficacy of gibberellins varies across species and conditions, highlighting the need for reference studies. This work presents an alternative option for optimizing gibberellin use to support sustainable citrus production practices.

**Keywords:** Exogenous Gibberellin · Flowering · Fruit Ripening · Fruit Quality · Seed Germination.

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## Introduction

Gibberellins, a class of plant hormones, have long been recognized for their pivotal role in regulating a wide range of plant physiological processes. Since their discovery, these hormones have been widely studied and used in agriculture to boost plant growth, development, and yield. Citrus trees have become a major focus of research on gibberellins because of their economic value and the challenges involved in growing them (Gill et al., 2022).

Citrus fruits, including oranges (*Citrus sinensis*), lemons (*C. limon*), grapefruits (*C. paradisi*), and mandarins (*C. reticulate*), are among the most widely grown and consumed fruits globally (Spreen et al., 2020; Richa et al., 2023). These fruits are not only valued for their nutritional content and refreshing flavor but also represent a critical component of the agricultural economy in many regions (Vashisth & Kadyampakeni, 2020). However, citrus cultivation is often challenged by issues such as irregular fruit set (Ahmad et al., 2022), size variability (Singh et al., 2022), alternate bearing cycles (Raveh et al., 2020; Goldschmidt & Sadka, 2021; Hazarika, 2023), and susceptibility to environmental stressors (Bacelar et al., 2024). These challenges can significantly affect fruit quality, marketable yield, and, ultimately, the profitability of citrus farming.

In response to these challenges, the application of gibberellins in citrus cultivation has gained considerable attention from researchers and growers. Gibberellins are known to influence several key aspects of plant growth and development, including cell elongation, seed germination, flowering, and fruit development (Miransari & Smith, 2014; Hedden & Sponsel, 2015; Rahman et al., 2018; Hedden & Thomas, 2016; Vishal & Kumar, 2018; Binenbaum et al., 2018). Gibberellin has shown the potential to address some of the most pressing issues in citrus cultivation by promoting more uniform fruit development (Livingston & Vashisth, 2022), synchronizing flowering (Bauerle, 2022), enhancing fruit size (Elmenofy et al., 2021), and improving overall yield (Kumara et al., 2023).

This review aims to provide a comprehensive overview of the current knowledge on gibberellin application in citrus, exploring its effects on growth, yield, and quality parameters. By exploring the existing literature, this review seeks to highlight the potential benefits and limitations of gibberellin use in citrus cultivation, offering insights for researchers and growers looking to optimize citrus production. Through a detailed examination of gibberellin's impact on citrus, this review contributes to the ongoing efforts to improve agricultural practices and enhance the economic viability of citrus farming.

**Gibberellin accelerates seed germination and seedling growth.** Gibberellins can significantly enhance the germination process by breaking seed dormancy (Lee et al., 2022), promoting the mobilization of stored nutrients (Niharika et al., 2021; Xiong et al., 2022), and accelerating the radicle emergence (Wu et al., 2021; Ge et al., 2023).

**Table 1. Impact of gibberellin on seed germination and seedling growth of citrus.**

| Citrus Species | Gibberellin Concentration | Application Time | Effect | Reference |
|---|---|---|---|---|
| Kagzi Lime | 80 mg/L* | 12 hours | Increase germination percentage and growth | Dilip et al., 2017 |
| Acid Lime | 3000 mg/L | Seed soaking overnight | Maximum growth in respect of germination percentage, height of seedling, number of leaves, stem diameter, and leaf area | Meshram et al. (2015); (Al-Musawi et al., 2020) |
| Cleopatra mandarin | 2000 mg/L* | Seed soaked 24 hours | Increase germination percentage, leaf mineral content and total carbohydrate content | Sharaf et al. (2016); El-Sayed (2018) |
| Pummelo | 50 mg/L* | Seed soaked 24 hours | Accelerate germination and growth | Khopkar et al., 2017 |
| Rangpur lime | 750 mg/L | 16 hours of light at 30 °C and 8 hours of darkness at 20 °C | Accelerate germination, form vigorous seedlings and increase SOD and POD activity | Neto et al., 2024 |

*: converted from ppm

This results in a more uniform and faster germination rate compared to untreated seeds. Additionally, gibberellin application can influence seedling growth by stimulating cell elongation and division (Shah et al., 2023), leading to taller and more vigorous seedlings with enhanced root and shoot development. The overall impact of gibberellins on citrus seed germination and seedling growth is highly beneficial, contributing to improved early-stage plant establishment and potentially higher yields (Adhikary, 2022).

Germination and seedling growth parameters were enhanced by soaking seeds from various plants in GA3 and Zn. Studies by Meshram et al. (2015) on acid lime, Sharaf et al. (2016) on Cleopatra mandarin and Rangpur lime, Dilip et al. (2017) on Kagzi lime and Rangpur lime, Khopkar et al. (2017) on Pummelo, and El-Sayed (2018) on Cleopatra mandarin have demonstrated these effects. The germination percentages were significantly increased following by GA3 treatments. However, higher concentrations of GA3 and $ZnSO_4$ (750, 1500, and 3000 mg/L) led to a reduction of seed germination percentage of acid lime, while promoting better vegetative growth (Al-Musawi et al., 2020).

Gibberellic acid (GA) at 80 ppm has been shown to significantly affect seed germination and seedling growth in Rangpur lime, making it a recommended treatment for growers seeking enhanced growth and yield (Dilip et al., 2017). The application of GA3 significantly accelerates the germination process and promotes improved seedling growth and development, resulting in more vigorous seedlings. Furthermore, GA3 treatment not only accelerates germination but also increases enzymatic activities, such as superoxide dismutase (SOD) and peroxidase (POD), which help mitigate oxidative stress and enhance seedling vigor in Rangpur lime cv. Santa Cruz (Neto et al., 2024). Gibberellin increases the activities of antioxidant enzymes like SOD and POD because it activates protective mechanisms against oxidative stress (Forghani et al., 2020; Zhu et al., 2019). Gibberellins are involved in the plant's response to stress, including oxidative stress, which occurs when there is an accumulation of ROS such as superoxide anions ($O_2^-$) and hydrogen peroxide ($H_2O_2$) (Mishra et al., 2017). Both SOD and POD are antioxidant enzymes that help neutralize these harmful ROS and protect plant cells from oxidative damage. Accordingly, Table 1 summarizes several studies on the effects of various gibberellin concentrations on seed germination and seedling growth in citrus.

**Gibberellin enhances vegetative growth**. By stimulating cell division and elongation, gibberellin can increase shoot length, leaf area, and overall plant vigor. This enhanced vegetative growth is beneficial for citrus trees, as it can lead to increased yield potential and improved fruit quality. Moreover, gibberellin can influence the branching pattern of citrus trees (Castro-Camba, 2022). By promoting the development of lateral shoots, gibberellin helps create a more open and productive canopy (Ni et al., 2015), which facilitates better light penetration (Huber et al., 2021) and enhances fruit set. While gibberellin application can be a valuable tool for improving citrus vegetative growth, it is important to note that the optimal concentration and timing of application may vary depending on the citrus variety, environmental conditions, and specific growth objectives.

**Table 2. Impact of various applications of gibberellin on vegetative growth of citrus.**

| Citrus Species | Gibberellin Concentration | Application Time | Effect | Reference |
|---|---|---|---|---|
| Kaffir lime | 200 mg/L | Once a week until 8 weeks | Longest flush, increase in the number and weight of leaves | Budiarto et al., 2023 |
| Acid lime cv. Hasta Bahar | 50 mg/L | Once in 7-10 days interval | Increase in plant height, canopy spreads, canopy volume, and shoot length | Rai et al., 2018 |
| Acid lime | 3000 mg/L | - | Increase plant height, stem diameter, leaf number, leaf area, plant fresh and dry weight | Al-Musawi et al., 2020 |
| Acid lime cv. Vikram | 50 mg/L | - | Increase height, number of leaves, and girth of stem | Parmar et al., 2019 |

Without pruning, the application of 0.02% gibberellin could produce the longest flush, with increases in the number and weight of leaves by about 77% and 64%, respectively, compared with the control (Budiarto et al., 2023). Gibberellin application also significantly influenced the number of shoots. Plant height, stem diameter, leaf number, leaf area, and both fresh and dry plant weight were progressively increased with higher concentrations of GA3 (Al-Musawi et al., 2020). GA3 application at 50 ppm recorded the highest increase in acid lime height, canopy spreads, canopy volume, and shoot length (Rai et al., 2018). Table 2 summarizes various studies that examine the effects of different gibberellin concentrations on vegetative growth of several citrus species.

**Gibberellin inhibits flowering**. Earlier study indicates that gibberellin application before flowering can counteract the floral induction in citrus (Garmendia et al., 2019). In citrus trees, gibberellin application can significantly influence the timing and intensity of flowering (Agustí et al., 2022). These hormones are commonly used to manipulate the flowering process, particularly in commercial citrus production, to enhance yield and synchronize fruit development. Gibberellins promote floral bud growth, break dormancy, and encourage early flowering (Thirugnanasambantham et al., 2020). However, the effects of gibberellin application can vary depending on the timing, concentration, and environmental conditions. When applied appropriately, gibberellins can result in more uniform flowering, which is beneficial for the overall productivity and quality of citrus crops. Conversely, improper application can lead to uneven flowering or excessive vegetative growth at the expense of flower production, ultimately affecting fruit yield. Therefore, understanding the optimal conditions and proper use of gibberellins is crucial for maximizing their benefits in citrus cultivation.

Exogenous GA applications during the induction period consistently reduce flower formation (Kupke et al., 2022). The use of 40 mg/L GA3 in two, three, or four sequential applications, from May to June, May to July, and from May to August, at 21-day intervals, reduces the intensity of flowering and sprouting in alternate-bearing plants during the subsequent spring (Griebeler et al., 2021). This treatment increases the number of mixed shoots while decreasing the number of floral shoots. Gibberellins increase the number of mixed shoots by promoting vegetative growth and cell elongation. At the same time, they decrease the number of floral shoots because they inhibit the transition from vegetative growth to flowering due to the repression of the expression of the Citrus FLOWERING LOCUS T (CiFT) gene (Bennici et al., 2021). Flowering in citrus is inhibited by the application of gibberellins before inductive stress conditions. As a result, antigibberellin chemical compounds, such as CCC, SADH, benzothiazole, and triazoles have been observed to induce flowering in citrus (Huchche & Ladaniya, 2014). The application of GA3 at 21 mg/L reduced the formation of floral structures, leading to a quadratic increase in field production by reducing competition for assimilates among fruits in 'Tahiti' acid lime (Pereira et al., 2014).

**Gibberellin delays fruit ripening**. It is important to highlight the role of gibberellic acid in delaying fruit aging. GA treatments can reduce or correct peel disorders, such as blemishes and pitting, by creating a denser albedo texture when applied to citrus fruits still on the tree (Kalatippi, 2024). During the regreening process, fruits treated with GA turned green more rapidly. Compared to untreated fruits, GA treatment induces chlorophyll accumulation and decreases the content of carotenoids, such as β-cryptoxanthin, all-*trans*-violaxanthin, and 9-*cis*-violaxanthin, in Valencia oranges (Keawmanee et al., 2022).

Gibberellic acid delays peel senescence. In addition to its favorable effects on peel disorders, GA causes a typically undesirable delay in degreening, whether applied on the tree or after harvest (Lurie, 2024; Rezk et al., 2024). However, this effect has proven beneficial for lemons in cooler regions of California, where they mature later in the winter, as well as for grapefruits in semi-tropical areas (Aliyev & Latif, 2022; Adewoyin et al., 2023). Additionally, dipping harvested fruits in GA solutions helps delay the formation of pigments associated with fruit aging and preserves healthy peel tissues, a technique now being adopted on a commercial scale.

Pre-harvest application of GA3 has been shown to delay fruit softening (Ayaz et al., 2023), slow down rind color change (Yamaga et al., 2024), and reduce fruit drop and puffiness (Khalil, 2020). Gibberellins can extend the period

**Table 3. Impact of various applications of gibberellin on delay fruit ripening of citrus.**

| Citrus Species | Gibberellin Concentration | Application Time | Effect | Sources |
|---|---|---|---|---|
| Mandarin orange | 30 mg/L* | - | Extending shelf life and reducing physiological weight loss | Rokaya et al., 2016 |
| Valencia orange | 0.5 mg/L | Every 2 weeks for 3 times | Delays peel color development and increases PPF | Keawmanee et al., 2022 |
| Kumquat | 20 mg/L | - | Lower contents of abscisic acid and titratable acid | Cai et al., 2021 |

before ripening starts by slowing down the processes that lead to the breakdown of cellular structures and the loss of chlorophyll (Baseer et al., 2024). Ethylene is a key hormone for initiating ripening, gibberellins can interact with ethylene signaling to modify the timing or intensity of ripening (Alferez et al., 2021). Gibberellins can effectively enhance fruit storage quality by significantly increasing flesh firmness, reducing respiration rate, inhibiting the release of endogenous ethylene, and preventing fruit softening and ripening (Zhang et al., 2023). Additionally, GA3 improves both the internal and external quality of stored fruit by enhancing fruit shape, regulating color, delaying the decline of soluble solids, promoting sugar accumulation, and slowing vitamin loss. A gibberellin application at 20 ppm was particularly effective in increasing fruit weight and overall quality, while a concentration of 30 ppm was superior for extending shelf life and reducing physiological weight loss and decay in mandarin oranges (Rokaya et al., 2016). Pre-harvest application of GA3 spray at a concentration of 20 mg/L had a positive effect on the nutritional quality and exterior color of 'Jindan' kumquat fruits (Cai et al., 2021). The results also indicated that GA3 treatment significantly increased the contents of IAA, GA, ZRs, TSS, and VC in kumquat. Table 3 summarizes several studies on the effects of applying various concentrations of gibberellin on delay fruit ripening of citrus.

**Gibberellin improves fruit quality**. The application of gibberellins, particularly GA3, has been extensively studied for its effects on citrus fruiting. When applied to citrus trees, gibberellins can significantly influence fruit set, size, and quality. For example, GA3 application is known to enhance fruit set by reducing fruit drop during the early stages of development. It also promotes fruit enlargement by stimulating cell division and elongation, leading to larger and more uniform fruits. Additionally, gibberellins can delay fruit maturation, which is beneficial for extending the harvest period and improving fruit quality by allowing more time for sugar accumulation. However, the effects of gibberellin application can vary depending on the timing, concentration, and method of application, as well as the specific citrus variety being treated. Proper management of gibberellin application is crucial for maximizing its benefits and avoiding potential negative effects, such as excessive vegetative growth at the expense of fruit development.

Gibberellic acid at 50 ppm increased the level of Chlorophyll (Ch) a, Ch b, Ch total (Ch a+b), carotenoid content, fruit juice content, vitamin C, as well as the activities of superoxide dismutase (SOD) and peroxidase dismutase (POD). Meanwhile, the highest fruit firmness and total soluble solids (TSS) were recorded with 40 ppm GA3 (Khan et al., 2024). $GA_3$ can increase chlorophyll content in plants by promoting cell division and expansion, leading to larger and more functional chloroplasts (Bagnazari et al., 2018). It also enhances the activity of enzymes involved in chlorophyll biosynthesis, such as glutamyl tRNA reductase and porphobilinogen deaminase, which are critical for the production of chlorophyll (Chai et al., 2023). The increase in chlorophyll content improves the plant's ability to perform photosynthesis (Croft et al., 2017). This is important for energy production and growth, especially in young plants or during periods of active growth. $GA_3$ also affects the carotenoid biosynthesis pathway by stimulating the expression of genes encoding enzymes involved in carotenoid production, such as phytoene synthase and lycopene β-cyclase (Keawmanee et al., 2022).

**Table 4. Impact of various applications of gibberellin on fruit quality of citrus.**

| Citrus Species | Gibberellin Concentration | Application Time | Effect | Reference |
|---|---|---|---|---|
| Balady Lime | 20 mg/L | - | Improve physical and chemical fruit characteristics | Gomaa, 2020 |
| Bac Son mandarin fruit | 100 mg/L | - | Reduce the number of seeds and increase the quality | Hung et al., 2023 |
| Sweet lime | 50 mg/L | 5, 10 and 15 days after bud break | High values of Ch a, Ch b, Ch total, carotenoid, fruit juice, vitamin C, superoxide dismutase (SOD) and peroxidase dismutase (POD) activity | Khan et al., 2024 |
| Kinnow Mandarin | 25, 45, and 65 mg/L | At pre-harvest stage | Improved the physical and biochemical properties | Talat et al., 2020 |

$GA_3$ plays a role in fruit growth and development. It promotes cell division and elongation, leading to larger fruit size and increased juice yield (Chauhan et al., 2020). $GA_3$ can also influence the metabolic pathways that control the accumulation of sugars, acids, and other components in fruit Shinozaki et al., 2020; Du et al., 2024; Ochiki et al., 2024). $GA_3$ may influence the synthesis of vitamin C (ascorbic acid) by stimulating the enzymes involved in the biosynthetic pathway (Arya & Viji, 2024).

Spraying GA3 in combination with naphthalene acetic acid (NAA) significantly improved the physical and chemical characteristics of Balady lime fruit (*Citrus aurantifoli*a L) (Gomaa, 2020). In previous experiment, when fruit set increased excessively due to GA applications, a noticeable reduction in average fruit weight was recorded, indicating lower commercial value (Bisht et al., 2018). Spraying GA3 also resulted in a lower seed count and a higher actual yield in Bac Son mandarin fruit (Hung et al., 2023). The application of GA3 at 65 ppm significantly improved physical attributes such as peel color, fruit weight, and juice weight, while the application of GA3 at 25 ppm and 45 ppm enhanced the biochemical quality attributes (total soluble solids, acidity, ascorbic acid, antioxidants, phenols, flavonoids, and carotenoids) of Kinnow fruit (Talat et al., 2020). Table 4 summarizes various studies examining the effects of different concentrations of gibberellin on fruit quality of several citrus species.

**Future Perspective**. Gibberellin has shown significant promise in influencing various aspects of citrus growth and development. Future research could investigate deeper into the mechanisms by which gibberellin promotes seed germination, vegetative growth, and flowering in citrus. Additionally, exploring the potential of gibberellin inhibitors to delay fruit ripening and enhance fruit quality could offer innovative agricultural practices. Understanding the complex interactions between gibberellin and citrus physiology could allow researchers to develop targeted strategies to optimize fruit production and quality, ensuring a sustainable citrus supply for consumers worldwide.

Further studies might also focus on the effects of combining gibberellin with other plant growth regulators to identify synergistic effects that optimize growth stages, improve stress tolerance, and enhance nutrient uptake. This research could reveal methods to balance gibberellin with hormones such as auxin and cytokinin, potentially leading to proper management of plant physiology in response to environmental changes. Ultimately, continued exploration of gibberellin's multifaceted role in citrus development may result in the establishment of more adaptable, resource-efficient, and high-yielding orchards, supporting the global citrus supply and reducing the environmental footprint of citrus production.

## Conclusion

Gibberellins have been extensively studied for their potential to improve various aspects of citrus production. Gibberellin applications can positively influence fruit sets, delay ripening, and enhance fruit quality, contributing to better marketability; however, the impacts may vary depending on application timing, concentration, and cultivar. Those variabilities highlight the need for tailored gibberellin application strategies. This overview compiles data to maximize gibberellin benefits for sustainable citrus production.

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