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STRATEGIC USE OF PHYTOHORMONES TO BOOST LITCHI (*LITCHI CHINENSIS* SONN.) PRODUCTION AND FRUIT EXCELLENCE

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ABSTRACT

Litchi, a commercially significant subtropical fruit crop, is highly sensitive to abiotic stresses such as drought, salinity, and temperature extremes, which adversely affect its growth, flowering, fruit set, and yield. This review synthesizes current knowledge on the physiological, biochemical, and molecular mechanisms underlying litchi's response to these stresses, with a particular focus on the role of phytohormones. Hormonal signaling pathways involving abscisic acid, ethylene, auxins, gibberellins, cytokinins, paclobutrazol, salicylic acid and maleic hydrazide are critically reviewed for their influence on stress adaptation and reproductive development. The interaction between hormonal networks and environmental cause is discussed in relation to fruit drop, flowering time, and postharvest physiology. The review also highlights recent advances in transcriptomics and metabolomics that elucidate stress responsive gene expression and metabolic pathways. Understanding these regulatory networks provides a foundation for developing stress resilient litchi cultivars through integrated breeding and biotechnological approaches.
***Keywords* :** Phytohormones, Litchi, Abiotic Stress, Improvement, Physiology

Introduction

Litchi (*Litchi chinensis* Sonn.), a member of the Sapindaceae family and Nephaleae sub family, is widely acknowledged as the most prominent evergreen fruit tree in subtropical regions. Cultivation of this species dates as far back as 1766 BC, primarily due to its high quality fruit (Menzel, 1984). Renowned for its distinctive taste, striking appearance, and appealing aroma, litchi surpasses many fruits in sensory attributes. In China, it is revered as the "king of fruits" due to its flavor and nutritional profile (Zhang *et al.*, 1997). Major global producers include China, India, Taiwan, Vietnam, and Thailand. Introduced to India during the 18th century, the country now ranks as the second largest producer, with key growing areas in Bihar, West Bengal, Tripura, Uttarakhand, Uttar Pradesh, and Punjab (Sarkar *et al.*, 2018).

In recognition of its unique origin and exceptional characteristics, Bihar's 'Shahi' litchi received Geographical Indication (GI) status from the Indian Patent Office in 2018. Known by names such as lichee, lychee, laichi, or lici globally, the fruit is consistently referred to as litchi in India. The edible part, the translucent and juicy aril, is typically consumed fresh or processed into various products like juice, wine, jelly, and vinegar. Its red skin is primarily pigmented by anthocyanins, especially Cyanidin-3-O-rutinoside, which constitutes between 67% and over 95% of the total anthocyanins in several varieties. Other pigments contributing to the coloration include Cyanidin-3-O-glucoside, Malvidin-3-O-glucoside, and Peonidin-3-O-rutinoside (Mir *et al.*, 2016). These anthocyanins possess notable health promoting properties, including antioxidant, anti-inflammatory, antimicrobial, and anticancer activities (Faramarzi *et al.,* 2015). Traditionally, various parts of the litchi plant have been used in folk medicine to manage ailments such as stomach ulcers, obesity, diabetes, coughs, and intestinal worms, and are also considered to have pain relieving effects (Obrosova *et al.,* 2010). The seeds are also nutritionally valuable, being rich in fatty acids, polyphenols, flavonoids, saponins, sterols, and volatile compounds (Prasad *et al.,* 2009). Despite its long standing cultivation and popularity in domestic and export markets, litchi production in several areas remains suboptimal. Factors such as high temperatures during flowering, the use of unsuitable cultivars, and substandard orchard practices contribute to reduced productivity. Key issues include a significant gap between actual and potential yields, inferior fruit quality, and limited export potential for premium varieties. Addressing these concerns is essential to advancing litchi cultivation in response to increasing food demand and to maximize economic returns.

Plant hormones are vital in orchestrating various developmental stages of fruit, directly affecting both yield and quality. The exogenous application of phytohormones in minimal quantities has proven to be an effective method to manipulate physiological responses, particularly when endogenous hormone levels are inadequate for optimal growth. This practice aids in managing challenges such as fruit drop and subpar quality, ultimately enhancing overall productivity. In this context, the current literature review seeks to elucidate the principles and applications of different phytohormones aimed at improving fruit growth, development, yield, post-harvest quality, and storage longevity in litchi cultivation.

Litchi Phytohormones

Understanding the basic principles of phytohormone use is essential in litchi cultivation. Hormonal imbalances or deficiencies often resulting from poor pollination or fertilization can lead to physiological problems such as excessive fruit drop or early fruit detachment, as these hormones are crucial for proper embryo and fruit development. The flowering process is intricately tied to morphological aspects like the timing of shoot flushes and their level of maturity. Additionally, the physiological and biochemical state of the shoots particularly the carbon to nitrogen (C:N) ratio and internal hormonal equilibrium involving auxins, cytokinins, and gibberellin like compounds plays a significant role in initiating floral development, especially under warm subtropical conditions. A strong relationship has been observed between winter vegetative flushes and flowering, though floral initiation typically follows a period of dormancy in the shoots. To improve flowering consistency in low yielding varieties, growers often inhibit autumn vegetative growth and allow the stems to mature adequately before cooler winter nights begin (Menzel, 1983). Effectively addressing these challenges requires a comprehensive understanding of how different phytohormones are applied at various developmental stages of the litchi plant across the world.

1. Role of Auxin

Auxin plays a critical role in various physiological processes in litchi (*Litchi chinensis* Sonn.), particularly in floral differentiation, fruit abscission, and overall yield enhancement. Research indicates that auxin influences the balance between male and female flower development, with higher levels of auxin metabolites found in male flowers, suggesting its involvement in sexual differentiation (Chen *et al.,* 2024). Additionally, auxin interacts with ethylene signaling to regulate fruitlet abscission, where specific auxin response factors (ARFs) are crucial for this process (Ma *et al.,* 2024).

Auxin in Floral Differentiation

- Auxin levels are significantly higher in male flowers compared to female flowers, impacting the sex ratio of flowers.
- Differentially expressed genes related to auxin pathways are upregulated during male flower bud differentiation, indicating auxin's role in determining floral sex (Chen *et al.,* 2024).

Auxin in Fruit Abscission

- Auxin response factors (ARFs) regulate the expression of genes involved in fruit abscission, with some ARFs acting as repressors and others as activators (Zhang *et al.,* 2019).
- The interplay between auxin and carbohydrate stress affects fruitlet abscission, with specific auxin-related genes showing altered expression under stress conditions (Kuang *et al.,* 2012).

Enhancing Yield with Synthetic Auxin

The synthetic auxin 3,5,6-TPA has been shown to significantly reduce fruit drop and increase yield in litchi, demonstrating practical applications of auxin in cultivation (Stern and Gazit, 1999). Conversely, while auxin is essential for promoting flower and fruit development, excessive auxin levels can lead to undesirable outcomes, such as increased fruit drop or poor fruit quality, highlighting the need for careful management in litchi cultivation.

Chen (1990) studied the internal hormone levels across several growth phases in the litchi cultivar 'Heh Yeh' from leaf expansion and post leaf fall dormancy to 30 days before flower initiation, flower bud development, and full bloom. His findings showed that the concentration of indole-3-acetic acid (IAA) remained relatively constant through all these stages. Building on this, Stern *et al.* (2001) determined the ideal dosage, timing, and developmental stage for applying auxins in various litchi varieties: for 'Kaimana', 0.5 g was effective when the fruit reached 15 mm or at three weeks after pollination; for 'Floridian', 1–2 g was suitable at 22–24 mm or four weeks post pollination; and for 'Mauritius', 2 g was optimal at the same size, five weeks after pollination. Earlier studies by Stern and Gazit (1997, 1999) demonstrated that applying synthetic auxins shortly after fruit set notably reduced fruit drop and increased yields by 130% in 'Mauritius' and 170% in 'Kaimana'. Auxins such as 2,4,5-TP at 67 ppm and 3,5,6-TPA at 50 ppm effectively improved the number of fruits per tree, yield, fruit size, and color in 'Fei Zi Xiao' and 'Hei Ye' (Stern *et al.,* 2001), with similar results noted by Sarkar *et al.* (1984b). Drinnan (2014) found that foliar application of 3,5,6-TPA at 50 ppm enhanced fruit size and reduced drop in 'Fay Zee Siu', 'Kaimana', 'Kwai Mai Pink', 'Souey Tung', and 'Tai So' when fruits were over 12 mm in size; however, the treatment increased drop in smaller fruits. Kumar *et al.* (2009) reported that in the 'Purbi' cultivar, a 10 ppm spray of 2,4-D yielded the highest values for aril content, fruit weight, and fruit count per tree. According to Rani and Brahmachari (2001b), three applications of 20 ppm NAA before flowering, after fruit set, and before color break significantly lowered fruit cracking incidence in 'China' litchi compared to a lower 10 ppm dose. In 'Dehradun', 2.5 ppm NAA resulted in the highest initial fruit set (74.25 fruits per panicle), while a 5 ppm dose led to peak total soluble solids (19%), and 100 ppm improved ascorbic acid content, findings corroborated by Singh and Phogat (1983), Anand *et al.* (2003), and Sharma *et al.* (2005) in 'Calcuttia'. Leonel *et al.* (1994) assessed the rooting success of litchi cuttings treated with varying concentrations of IBA, NAA, and commercial rooting agents like Q-Muda and Nafusaku, concluding that Q-Muda (containing 0.5% IBA) provided the best survival rate, callus formation, and root development after 120 days. Sinha and Ray (2002) found that ringed branches of the 'Bombai' cultivar treated with a combination of 5000 ppm NAA and 200 ppm p-hydroxy benzoic acid (PHB) had the best rooting success, root number, and survival rate. Supporting this, Ray and Takawale (2013) tested eight litchi cultivars and observed that treatments with NAA + PHB produced the most roots, while IBA + PHB combinations resulted in the longest root lengths across all varieties.

2. Role of Cytokinins

Cytokinins play a crucial role in various developmental processes in litchi (*Litchi chinensis*), influencing flowering, fruit growth, and storage life. These plant hormones are involved in regulating shoot and flower development, as well as fruit size and quality. The following sections detail their specific functions.

Cytokinins in Flower Bud Differentiation

Cytokinins are essential for flower bud differentiation in litchi. Studies show that their levels increase during this process, with exogenous application of kinetin significantly promoting differentiation after bud dormancy (Chen, 1991). This suggests that while cytokinin levels rise during differentiation, they may not directly initiate the process.

Impact on Fruit Growth

The concentration of cytokinins in the pericarp is linked to fruit size. Higher cytokinin levels correlate with larger fruit, as seen in the cv. ‘Erdanli’ compared to ‘Huaizhi’ (Li *et al.,* 2005). A favorable cytokinin to abscisic acid ratio enhances fruit growth, indicating the importance of these hormones in fruit development.

Delaying Maturity and Extending Storage Life

The synthetic cytokinin CPPU has been shown to delay maturity in litchi, allowing for a longer harvest season. Treated fruits were larger and maintained quality during storage, demonstrating the potential of cytokinins in post-harvest management (Stern *et al.,* 2006). While cytokinins are vital for promoting growth and development, excessive levels can lead to imbalances that may negatively affect other physiological processes, highlighting the need for careful regulation in agricultural practices.

In several litchi cultivars such as 'Erdanli', 'Huaizhi', and 'Feizixiao', elevated cytokinin levels were identified in the pericarp during the early flowering phase, and a higher cytokinin to abscisic acid (CTK:ABA) ratio was linked with enhanced fruit development (Li *et al.,* 2005). In the 'Heh Yeh' variety, Chen (1990) noted that cytokinin concentrations in the xylem sap peaked during flower bud emergence and full bloom. Research by O’Hare and Turnbull (2004) showed that in potted 'Tai So' plants, the cytokinin zeatin riboside accumulated in terminal buds just prior to shoot emergence, and external application to dormant buds successfully initiated bud break. Mishra *et al.* (2012) reported that foliar application of benzyl adenine (BA) at 40 ppm effectively delayed ripening and boosted ascorbic acid content in the 'Rose Scented' cultivar. Similarly, Stern *et al.* (2006) demonstrated that treating green to lightly red fruitlets of the 'Mauritius' cultivar with the synthetic cytokinin CPPU (N-(2-chloro-4-pyridyl)-N'-phenylurea) at concentrations of 5–10 mg/l delayed harvest by 2–3 weeks. These fruits developed deeper red coloration, were 20–25% larger, exhibited higher total soluble solids (TSS) to acid ratio, and retained quality for up to six weeks during storage due to reduced browning.

3. Role of Gibberellic acid

Gibberellic acid (GA3) plays a significant role in the growth and development of litchi (*Litchi chinensis*), particularly in influencing flowering and fruit set. Its application can enhance various physiological processes, leading to improved yield and quality of litchi crops. The following sections outline the key aspects of GA3's role in litchi cultivation.

Flowering Induction

- GA3 promotes the transition from vegetative to flowering stages in litchi, facilitating the production of flowers.
- Studies indicate that GA3 application increases the number of male flowers, which is crucial for pollination and fruit set (Kerdchoechuen and Matta, 2008).

Sex Expression

- The hormone influences sex expression in litchi flowers, with specific concentrations of GA3 leading to a higher ratio of hermaphrodite flowers functioning as females, which are essential for fruit development (Kerdchoechuen and Matta, 2008).
- This modulation of sex expression can significantly impact overall fruit yield and quality (Shah *et al.,* 2023).

Fruit Set and Quality

- Exogenous application of GA3 has been shown to enhance fruit set percentages, thereby increasing the overall yield of litchi (Shah *et al.,* 2023).
- The hormone also contributes to the development of high-quality fruits, which are more marketable (Cm *et al.,* 2020).

In contrast, while GA3 has beneficial effects, excessive application can lead to imbalances in flower production and fruit set, highlighting the need for careful management of its use in litchi cultivation.

Chen (1990) found that in the 'Heh Yeh' litchi cultivar, gibberellin concentrations in the xylem sap were highest during leaf expansion but declined sharply approximately a month before and during flower bud development. In 'Ambika Litchi-1', a treatment combining 0.4% borax with 20 ppm GA_3 achieved the best fruit retention and highest yields (Dixit *et al.,* 2013). Kumar *et al.* (2009) also observed that applying GA_3 at 20 ppm in the 'Purbi' cultivar significantly improved fruit count, individual fruit weight, and overall productivity in Bihar. According to Rani and Brahmachari (2001b), a 100 ppm GA application in the 'China' variety produced the largest fruits with superior aril content. Brahmachari *et al.* (1996) reported that spraying GA_3 at 50, 100, and 150 ppm at the pea stage and again three weeks later enhanced fruit traits such as size, diameter, weight, and volume in 'Purbi', with the 50 ppm dose yielding the best results. Mishra *et al.* (2012) found that 40 ppm GA_3 reduced fruit cracking while improving total soluble solids and sugar content in 'Rose Scented' litchis. In the 'Yu Her Pau' cultivar, which features shriveled seeds, GA_3 applied at 5 and 10 mg/L two weeks after full bloom significantly improved fruit diameter, weight, aril mass, and pericarp weight over untreated controls (Chang and Lin, 2006). Regarding post-harvest performance, Nigam *et al.* (2001) reported that immersing 'Rose Scented' fruits in a 200 ppm GA_3 solution for two minutes, followed by storage at 5°C, reduced weight loss and spoilage, extending shelf life by five days. Additionally, Chen *et al.* (2014) showed that a 100 ppm GA_3 foliar spray in 'Yu Her Pau' notably increased fruit number per branch and total yield. A combined application of 100 ppm GA_3 and 25 ppm kinetin during aril development in the 'Bombai' cultivar delayed ripening by roughly four days and improved fruit quality (Dhua *et al.,* 2005).

4. Role of Ethephon

Ethephon plays a significant role in the cultivation and post-harvest management of litchi (*Litchi chinensis*). This plant growth regulator, which releases ethylene upon application, is utilized for various purposes including enhancing flowering, managing fruit abscission, and promoting ripening. The following sections detail its specific applications and effects.

Enhancing Flowering

Ethephon is effective in promoting flowering in litchi by enforcing bud dormancy and enhancing the flowering response to chilling. Studies indicate that a single application of 1000 mg/L can significantly increase the panicle emergence rate and number, thereby improving flowering outcomes (Wen *et al.,* 2024).

Inducing Fruit Abscission

Ethephon treatment has been linked to increased fruitlet abscission, which is crucial for managing yield. The treatment triggers ethylene production, affecting gene expression related to abscission, thus facilitating the harvest process (Li *et al.,* 2015).

Accelerating Ripening

Post-harvest, ethephon is used to accelerate the ripening of litchi fruits. Dipping fruits in ethephon solutions enhances color development and increases sugar content, improving market quality (Sadhu and Chattopadhyay, 1989). Conversely, while ethephon can enhance flowering and ripening, excessive use may lead to adverse effects such as reduced leaf health and potential phytotoxicity, necessitating careful dosage management (Wen *et al.,* 2024) (Sadhu and Chattopadhyay, 1989).

Olesen *et al.* (1999) discovered that applying ethephon in May or June effectively delayed early red flush development in litchi and encouraged new bud emergence behind damaged shoots within weeks a chemical alternative to mechanical pruning. According to Sadhu and Chattopadhyay (1989), using 2500 ppm ethephon enhanced ripening and peel coloration by increasing anthocyanin levels while simultaneously raising total soluble solids (TSS), sugars, and ascorbic acid content, and reducing pulp acidity. In a similar study, Wang *et al.* (2007) noted that ethrel applied at 800 mg/L during the color break stage maximized anthocyanin accumulation in the 'Nuomici' variety. Mandal *et al.* (2014) compared treatments such as paclobutrazol (2–3 ml a.i./m²), ethrel (1–2 ml/L), and cincturing, identifying ethrel at 2 ml/L as the most effective in enhancing flowering and fruiting in the 'Bombai' cultivar. This was consistent with earlier findings by Subhadrabandhu and Duang (1987), who observed positive results using ethrel in 'Hong Huay', though it was ineffective and even counterproductive in 'Ouxia', reducing flower production. Li *et al.* (1992) reported that ethephon postponed winter shoot emergence by 22–27 days in 'Baila', 'Heiye', and 'Guiwei' cultivars. When applied during flower bud differentiation, it reduced the number of flowers per panicle, thereby improving overall fruit quality. Zhu *et al.* (2011) demonstrated that combinations of PP333 and ethrel at different developmental phases could effectively induce flowering in the 'Sijimi' cultivar. Similarly, Xu *et al.* (2011) showed that treatments using 233 mg/L or 300 mg/L ethephon with 90 mg/L paclobutrazol led to more panicles containing only flowers and reduced leafy growth in 'Shixia' longan. Mahajan and Sharma (1995) observed that ethrel at 500 ppm advanced ripening and improved fruit quality in the 'Dehradun' cultivar. Diao (2006) found that combining low doses of ethephon (0.05–0.06%) and paclobutrazol (0.05%) suppressed apical shoot growth, decreased the number of male flowers, and reduced nutrient demand. However, Yu (2008) warned that higher ethephon levels (≥700 mg/kg) could cause phytotoxicity, though minimal leaf drop occurred at lower concentrations. Tang (2006) concluded that high dose ethephon (800 mg/L) combined with a lower paclobutrazol concentration (400 mg/L) lowered IAA and GA_3 levels while raising ABA, effectively encouraging flowering in the 'Jizui' cultivar, supporting earlier conclusions by Mitra and Sanyal (2000). In addition, Sharma *et al.* (1986) noted that ethrel application accelerated ripening by approximately three weeks in the 'Shashi' cultivar.

5. Role of Abscisic acid

Abscisic acid (ABA) plays a significant role in the maturation and quality of litchi fruit, influencing various physiological processes. Its concentration increases during fruit maturation, promoting sugar accumulation and anthocyanin synthesis, which are crucial for fruit flavor and color development. The following sections elaborate on the specific roles of ABA in litchi.

Fruit Maturation and Sugar Accumulation

- ABA levels rise in both the aril and pericarp as litchi matures, facilitating sugar accumulation essential for fruit sweetness (Wang *et al.,* 2007).
- Exogenous ABA application accelerates sugar accumulation, while other growth regulators like 6-benzyl aminopurine inhibit this process (Wang *et al.,* 2007).

Anthocyanin Biosynthesis

- ABA significantly promotes anthocyanin biosynthesis, enhancing the fruit's color and appeal (Hu *et al.,* 2018).
- Transcriptome analysis reveals that ABA up-regulates genes involved in flavonoid and anthocyanin pathways, indicating its critical role in color development (Hu *et al.,* 2018).

Browning Control

ABA is effective in controlling browning of litchi peel by reducing the activity of polyphenol oxidase and peroxidase, thus maintaining fruit quality during storage (Shijiang and Ming, 2017). Conversely, while ABA is vital for enhancing fruit quality, excessive application or imbalance with other hormones may lead to adverse effects, such as inhibited chlorophyll degradation, which can affect overall fruit ripening and marketability.

Chen (1990) observed that in the 'Heh Yeh' cultivar, levels of abscisic acid (ABA) began to rise around 30 days before flower bud formation, which was associated with a decrease in shoot growth. Singh *et al.* (2014) reported that pre-harvest application of ABA at concentrations of 150 ppm and 300 ppm during the color break stage in the 'Calcuttia' cultivar significantly increased anthocyanin content in the pericarp, without negatively affecting post-harvest fruit quality. Wang *et al.* (2007) examined ABA fluctuations in the 'Feizixiao' and 'Nuomici' cultivars, noting that ABA concentrations in both the aril and pericarp progressively increased during fruit development and ripening. They highlighted that ABA plays a pivotal role in sugar accumulation and that its external application enhanced anthocyanin production. In a separate study, Hu *et al.* (2010) demonstrated that treating 'Guiwei' fruits with 100 µmol/l ABA, followed by storage at 0±2ºC, delayed the development of red coloration, decreased anthocyanin levels, and reduced polyphenol oxidase activity. This treatment also helped reduce pericarp browning, thus enhancing the fruit's resistance to chilling injury.

A 2000 ppm dose of CCC (Cycocel) was shown to significantly improve pulp weight, pulp to stone ratio, total soluble solids (TSS), and reduce acidity in the 'Calcuttia' cultivar of litchi (Singh *et al.,* 2012). In the same cultivar, a 500 ppm CCC application resulted in a notable reduction in both seed and peel weight. For the 'China' cultivar, a 500 ppm CCC spray increased TSS, total sugar content, and ascorbic acid levels, while also decreasing acidity (Rani and Brahmachari, 2001b). Thakur *et al.* (1990) found that a 2000 ppm dose of CCC significantly enhanced fruit set, size, and retention in the 'Purbi' and 'Deshi' cultivars. Additionally, in the 'Purbi' cultivar, two applications of CCC at 300 ppm one at the pea stage and the second 21 days later effectively reduced fruit drop compared to other treatments (Brahmachari *et al.,* 1996).

6. Role of Paclobutrazol

Paclobutrazol plays a significant role in the cultivation of litchi by influencing growth, flowering, and fruit quality. It acts as a plant growth retardant, primarily by inhibiting gibberellin biosynthesis, which results in reduced vegetative growth and enhanced flowering and fruiting. The application of paclobutrazol has been shown to improve the chemical quality of litchi fruits, increase yield, and manage vegetative growth effectively. The following sections detail its specific roles and effects.

Growth Regulation

- Paclobutrazol effectively suppresses vegetative growth in litchi trees, which is beneficial for managing tree size and promoting flowering. Higher doses, such as 3.0 g and 4.0 g a.i. per meter canopy diameter, have been particularly effective in reducing vegetative growth (Jain *et al.,* 2022) (Ray and Rani, 2004).
- The application of paclobutrazol reduces shoot growth significantly, leading to increased flowering and fruit set (Ahmad *et al.,* 2000).

Flowering and Yield Enhancement

- Paclobutrazol increases the percentage of terminal branches that produce flowering shoots, thereby enhancing flowering and subsequent fruit yield. A notable yield gain of 52% was recorded in the second year after treatment (Ray and Rani, 2004).
- The chemical is most effective when applied 90 days before bud break, resulting in higher flowering and yield compared to applications made 60 days prior (Ahmad *et al.,* 2000).

Improvement in Fruit Quality

- The application of paclobutrazol improves the chemical quality of litchi fruits, increasing ascorbic acid, total soluble solids, total sugar, and anthocyanin content. For instance, a dose of 40 ml/tree significantly increased ascorbic acid content to 27.29 mg/100g compared to the control (Pant *et al.,* 2020).
- Higher doses of paclobutrazol also result in higher TSS content in litchi fruits, contributing to better fruit quality (Ahmad *et al.,* 2000).

While paclobutrazol is effective in enhancing flowering and fruit quality, its effects can vary based on application timing and environmental conditions. In some cases, excessive vegetative growth can limit the effectiveness of paclobutrazol in promoting flowering (Menzel and Simpson, 1990). Additionally, the residual effects of paclobutrazol can persist, influencing flowering and fruiting in subsequent seasons (Jain *et al.,* 2022).

Singh *et al.* (2012) found that applying paclobutrazol (PBZ) at 7.5 g per tree effectively restricted shoot growth, reduced panicle size and the percentage of male flowers, minimized fruit drop, and increased the proportion of hermaphrodite flowers. This treatment also improved sugar content, fruit size, and overall yield in the 'Calcuttia' cultivar of litchi. In a different study, Singh *et al.* (2017) applied PBZ at varying rates of 1, 2, 3, and 4 g active ingredient (a.i.) per meter of tree canopy as a soil drench, in combination with potassium nitrate at concentrations of 100 and 200 mg/l, applied in three 15 day intervals starting three months after harvest in the 'China' cultivar. This combination effectively reduced vegetative winter flushes and promoted floral shoot emergence when compared to the control. Pires and Yamanishi (2014) reported that in 'Bengal' litchi trees, applying PBZ at 500, 1000, and 2000 mg a.i. per meter of canopy diameter in May, following trunk girdling, significantly increased yield by 4 to 6 times compared to the control. Additionally, Singh *et al.* (2017) observed that PBZ at 4 g a.i./m canopy reduced vegetative flushing during winter and promoted floral branch emergence in 66% of treated shoots. In another study, Hung and Nghi (2006) found that applying PBZ at 20 g a.i. per tree in late August to early September at the mature bud stage in the 'Binhkhe' cultivar suppressed winter bud emergence, reduced inflorescence size, and increased female flower production, fruit set, and yield by 61.5–85.2% compared to untreated trees.

Applying paclobutrazol at 3 ml a.i./m² of canopy surface area in the 'China' cultivar led to earlier flower emergence by six to seven days. The treatment induced flowering, resulting in an increase in the carbon to nitrogen (C:N) ratio and leaf water potential, particularly at the time of bud break. A positive correlation between the C:N ratio in shoots and abscisic acid (ABA) levels in the buds was noted. Lower doses of paclobutrazol (1.0 and 1.5 g) caused a reduction in nitrogen and carbon concentrations in leaves, affecting the C:N ratio. In 'Xiangli' litchi, a 0.1 g spray of paclobutrazol increased the proportion of pure panicles fourfold. In addition to reducing gibberellin activity, paclobutrazol also raised ABA and cytokinin levels and improved the C:N ratio and leaf water status, which are key factors that stimulate floral initiation, as also observed in mango buds.

7. Role of Salicylic acid

Salicylic acid (SA) plays a significant role in maintaining the quality and extending the shelf life of litchi fruits. Postharvest SA treatment (1.2 mM) reduces pericarp browning, maintains membrane stability, and decreases fruit decay during storage (Pongener *et al.*, 2018). As an alternative to SO2 fumigation, 0.5% SA treatment effectively reduces browning, polyphenol oxidase activity, and decay while preserving anthocyanin content (Kumar *et al.*, 2013). Pre-harvest SA application (150 ppm) increases total soluble solids, sugars, ascorbic acid, and anthocyanin content, extending shelf life to 4 days under ambient conditions (Kumari et al., 2023). SA treatment also enhances disease resistance in longan fruits by maintaining cell membrane integrity, reducing lipid-degrading enzyme activities, and preserving unsaturated fatty acids (Chen *et al.*, 2020). These studies demonstrate that SA is an eco-friendly approach to improve postharvest quality and storage life of litchi and related fruits.

8. Role of Maleic hydrazide

Biao and Fang (1998) conducted experiments with various plant growth regulators to induce seedlessness or the formation of mini kernels in litchi cv. Huaizhi. They found that two sprays of 1 mM maleic hydrazide (MH) were the most effective, achieving 100% success in producing fruits with mini or aborted kernels. Liang and Qiu (1998) reported that applying MH at 1000 mg/l about two weeks after full bloom in the same cultivar did not alter overall fruit weight but resulted in shriveled seeds and a 10% increase in aril content compared to untreated controls. Win *et al.* (1998) observed that spraying PP333 or a combination of ethrel and MH on litchi flower clusters extended the flowering period by 10 to 14 days, leading to an increase in fruit production.

Conclusion and Future Thrust

Conclusion

The use of phytohormones in litchi farming has become an essential strategy for addressing various challenges associated with fruit production, including excessive fruit drop, low yields, and poor fruit quality. Extensive studies have highlighted the significant roles of plant growth regulators such as auxins, cytokinins, gibberellins, abscisic acid, ethylene, CCC, and paclobutrazol in promoting flowering, improving fruit retention, enhancing fruit size and sugar content, prolonging shelf life, and boosting resistance to environmental stress. When applied correctly at the right stages and in appropriate doses, these hormones can have a profound impact on critical physiological processes like shoot maturation, floral induction, fruit set, and post-harvest quality. By tailoring hormone applications to specific cultivar needs, growers can bridge the gap between potential and actual yields, achieve high quality fruit suitable for export, and enhance the economic sustainability of litchi farming.

Future Thrust:

Looking ahead, the focus should be on:

1. **Standardizing Hormonal Protocols**: Developing region and cultivar specific protocols to ensure

optimal and consistent application of phytohormones, leading to reliable and reproducible results across different environments.

2. **Integrative Management**: Combining hormonal treatments with advanced horticultural techniques, such as fertigation and canopy management, for comprehensive crop improvement, optimizing both yield and fruit quality.
3. **Sustainable and Eco-friendly Practices**: Investigating the use of bio-stimulants and naturally derived plant growth regulators to reduce the reliance on synthetic chemicals, fostering sustainable and organic litchi production methods.
4. **Molecular and Genomic Insights**: Conducting research into the molecular mechanisms and gene expression changes induced by hormone treatments to gain a deeper understanding of hormone signaling pathways, enabling more targeted and efficient applications.
5. **Post-Harvest Applications**: Expanding the use of hormones in post-harvest management, focusing on extending shelf life, reducing spoilage, and improving fruit quality during storage and transportation, thus enhancing marketability.
6. **Climate Resilience**: Tailoring hormone use to mitigate the impact of climate change, particularly addressing irregular flowering patterns due to temperature fluctuations and other environmental stressors.

Focused research and innovation in these areas will greatly improve the productivity, quality, and global competitiveness of litchi, solidifying its position as a premium subtropical fruit crop. Future research should prioritize developing enhanced formulations and adjuvants for phytohormones, with an emphasis on understanding the precise timing and application of hormonal treatments at key phenological stages. This approach will optimize physiological processes and contribute to more effective crop management and higher yields.

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