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Managing cotton canopy architecture for machine picking cotton via high plant density and plant growth retardants

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Abstract

Machine picking in cotton is an emerging practice in India, to solve the problems of labour shortages and production costs increasing. Cotton production has been declining in recent years; however, the high density planting system (HDPS) offers a viable method to enhance productivity by increasing plant populations per unit area, optimizing resource utilization, and facilitating machine picking. Cotton is an indeterminate plant that produce excessive vegetative growth in favorable soil fertility and moisture conditions, which posing challenges for efficient machine picking. To address this issue, the application of plant growth retardants (PGRs) is essential for controlling canopy architecture. PGRs reduce internode elongation, promote regulated branching, and increase plant compactness, making cotton plants better suited for machine picking. PGRs application also optimizes photosynthates distribution between vegetative and reproductive growth, resulting in higher yields and improved fibre quality. The integration of HDPS and PGRs applications results in an optimal plant architecture for improving machine picking efficiency. However, the success of this integration is determined by some factors, including cotton variety, environmental conditions, and geographical variations. These approaches not only address yield stagnation and labour shortages but also help to establish more effective and sustainable cotton farming practices, resulting in higher cotton productivity.

Keywords Cotton, High density planting system, Plant growth retardant, Canopy management, Defoliators, Machine picking, Yield improvement

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Background

Cotton (*Gossypium hirsutum* L.) is one of the most important commercially valuable fibre crops in the world, due to its importance in agriculture and industrial economy (Udikeri et al. 2017). Cotton cultivation is distinguished globally due to the factors such as variety, superior fibre quality, and advanced agricultural practices (Blaise et al. 2019). In India, cotton is cultivated in an area of 12.35 million hectares and production of 34.06 million bales with the productivity of 510 kg·ha^{-1} (https://www.indiastat.com/). Cotton production in India is closely connected to the textile industry, which ranks among the largest contributors to the economy and boasts over 1 062 textile mills nationwide. Its production plays a vital role in employing over 50 million people and supporting the livelihoods of 6 million farmers in India (Chandrasekaran et al. 2023). India witnessed the "Silver Fibre Revolution" in the first decade after the approval of commercial cultivation of *Bacillus thuringiensis* (Bt) cotton in 2002. As a result, within less than a decade, India tripled its cotton production, rising from approximately 13 million to 40 million bales in 2013 to 2014, and became an important exporter of cotton in the world. These achievements are commendable, but since 2015, there has been a steady decline in total production (from 40 million bales to 31 million bales) and stagnancy in yield due to the resurgence of pests and the impact of adverse climatic conditions. At the same time, the national average cotton productivity is 433 $kg·ha^{-1}$, which is lower than the global average of 768 $kg·ha^{-1}$. This highlights the need for sustained efforts towards cotton genetic improvement and the implementation of effective agronomic practices (https://www.indiastat.com/). Further, by 2026, the Indian textile sector will require around 45 million bales of cotton; bridging this gap will necessitate an expansion in cotton cultivation area, increased production, and improved productivity. The high density planting system (HDPS) in cotton has been globally recognized for improving yield (up to 30%) and facilitating machine picking, offering a proven technology for this purpose. Cotton cultivation is labour-intensive, requiring around 250 man-days per hectare, will harvesting accounting for more than half of the total labour requirement. Given the high cost associated with manual picking, there is a pressing need to introduce mechanical picking in cotton production (Venugopalan et al. 2023).

Closer plant spacing induces excessive vegetative growth in cotton, which can cause self-shading, hindering solar radiation, and affecting seed cotton yield and harvesting efficiency (Lamas 2001). Solar radiation is essential for photosynthesis, and in sub-tropical regions, heavy rainfall during the growing season, increases vulnerability to pests and reduced yield (Wang et al. 2014). Cotton plants respond to both field management practices and adverse weather conditions, therefore topping and thinning are effective in regulating vegetative growth (Tung et al. 2020). Though labor-intensive, in times of labor scarcity, plant growth retardants (PGRs), such as mepiquat chloride (MC), cyclanilide (CY), cycocel, maleic hydrazide (MH), paclobutrazol (PBZ), and triiodobenzoic acid (TIBA), become essential for adjusting hormonal balance, modifying canopy structure, and improving the source-sink relationship (Souza et al. 2007). The application of PGRs, in combination with planting techniques, has a significant impact on cotton growth, production, and quality. These approaches help to maintain a robust crop stand, to increase radiation use efficiency, and to modulate plant canopy (Echer et al. 2017; Zhao et al. 2017).

There is a critical need to focus on developing cotton varieties that are well-suited for HDPS, utilizing defoliants to reduce trash content, and implementing machine picking. PGRs are used to facilitate canopy management and achieve the ideal plant structure. This article emphasizes the importance of HDPS cotton cultivation in conjunction with PGRs application managing canopy architecture by controlling plant height, shape, and structure, to facilitate efficient machine picking, reduce labour dependency, improve crop uniformity, and increase overall productivity.

Importance of high-density planting system in cotton production

A novel approach called HDPS is gaining attraction as a potential alternative production system to enhance the productivity and profitability of cotton cultivation in India (Mayee et al. 2021). The HDPS originated from the work of the narrow row planting system (Briggs et al. 1967), and it is widely used in several countries, including Brazil, China, Australia, Spain, Uzbekistan, Argentina, the United States, and Greece. To achieve higher productivity, it is essential to develop compact sympodial cotton varieties that are well-suited for high density planting (Latha et al. 2011). HDPS allows for the cultivation of a larger number of plants, ranging from 150 000 to 250 000 plants per hectare, resulting in the production of 8 to 14 bolls per plant with an average boll weight of 4.0 g (Venugopalan et al. 2023). Increased plant population resulted in smaller cotton plants that exhibit higher resource use efficiency due to competition for resources, but this also resulted in lower boll numbers (Liu et al. 2020; Luo et al. 2018). Therefore, achieving an optimal plant stand is also essential for maximizing yields.

The HDPS offers a viable option to increase productivity and sustainability in rain-fed regions (Desai et al. 2019). Sowing of cotton in closer plant spacing resulted in higher seed cotton yields, increased productivity, and enhanced profitability than wider plant spacing (Wagh et al. 2024). HDPS provides several advantages, including increased input use efficiency, reduced input costs, and minimized risks associated with cotton production (Anbarasan et al. 2023). Thus, combining HDPS, together with targeted fertilizer management for different genotypes and effective bollworm control techniques, has the potential to overcome production standstill in rainfed cotton. HDPS plays a crucial role in quickly establishing a canopy that helps to reduce soil water evaporation (Venugopalan 2019), improve light interception, and develop efficient leaf area, which effectively shades out weeds and reduces their competitive impact (Madavi et al. 2017;

Wright et al. 2011). Consequently, cotton production has increased significantly, reaching 5 500 to 6 500 kg of seed cotton per hectare (Anbarasan et al. 2022).

The optimization of plant population for HDPS depends on various factors such as varietal characteristics, soil properties, climatic conditions, and management practices. HDPS prefers plant types with compact growth habits, no monopodia, and improved sympodial development, which are favorable for machine picking. Cotton squares mature earlier in narrow row spacing than in wider row spacing, promoting earlier maturity (Venugopalan 2019). While dense planting reduces plant height, boll number per plant, boll weight, dry matter accumulation, and individual plant output, these challenges can be addressed through effective plant population management and canopy control.

Importance of altering canopy architecture in HDPS

The arrangement of photosynthetic functional leaves within a plant, referred to as canopy architecture, varies significantly between plant species (Barthélémy et al. 2007). This diversity under HDPS significantly affects how light penetrates the canopy, thereby influencing the rate of photosynthesis (Song et al. 2013). Within a closed canopy, the availability of light can vary significantly, ranging from approximately 20 to 50 times from the top to the bottom (Lieffers et al. 1999). Several factors contribute to this variation in photosynthetic function, including leaf orientation, shape, spatial arrangement, sun angle, and variations in the spectral distribution of photosynthetic photon flux density (PPFD) throughout the canopy (Murchie et al. 2012).

Cotton crops have two primary types of canopies: open and closed. These canopy types are closely related to leaf morphology and structure. Leaves with a divided, okra-shaped appearance result in an open canopy, whereas leaves with weakly divided or normal shapes produce a closed canopy (Zhao et al. 1998). These different canopy structures have a divergent impact on light interception and overall yield. Wells et al. (1986) found that cultivars with okra-shaped or sub-okra-shaped leaves can produce yields that are competitive with or higher than those of normal leaf types. Lower cotton boll development is highly dependent on the nearby leaves, with the leaves openness allowing light to penetrate to lower parts of the plant (Kerby et al. 1980). For example, okra-shaped leaf varieties allow greater interception of light by the lower leaves (Andres et al. 2016; Zhu et al. 2008). Factors such as early row closure and excessive vegetative growth above developing fruiting branches can reduce the entry of sunlight into the canopy, resulting in higher fruiting form abscission and lower fibre quality (Kerby et al. 1992). The reduced light penetration is attributed to shaded leaves produce fewer assimilates, leading to reduced foliage at maturity compared with cotton varieties with normal leaf types, which accounts for the reduced light penetration.

Canopies with more erect leaves (erectophile) require a greater leaf area index (LAI) to absorb an equivalent amount of PPFD compared with canopies with more horizontal leaves (planophile) (Valladares et al. 2007). At higher LAI, however, the differences in PPFD absorption between the two canopy types became less pronounced (Struik et al. 2003). Nevertheless, erectophile canopies distribute absorbed PPFD across a wider sunlight leaf area, giving in a lower absorbed PPFD per unit of sunlight leaf area. As a result, canopy photosynthesis is higher in erectophile canopies compared with planophile canopies, especially when PPFD absorption rates are comparable (Du et al. 2017).

Characteristics of varieties suitable for HDPS

Cotton productivity has been greatly influenced by high yielding varieties, hybrids, and advanced agronomic practices (Heitholt 1994). Developing optimal genotypes for HDPS involves addressing challenges such as rising labor costs and increasing inputs such as fertilizers and pesticides. Hybrid cotton cultivation usually produce extra biomass with rapid and spreading growth patterns, resulting in a lower boll-to-biomass ratio. HDPS emphasizes that early-maturing, semi-compact or compact genotypes are ideal for maximizing yields, particularly under rainfed conditions. Selected HDPS genotypes should have a maximum plant height of 1 m, greater sympodial branching, no monopodia, shorter internodal lengths, increased boll weight, and synchronized maturation and busting (Narayana et al. 2018). The Central Institute of Cotton Research (CICR) Nagpur, started the research on HDPS for cotton in 2010, following the All India Coordinated Research Project (AICRP), launching a separate trial to evaluate the HDPS genotypes under irrigated and rainfed conditions to release compact genotypes suitable for HDPS. CSH 3075 was the first cotton variety released for HDPS in India (Kumar et al. 2021). Table 1 lists the recently released compact and semi-compact cotton cultivars that are suitable for HDPS and machine picking.

Suitable edaphic and environmental factors for HDPS and PGRs application in cotton

HDPS is particularly suitable for cotton cultivation in low-productivity areas, especially in semi-arid agroclimatic zones with shallow to medium soils and rainfed conditions (Gouthami et al. 2023). It is ideal for regions such as Maharashtra, Madhya Pradesh, Telangana, Andhra Pradesh, Karnataka, Gujarat, and the Cauvery Delta in Tamil Nadu, India. In fertile, irrigated soils with longer growth seasons, wider spacing is necessary

Table 1 Recently released varieties suited for the high density planting system in India

Varieties name	Parentage	Released year	Suitable area in India	Yield potential
CSH 3075	-	2017	Punjab, Haryana, and Rajasthan	2 290 kg·ha^{-1}
Subiksha	Bunny× (MCU 5×Z2)	2018	Tamil Nadu, Karnataka, and Andhra Pradesh	4 200 kg·ha^{-1}
Suraksha	Surabhi× (MCU 5×Z2)	2021	Madhya Pradesh, Maharashtra, Gujarat, Telangana, South Rajasthan, Tamil Nadu, Karnataka, and Andhra Pradesh	4 000 kg·ha^{-1}
CICR-H Cotton 54 (Nano)	Surabhi×Rai-4 A-3-2	2022	Irrigated condition of the Central and South zone of Andhra Pradesh, Telangana, Karnataka, Tamil Nadu, Maharashtra, Madhya Pradesh, Gujarat, and Odisha.	2 850 kg·ha^{-1}
CO 15	Multiple cross derivatives involving four parents (LRA 5166, AKH 2053, Surabhi, and MCU 12)	2018	Cauvery Delta Zone of Tamil Nadu	2 400–2 580 kg·ha^{-1}
CO 17	Khandwa 2×LH 2220	2020	Cauvery Delta Zone of Tamil Nadu	2 360 kg·ha^{-1}
VPT 2	Suraj×TCH 1819	2023	Rainfed regions of Tamil Nadu	2 230 kg·ha^{-1}

Data from Central Institute of Cotton Research, Coimbatore, Tamil Nadu, India (Kumar et al. 2021)

(Venugopalan et al. 2023). Medium-deep soils require row spacing of 90 to 120 cm and plant spacing of 30 cm. In shallow soils, such as red soils, narrower row spacing of 90 cm and plant spacing of 15 to 20 cm are recommended. HDPS requires compact, short-statured, early-maturing cotton genotypes with medium to large bolls. Bt hybrids and semi-compact genotypes are commonly used to maximize yields under these conditions (Sankaranarayanan et al. 2018). During the vegetative stage of cotton, growth retardants are used to limit excessive growth, improve plant structure, and distribute nutrients more efficiently. In the reproductive stage, PGRs balance vegetative and reproductive growth, resulting in an increased fruit set, while excessive use may inhibit flowering. Environmental factors such as temperature, light, water, and soil fertility can impact the effectiveness of PGRs, with warmer conditions accelerating breakdown and cooler, humid environments prolonging activity. In dryland cotton, it is important to check a 7 to 10-day weather forecast to avoid plant stress (Venugopalan et al. 2023).

Role of plant growth retardants on cotton

Plant growth retardants are natural or synthetic organic compounds used to reduce plant height by decreasing internode lengths (Kumari et al. 2018). Cotton plants have indeterminate growth habits and should be managed with synthetic chemicals (Li et al. 2020). PGRs are used to control plant height, regulate vegetative to reproductive growth balance, and enhance overall production (Murtza et al. 2022). These regulators have a significant impact on crop development, yield, and quality of crops, which also protect plants from various stress conditions (Vineeth et al. 2016). The application of PGRs inhibits the synthesis of gibberellic acid (GA) when absorbed by leaves, resulting in improved plant systems (Guo et al. 1994). PGRs are mainly used for increasing nutrient uptake, elevating carbohydrate content, boosting photosynthesis activity, improving reproductive organ partitioning, and expediting maturation in cotton (Zhao et al. 2000). The effects of PGRs are influenced by factors such as the plant growth stage, rate of applications, and the environmental conditions at the time of application (Zaman et al. 2021). PGRs are typically applied in small amounts to modify plant growth by stimulating or inhibiting specific natural processes. These results lead to advanced crop maturation, enhanced reproductive structures, and improved nutrient uptake in cotton (Priyanka et al. 2022). Brodrick et al. (2013) and Sabale et al. (2017) highlighted the positive effects of applied PGRs on cotton yield, plant height, open bolls, sympodia, boll weight, lint percentage, seed index, and other traits. Additionally, PGRs may enhance chlorophyll content, extending the functional life of the source for increased productivity (Kumar et al. 2005).

Effect of mepiquat chloride on growth and yield attributes of cotton

Mepiquat chloride (N, N-dimethylpiperidium chloride), commercially known as Pix, is a widely used plant growth retardant in cotton, to achieve a balance between vegetative and reproductive growth, thereby increasing the yield of cotton (Yang et al. 2014). The MC primarily acts as an anti-gibberellin compound, inhibiting cell elongation, and reducing main-stem nodes (Pettigrew et al. 2005). It limits GA signaling by stimulating enzymes that convert GA20 into its inactive form, disturbing gibberellic homeostasis. This disruption reduces cell elongation by lowering GA concentration, increasing cell wall rigidity, but decreasing plasticity (Yang et al. 2014) (Fig. 1). MC affects GA biosynthetic and metabolic genes, shortening internodes, and modifying canopy structure. It upregulates DELLA-like genes (*GhGAI4a*, *GhGAI4b*) and GA catabolism gene *GA2ox,* while downregulating GA biosynthesis genes *CPS*, *GA20oxs,* and *GA3ox*. Consequently, bioactive GA levels (GA3 and GA4) decrease by 30.4% and 43.0%, respectively, along with reduced expression of *GhEXP* and *GhXTH2* genes (Achard et al. 2009; Wang et al. 2014).

Manipulation of canopy architecture using MC is one of the agricultural practices used to boost cotton productivity (Mao et al. 2015; Gu et al. 2014). It aims to regulate plant growth, particularly in high-density planting scenarios to accelerate maturation, initially developed to enhance carbohydrate source-sink relations for improved yield efficiency in cotton (Stuart et al. 1984). MC applications significantly inhibit apical dominance and stimulate lateral bud growth, thereby increasing branch numbers, decreasing plant height, height-to-node ratio, and leaf area, enhancing light interception, increasing boll weight, accelerating the maturation of bolls and consequently boosting yield (Abbas et al. 2022; Tung et al. 2020). Applying MC at the squaring stage inhibits the partitioning of photoassimilates towards the main stem, branches, and growth points, while increasing partitioning to the reproductive organs (Mao et al. 2015).

The application of MC in cotton offers several advantages, such as enhancing plant structure, increasing boll retention, promoting earlier boll opening, improving quality, and enhancing harvesting efficiency (Bogiani et al. 2009). Studies from various regions, including China, and Tamil Nadu, Junagadh, and Ludhiana in India, show that MC is beneficial in reducing plant height and improving cotton traits (Wang et al. 2014; Gobi et al. 2013). The MC application also improves flower and fruit retention, improving light interception, and yield (Ashok et al. 2020; Nuti et al. 2006). Using closer spacing combined with MC at a 100 $g{\cdot}hm^{-2}$ application significantly improved cotton physiological growth parameters and increased seed cotton yield (Maheswari et al. 2019). Application of MC at 50 $g{\cdot}ha^{-1}$ during square formation and flowering reduced plant height while increasing sympodial branches (Khetre et al. 2018). Similarly, MC spray at 25 $g{\cdot}hm^{-2}$ increased boll number, boll weight, and seed cotton yield, with no significant effect on fiber quality parameters (Kadiyam et al. 2022; Patel et al. 2021; Priyanka et al. 2019). Foliar spraying of MC at 20 to 30 $g{\cdot}ha^{-1}$ across multiple stages reduced plant height and enhanced production by up to 44.3% (Priyadrashini et al. 2023).

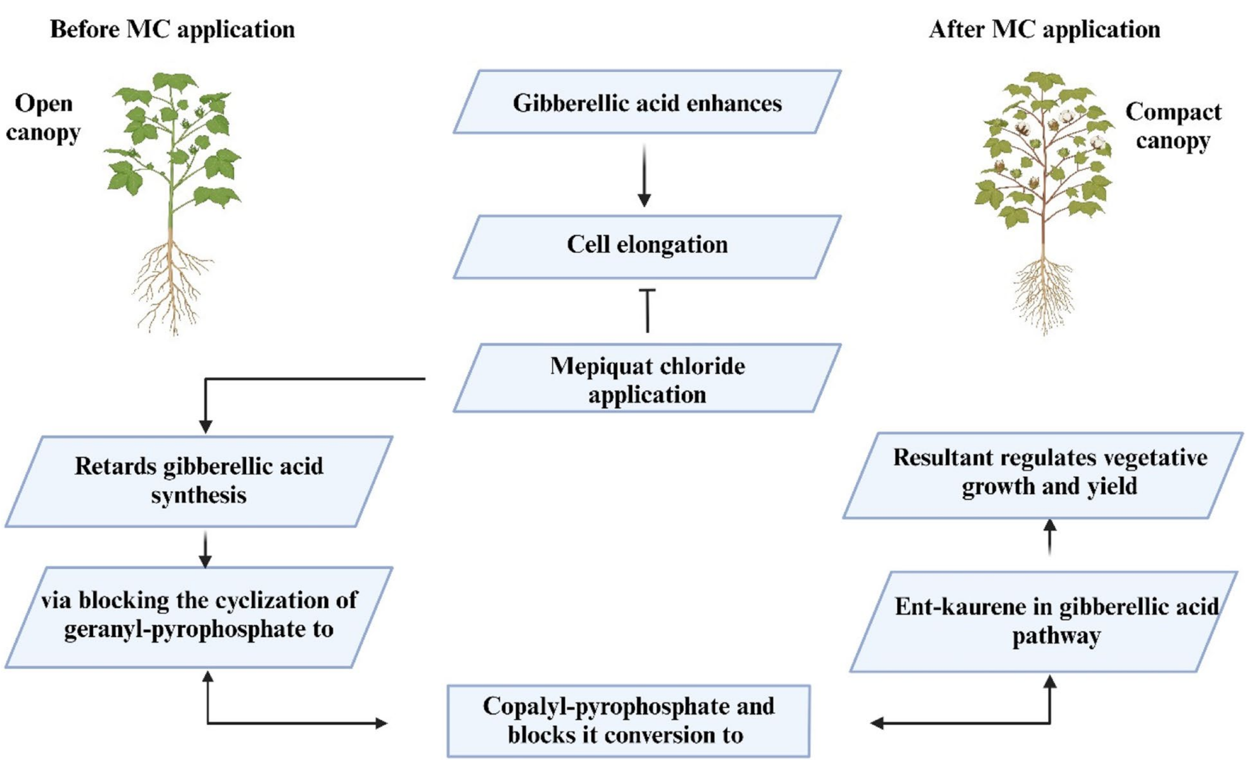

Fig. 1 Diagrammatic representation of the gibberellic acid inhibition mechanism through the MC application (Halmann 1990 ; Gu et al. 2014)

Effect of cyclanilide application in cotton

The chemical cyclanilide (CY) [1 - (2, 4 dichlorophenylaminocarbonyl) - cyclopropane carboxylic acid], also known as Stance, is a registered plant growth regulator with the potential to improve the efficiency of a gibberellin biosynthesis inhibitor (Burton et al. 2008). It is commonly used in conjunction with other plant growth regulators, such as MC and ethephon/ethrel, to perform a wide range of physiological functions. When combined with MC, it is used to reduce vegetative growth or accelerate senescence. When paired with ethephon, it enhances defoliation and promotes boll opening. CY is also used with cotton harvest aids and fungicides; it operates through interactions with auxin-regulated pathways. CY inhibits auxin transport, specifically in meristematic plant tissues. It is applied at the end of cotton growing season to promote boll opening, defoliation, and to prevent terminal foliar regrowth. This compound functions in a dual capacity by regulating two critical plant hormones: auxin and gibberellin (Rademacher 2015).

Effect of combined application of mepiquat chloride and cyclanilide in cotton

The combined application of MC and CY was registered for use in cotton to reduce vegetative growth (Thomas et al. 2007). Both MC and CY inhibit GA synthesis, both PGRs were recommended by Brazilian experts to use to manage vegetation, improve fruiting and boll retention, hence increasing cotton production. The combined application of MC and CY alters the canopy structure and enhances the effects of MC when compared with the MC treatment alone (Rademacher 2015).

The combination of MC and CY treatments reduced plant height by approximately 50%, while the MC treatment alone reduced plant height by 30% to 40%. The highest concentration of MC and CY treatments resulted in the greatest reduction in cotyledon node height and increased taproot length. In addition, the applications of MC + CY at 600 $mL \cdot ha^{-1}$ resulted in the greatest reduction of plant height, biomass, the number of monopods per plant, and monopodial length. However, it has a detrimental impact on yield, as indicated by a lower seed cotton yield compared with other chemical treatments (Rademacher 2015). Foliar application of Stance 110 suspension concentrate (SC) at 225 $mL \cdot ha^{-1}$ significantly enhances the yield without any negative impact on fiber quality (Ratnakumari et al. 2013). The application of Stance at 400 $mL \cdot ha^{-1}$ resulted in reduced plant height and compactness, leading to fewer sympodial branches per plant compared with MC applied at 1 250 $mL \cdot ha^{-1}$. While the application of MC and CY can reduce the plant height, and increase seed cotton yield (Soares et al. 2016; Ratnakumari et al. 2013).

Effect of paclobutrazol on growth and yield attributes of cotton

Paclobutrazol (PBZ), a triazole group of PGRs, plays an important role in agriculture by inhibiting cell elongation and internode expansion. PBZ inhibits both sterol and gibberellin synthesis, influencing plant growth by altering photosynthesis and phytohormone levels (Kim et al. 2012). It particularly inhibits ent-kaurene oxidase in the GA biosynthesis pathway, affecting plant height, stem diameter, leaf number, and root architecture (Kondhare et al. 2014). The spraying of PBZ improves drought resistance by stabilizing cytokinin levels, boosting leaf water potential, and increasing leaf thickness (Liu et al. 2020; Sankar et al. 2016). Figure 2 represents a pictorial representation of PBZ used to improve drought tolerance in cotton plants. PBZ modulates osmoprotectants and boosts antioxidant activity to alleviate drought stress (Jungklang et al. 2017). The stereochemical structure of PBZ may operate to inhibit GA synthesis (Fletcher 1988). It increases yield by reducing plant height, increasing stem diameter and leaf number, to directing resources toward seed development (Syahputra et al. 2013; Dewi et al. 2016).

PBZ is primarily used as a growth retardant and stress protectant, inhibiting the production of gibberellin, abscisic acid (ABA), and cytokinin (Hajihashemi et al. 2014). The application of PBZ can induce morphological modifications in leaves, such as smaller stomatal pores, thicker leaves, increased number and size of surface appendages, and enhanced root density, all of which contribute to greater environmental stress tolerance and disease resistance (Fletcher et al. 1988). Foliar application of 0.035% Paclobutrazol SC (23%, mass fraction) at 55 days after sowing (DAS) and at 85 DAS, combined with nipping at 90 DAS, ultimately reduced the plant height and maintained the source-sink relationship, and produced the highest seed cotton yield (2 788 $kg \cdot ha^{-1}$), a greater number of good opened bolls per plant (31.37), and increased the boll weight up to 5.12 g (Suma et al. 2019).

PBZ also protects plants against injuries induced by high temperatures (Kraus et al. 1994). This protection against high-temperature stress is achieved through the creation of low molecular mass stress proteins (Larsen et al. 1988) and an increase in antioxidant enzyme activity (Fletcher 1988). PBZ has a wide range of applications due to its efficacy in protecting crops from a variety of environmental stresses such as drought, cold, heat, and UV radiation (Orabi et al. 2010). PBZ affects nearly all plant species and is usually given via foliar sprays and medium drenches, with both approaches producing excellent results.

Effects of cycocel on growth and yield attributes of cotton

Cycocel, also known as chlomequat chloride, was once used mainly to treat lodging and height problems in

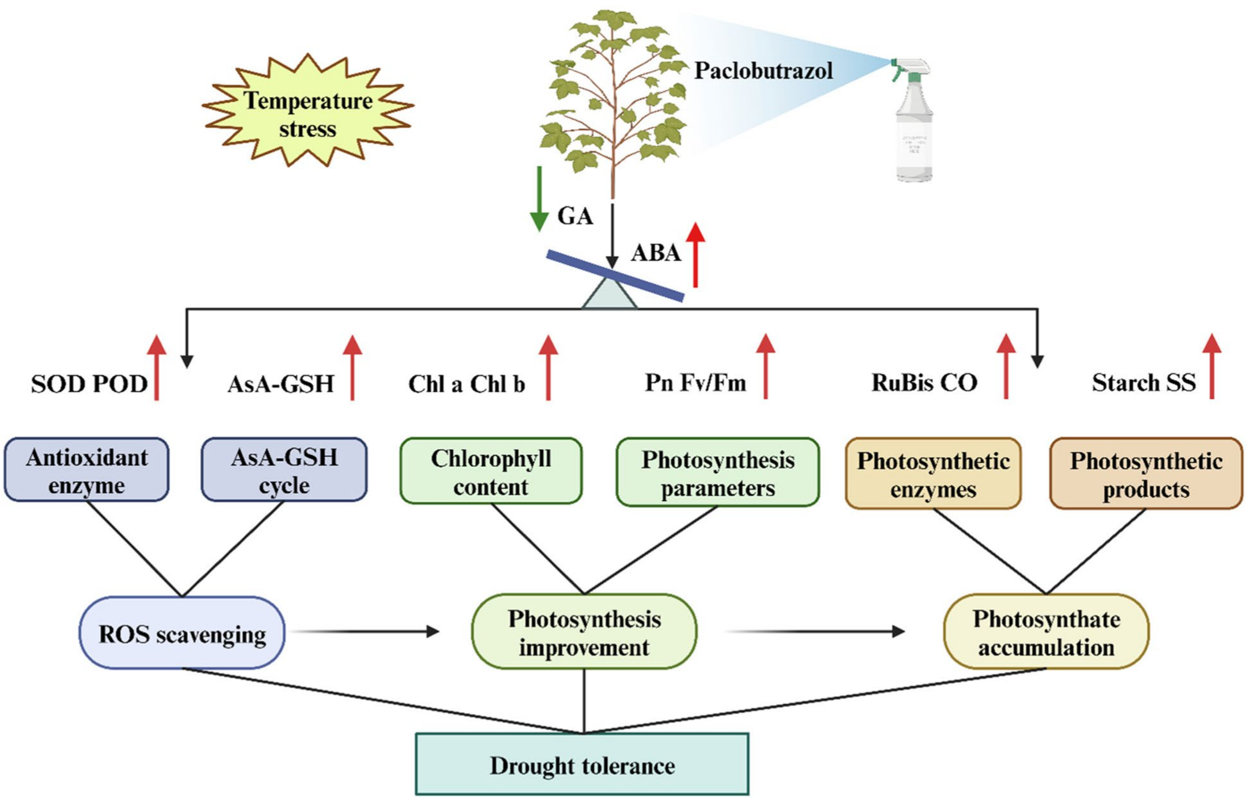

Fig. 2 The application of paclobutrazol improving drought tolerance in cotton plant (A modified diagram of Liu et al. 2020)

cereals. However, since shorter-statured cultivars have been introduced, the application of cycocel has decreased (Oosterhuis 1998). By reducing internodes and thickening stems, roots, and leaves, it modifies the morphology and biochemical makeup of plants (Kumari et al. 2019) (Fig. 3). In cycocel-treated plants, it increases the number of cells in the xylem vessels, phloem fiber, and xylem fiber. In addition, cycocel-treated cotton stems exhibit enhanced flavonoid accumulation, possibly indicating their function as signaling molecules, and the presence of S-lignin, G-lignin, and H-lignin, which contribute to disease resistance (Xu et al. 2011).

Cycocel is the principal growth retardant used in several cotton-producing nations, the application of chlormequat chloride 50% SL at 3 $mL·L^{-1}$ of water at 60 and 80 DAS had a significantly positive impact on growth parameters, including plant height, dry matter production, the number of main stem nodes per plant, the length of the top fourth and fifth internodes, the height-to-node ratio, as well as growth analysis indicators such as the LAI and chlorophyll content in the leaves (Celsia et al. 2024). The application of cycocel results in a decreased internode length while enhancing the thickness of stems, roots, and leaves (Kumari et al. 2019).

By applying chloromequat chloride and detopping under HDPS, hybrid cotton increased the number of sympodial branches (20.76) and bolls (35.89) per plant, and also increased the seed cotton production (1 635 $kg·ha^{-1}$). These results were significantly greater than those of the control. Additionally, the quality parameters did not exhibit significant differences, except in fiber strength (Shekar et al. 2015). Application of 150% recommended dose of fertilizers (RDF) along with cycocel spray at 55 to 60 DAS resulted in higher seedcotton yield (2 791 $kg·ha^{-1}$) compared with all other treatments (Rao et al. 2015). According to Sarlach et al. (2010), the foliar application of cycocel after 15 days of flower initiation recorded good yields.

Effect of maleic hydrazide application in cotton

Maleic hydrazide (MH) is a plant growth regulator inhibiting plant growth without inducing noticeable morphological abnormalities (Naylor et al. 1950). MH functions as an auxin inhibitor, restricting plant vegetative growth by acting as an antimitotic agent. It penetrates the cuticle and targets tissues involved in cell division, reducing the internodal length and overall growth (Ilić 2011). In cotton, MH disrupts GA_3 biosynthesis, which leads to reduced plant height (Thorat et al. 2012).

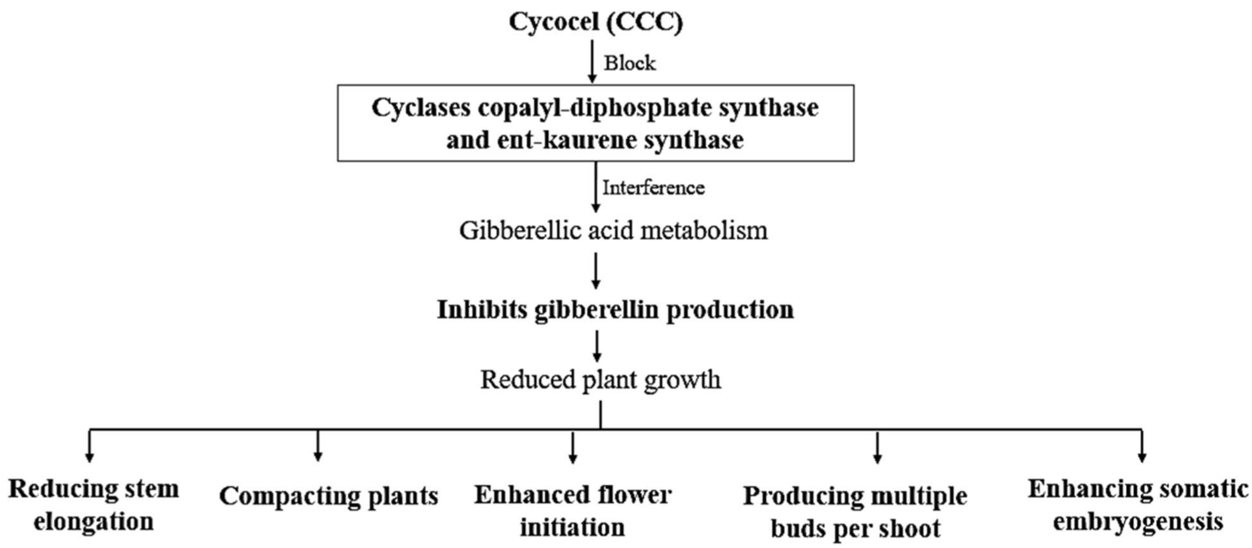

Fig. 3 Biochemical and morphological modifications in cotton plants while application of cycocel (Niazian et al. 2020)

Interesting properties of MH suggest that better assimilation in the fruiting structures, not the vegetative components, is the primary cause of the reduction in cotton plant height. The application of MH at 250 g·hm^{-2} during the peak boll development stage in cotton suppressed apical growth and extended the period of leaf expansion by approximately 10–15 days (Rahman et al. 2004).

Effect of 2, 3, 5-triiodobenzoic acid application in cotton

2, 3, 5-triiodobenzoic acid is an anti-auxin that disrupts the auxin-mediated transport of metabolites to the shoot apex, increasing dry matter allocation to developing sinks (Nuti et al. 2006; Dhanalakshmi 2003); it also inhibits stem elongation, resulting in shorter cotton plants (Djanaguiraman et al. 2005); and it blocks the polar transport of indole acetic acid, reducing plant height, increasing light penetration through vertical leaf orientation, and improving photosynthetic efficiency and yield (Dhillon et al. 1981).

The application of TIBA decreases internodal length, thereby reducing plant height, this reduction promotes the translocation of photosynthates towards reproductive sinks, particularly bolls, resulting in increased yields (Kumar et al. 2005). TIBA has the potential to induce various morphological and physiological alterations, and these changes appear to primarily arise from its interaction with auxin (Irving 1968). At higher concentrations, TIBA more effectively restrains plant height but increases the root length due to the redirection of hormones from the shoot apical meristem to other parts of the plant, thereby suppressing apical dominance (Dhillon et al. 1981); This effect could be attributed to enhanced growth of lateral buds (Rajput et al. 1973; Nakajaima 2001).

Role of defoliators in machine picking cotton

Cotton defoliation is a normal physiological process that occurs naturally to the plant, but when it occurs untimely or incompletely, it interferes with machine picking. Defoliants are used to combat this, promoting leaf drop and facilitating machine picking (Karademir et al. 2021). The defoliation process affects the plant's metabolism and leads to leaf shedding (Sravanthi et al. 2022). Defoliants hasten the development of abscission layers, which cause leaf drop at the point where leaf petioles connect to the stems. The mechanism of action of older defoliants involves contacting and damaging green tissues, which subsequently promote the growth of the abscission layer (Chandrasekaran et al. 2023). To conduct effective defoliation, it is important to consider the biological development of cotton (Fatullateshaev et al. 2015). Various defoliants, such as dropp ultra, ethrel, NaCl, and paraquat, are applied at varied rates and at the time of maximum sunshine to promote leaf drop and ensure even and early boll opening, enabling cotton single picking by machine. Effective defoliation depends on several factors, including crop density, plant maturity, time of application, type of chemical used, and application rate (Neupane et al. 2023).

Timing of defoliant application and yield improvement in cotton

The application of defoliants at the right time is crucial for cotton productivity. If applied too late, unfavourable weather conditions can lead reduction in fiber quality (Jones et al. 2019). The ideal time to apply defoliants is when the bolls are mature and ready for harvest. The timing of defoliant application in cotton is determined by several factors, such as the proportion of open bolls, nodes above cracked boll (NACB), nodes above white flower (NAWF), evaluations of seed and fibre maturity, and visual inspections of cut bolls (Sathiyamurthi et al. 2022).

Farmers can optimize cotton harvests both economically and effectively by choosing the appropriate defoliation method based on environmental and crop conditions. Generally, defoliation is considered safe when 50%–60% of the bolls are open and the NACB is four or fewer (Jones et al. 2019). However, it is important to consider the specific cotton variety, as the optimal timing can vary among cultivars (Neupane et al. 2023). A common rule is to defoliate when around 60% of the bolls are open, which usually works well in most cases. This practice not only accelerates boll opening but also results in higher yields (Meena et al. 2017).

Hormonal defoliant (thidiazuron) and herbicidal defoliant (diuron) are widely used defoliants. Thidiazuron enhances ethylene concentration relative to auxin in leaf petioles, which activates the leaf abscission layer (Zhang et al. 2017; Gormus et al. 2017). Leaf abscission is primarily associated with changes in leaf water potential and a reduction in total chlorophyll content (Primka et al. 2019). Chemical defoliant, induced abiotic stress in cotton leaves, leads to severe damage to the cell membrane system. This damage, induces water loss, membrane disruption, cell death, and oxidative damage, contributing to decreased chlorophyll content and subsequent leaf abscission. Additionally, the use of defoliants can significantly reduce the photosynthetic rate (P_n), stomatal conductance (G_s), and transpiration rate (E) of cotton leaves (Meena et al. 2016; Chandrasekaran et al. 2023, 2024). Diuron accelerates the process of leaf scorching and improves defoliation, especially under cooler temperatures (Çôpur et al. 2010). However, these defoliants can cause rapid leaf abscission, which may interfere with the timely transport of nutrients from the leaves to the cotton bolls. Additionally, they do not directly affect boll ripening and should be used in conjunction with a boll opener, such as ethephon, to achieve effective defoliation and boll opening (Du et al. 2014).

Defoliators and boll openers not only increased the efficiency of machine picking in cotton, and also improved the yield. Buttar et al. (2013) reported that the application of ethrel at 1 250 g·hm^{-2} at 145 DAS, increased the yield up to 3 065 kg·ha^{-1}. Similarly, Mrunalini et al. (2019) found that the application of etherel at 1 000 g·hm^{-2} at the 60% boll opening stage produced a higher yield of 2 359 kg·ha^{-1}. Relatively, applications of dropp ultra at 200 mL·ha^{-1} at 140 and 150 DAS increased the yield of 3 172 kg·ha^{-1} (Singh et al. 2015). Kaur et al. (2021) found that the application of dropp ultra at 175 mL·ha^{-1} at 70% boll opening resulted in higher yields. Raghavendra et al. (2020) reported that in the two-year study, with the application of dropp ultra at 250 mL·ha^{-1} at 120 and 140 DAS increased the yields of 2 621 and 2 207 kg·ha^{-1}.

Importance of synchronized maturity for machine picking cotton under HDPS

Cotton is harvested mechanically in developed countries such as USA, Canada, and Australia, which offers several benefits. In India, with continuously increasing labor costs, farmers consider manual harvesting of cotton increasingly expensive and are seeking opportunity to adopt mechanical harvesting. Additionally, experts also suggest that research should focus on reducing the cost of cultivation substantially by promoting the use of synchronized maturity varieties, defoliants, and machinery (Chandel et al. 2022). HDPS associated with PGRs provides synchronized flowering, uniform boll bursting, and early maturity (Gunasekaran et al. 2020). When PGRs and defoliants are applied to the plants, can alter the metabolism, and canopy structure causing the leaves to drop off, and increasing the machine picking efficiency.

Factors affecting machine picking cotton and some of the pre-requisites

In India, most farmers have fragmented and small landholdings, making it difficult to adopt machine picking (Venugopalan et al. 2023). Cotton grown in clay soils results in excessive vegetative growth due to high water retention and nutrient-rich properties of the soil, which makes it unsuitable for HDPS (Manibharathi et al. 2024). Under HDPS, cotton plants tend to grow excessively, causing self-shading, which necessitates managing the canopy structure with PGRs; when PGRs are not applied yield could be reduced by 5% to 10%. PGR overuse or improper timing can impede plant growth and have a detrimental effect on cotton output.

Challenges like the high cost of machinery, lack of harvest aid chemicals such as defoliants, adoption of different farming practices, and the unavailability of cleaning machines pose significant obstacles to adopting machine harvesting. Machine-picked cotton contains 17%–20% trash content, compared with 1%–6% in hand-harvested cotton, which affects cotton quality and reduces its market value. In India, mostly cotton is harvested by handpicking methods. Most of the Western countries followed machine picking in cotton, they mostly used spindle-type pickers and stripper-type machines (Venugopalan et al. 2023). Here, some of the prerequisites that need to be followed, to adapt machine picking in cotton are:

1. Large continuous land with long rows of cotton spaced apart to accommodate the picker header.

2. High density planting cotton with canopy management for easier machine picking.
3. The synchronized boll maturity and boll opening.
4. The availability of harvest aid chemicals *viz.*, defoliants and boll openers.
5. Finally, the availability of a pre-cleaning facility to reduce trash content in machine picked cotton.

Future perspectives

- ✓ Need to integrate advances in precision farming tools, such as sensors and artificial intelligence (AI), which allow for highly targeted PGR applications, optimizing canopy control for machine harvesting, and reducing chemicals waste.
- ✓ More research is needed on harvest aid chemicals to reduce trash content in machine-picked cotton and to improve the efficiency of cotton cleaning machines.
- ✓ There is a need to develop more region-specific compact and semi-compact hybrids/varieties in cotton that are tailored to local growing conditions ensuring high yields, and improved harvesting efficiency across diverse agricultural environments.
- ✓ In the future, genetically engineered cotton varieties with enhanced responsiveness to PGRs will provide more precise control over plant architecture, reducing the need for repeated chemical applications.

Conclusion

Managing cotton canopy architecture through the integration of high plant density and PGRs application offers a highly effective and transformative strategy for adopting and enhancing machine picking efficiency in cotton farming. High density planting significantly increases plant populations and optimizes the utilization of land and resources, while PGRs precisely regulate vegetative growth, promoting a compact and well-structured plant architecture tailored for machine picking in cotton. This integration delivers multiple benefits, including higher cotton yields, improved fiber quality, and greater operational efficiency, while also addressing pressing issues such as labour shortages and production costs rising. However, the success of this approach is contingent upon the careful selection of suitable cotton varieties and the adaptation of modern cultivation practices in response to environmental factors and regional conditions. In this context, this integrated system lays the foundation for more sustainable and productive cotton farming, enabling growers to meet the evolving challenges of modern agriculture while driving long-term profitability and resilience within the cotton production sector.

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