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Optimizing cotton (*Gossypium hirsutum L.*) production: The synergy of ultra-narrow row cropping and plant growth regulator application

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) is a globally important cash crop cultivated primarily for fiber, yet its indeterminate growth habit often results in excessive vegetative development and yield losses. Optimizing row spacing and plant growth regulator (PGR) use is particularly critical in the context of climate change, resource-use efficiency, and narrowing yield gaps in Bt cotton production systems. Plant growth regulators (PGRs), particularly mepiquat chloride (MC; 1,1-dimethylpiperidinium chloride), are widely used to manage canopy architecture and promote reproductive growth. This field study was conducted in Agricultural field of Ghazi University, Punjab, Pakistan, during the 2020 and 2022 cotton seasons, to evaluate the combined effects of ultra-narrow row (UNR) spacing (30 cm) and MC application on the growth and productivity of two Bt cotton cultivars (BS-70 and BS-15). A factorial randomized complete block design (RCBD) with a split-plot arrangement was used, comprising two row spacings (30 cm UNR and 75 cm conventional) and three MC regimes (none, 10-day interval, and 20-day interval). Results showed that UNR and MC significantly influenced plant height, node number, branching pattern, boll weight, and seed cotton yield, while fiber quality traits ginning outturn, fiber fineness, fiber length, and strength remained unaffected. The highest yield was recorded in BS-70 under UNR without MC, closely followed by UNR with 20-day MC application. In contrast, frequent MC application (10-day interval) suppressed reproductive development and reduced yield. These findings demonstrate that UNR planting combined with judicious MC application enhances cotton productivity without compromising fiber quality, offering a sustainable intensification strategy for cotton cultivation under changing climatic and resource-limited conditions.

Keywords: Plant growth regulators, mepiquat chloride, ultra-narrow row, *Gossypium hirsutum* L.

INTRODUCTION: One of Pakistan's most important and necessary cash crops is cotton (*Gossypium hirsutum* L.). It is a leading fiber crop and a crucial source of fiber raw materials for the textile industry, as cotton is the cornerstone of the nation's economic growth and the sector's ability to survive (Kouser and Qaim, 2013; Ali *et al.*, 2019). It has an irregular growth pattern and is a perennial crop. Cotton is used to make roughly 50% of the fiber for apparel and 16–24% of edible oil (Khan *et al.*, 2019; Raut *et al.*, 2019; Wang *et al.*, 2020). Cotton and its byproducts have a broad spectrum of uses, such as serving as a basis for dietary supplements, producing oil-free seed cake for animal feed, and managing organic waste post-harvest (Velmourougane *et al.*, 2021). Commonly known as "White Gold," cotton plays a vital role in the global economy and is cultivated in around 80 countries (Rajalakshmi *et al.*, 2018). The largest production of cotton takes place in Asia, with Asia and America collectively responsible for over 80% of the global output.In Pakistan, cotton remains a vital cash crop. During the 2023–2024 season, production rebounded strongly to approximately 10.22 million bales, following sharp declines in the flood-affected previous year (Pakistan Bureau of Statistics, 2024). Currently, cotton is cultivated on about 2.0 million hectares, with production for 2024/25 forecast at 5.2–5.55 million bales (USDA-FAS, 2024). These fluctuations highlight the vulnerability of the crop to climatic and biotic stresses, while underscoring its continued economic importance, as it contributes about 0.8% to GDP and supports the country's largest manufacturing and export sector (Rana *et al.*, 2020). Despite its economic importance, Pakistan's cotton industry faces significant challenges, primarily from diseases and pests. Major diseases include cotton leaf curl virus (CLCV), which is one of the most destructive viral diseases, and bacterial blight. Key insect pests are the whitefly (*Bemisia tabaci*), which acts as a vector for CLCV, and the bollworm complex, particularly the American bollworm (*Helicoverpa armigera*) and pink bollworm (*Pectinophora gossypiella*) (Aslam *et al*., 2025; Khan *et al.,* 2019). These biotic stresses, combined with the crop's vulnerability to climate change, can lead to substantial yield losses. Cotton is highly vulnerable to climate change due to its perennial growth pattern and diverse development cycle (Bange *et al.*, 2016). Its wide canopy and strong stem growth can create shadows that cause leaf and fruit loss, reducing yield (Zhao and Oosterhuis, 2000; Tariq *et al.*, 2017). A study by Roche and Bange (2022) found that an ultra-narrow row (UNR) system with row spacing less than 40 cm can increase plant density and uniform plant placement than traditional row systems, and is a potential approach to increase yield and accelerate plant maturity. However, the spreading growth pattern of cotton often requires additional labor for efficient crop management. Strategies to limit excessive leaf growth, including the use of short-lived varieties or genetically modified pests and disease-resistant varieties. Cotton growers are utilizing ultra-narrow row spacing (UNR) to increase plant population and decrease yield losses (Trehune, 1998; Hussain *et al.*, 2000; Nichols *et al.*, 2003; Nichols *et al.*, 2004; Vories and Glover, 2006; Nawaz *et al.*, 2019; Nawaz *et al.*, 2021). By optimizing canopy architecture, the UNR system enhances seed cotton yield, shortens the crop cycle, and improves harvest efficiency (Roche *et al.*, 2024). Furthermore, it promotes fruit set on lower branches and supports the development of fewer, but larger, bolls per plant due to higher planting densities, thereby increasing overall productivity and profitability (Boquet, 2005; Nawaz *et al.*, 2015; Phanindra *et al.*, 2024), maximizing net income (Manibharathi *et al.*, 2024; Sekar *et al.*, 2024). In addition to its yield-enhancing potential, the UNR system can reduce input costs by minimizing fertilizer requirements and enabling the use of cost-effective harvesting technologies such as cotton strippers, as opposed to spindle pickers (Asiimwe *et al.*, 2016; Bennett *et al.*, 2017).

Complementing spatial management practices, plant growth regulators (PGRs) serve as a practical and efficient tool to improve cotton yield and regulate plant development (Zhumanova *et al.*, 2024). These substances influence plant physiology by altering key processes such as photosynthesis, distribution of assimilates, and nutrient uptake and utilization (Zhumanova *et al.*, 2024). As a result, enhancements are observed in plant structure, boll retention and opening, as well as in the yield and quality characteristics (Klutse *et al.*, 2025). Within the spectrum of PGRs, compounds like Ethephon-6, Cyclanilide, and Mepiquat chloride (1,1-dimethylpiperidinum chloride)—commercially known as "First Pick," "Finish 6 Pro," and "Pix Ultra"—are commonly applied to control excessive vegetative growth in cotton crops (Siebert and Stewart, 2006).

Mepiquat chloride (MC) is globally recognized for its efficacy in promoting canopy growth and suppressing unwanted vegetative vigor in cotton. Its mechanism of action is to alter the order of nutrient uptake, translocation, reserve release, and assimilate distribution (Almeida and Rosolem, 2012; Malima *et al.*, 2025). Specifically, MC inhibits the biosynthesis of gibberellic acid by inhibiting the conversion of geranylgeranyl diphosphate to ent-kaurene—which results in reduced cell division and growth (Raut *et al.*, 2019). MC application consistently reduces plant height, reduces the number of nodes on the main stem, reduces internode spacing, and limits leaf elongation. Simultaneously, light utilization efficiency increases and crop yield increases (Rademacher, 2000; Siebert and Stewart, 2006; Ren *et al.*, 2013; Mao *et al.*, 2014; Wang *et al.*, 2014; Mao *et al.*, 2015; Niu *et al.*, 2016; Lakshmanan *et al.*, 2025). MC also positively increases photosynthetic efficiency—chlorophyll content, stomatal conductance, transpiration rate, leaf CO_2 exchange, and total CO_2 fixation increase (Ali and Mukhtar, 2025). It promotes the growth of cotton lateral roots and increases sink volume, which in turn delivers nutrient uptake to reproductive structures (Feng *et al.*, 2024). Cotton plants with MC treatments grow larger leaves and higher chlorophyll content (Yasmeen *et al.*, 2016). The photosynthetic activity induced by MC suggests that bolls of treated plants act as strong photosynthetic sinks, as MC source-sink dynamics can be easily altered to divert photo-assimilates and nutrients toward reproductive development (Gwathmey and Clement, 2010; Fan *et al.*, 2013; Vermeulen *et al.*, 2013). These adjustments promote fruitfulness and ripening of early fruits (Niu *et al.*, 2016), which improves seed and fiber quality by increasing boll retention (Ren *et al.*, 2013). Although the individual benefits of UNR spacing and MC application are known, their combined effects on cotton morphology, physiology, yield, and fiber quality have not yet been completely determined under field conditions, which reflect real ground farming conditions. Many studies have shown the effect of UNR or MC separately, but their combined effect on cotton productivity and cultivar performance has been less explored.

OBJECTIVES: This study was aimed to (i) assess the combined effects of ultra-narrow row spacing and mepiquat chloride application on cotton growth and yield; (ii) compare the performance of two Bt cultivars under UNR conditions; and (iii) evaluate implications for plant architecture, boll development, and seed cotton yield. This research provides new insight into sustainable intensification strategies for cotton production, with practical relevance for improving input use efficiency, reducing production costs, and supporting environmental management in cotton-growing regions.

RESULTS AND DISCUSSION

Plant height and node number: Plant height and number of nodes per plant were significantly affected by row spacing and Mepiquat Chloride (MC) application (table 1). The tallest plants (119.70 cm) were observed in the conventional row spacing (75 cm) without MC application (Control). Plant height was progressively reduced with decreasing row spacing and increasing MC application frequency. The shortest plants (72.80 cm) were recorded in the Ultra-Narrow Row (UNR) spacing (30 cm) with MC applied at 10-day intervals, followed by UNR with MC at 20-day intervals (91.33 cm). This trend was consistent across both cultivars (BS-70 and BS-15). Similarly, the highest number of nodes on a single plant was observed in Control (36.86) while the lowest was in UNR (30 cm), where MC was given after 10 days (28.06). The combined effect of UNR spacing and MC reduced both the length and number of nodes of the plant. These results are in agreement with previous experiments, which showed that UNR spacing and MC use significantly reduce vegetative growth of cotton. This is because mepiquat chloride is a gibberellic acid biosynthesis inhibitor, which reduces cell and internode elongation, while the high plant density in UNR systems increases inter-plant competition for resources, collectively suppressing vegetative growth and promoting a more compact plant architecture (Arefi, 2023; Feng *et al.*, 2024; Manibharathi *et al.*, 2024; Roche *et al.*, 2024).

Row Spacing and Growth Inhibitor	Cultivar	Plant Height (cm)	No. of Nodes per Plant	No. of Sympodial Branches per Plant	No. of Monopodial Branches per Plant	No. of Bolls per Plant	Boll Weight (g)	Seed Cotton Yield (kg ha^{-1})
T1: Control (75cm) No Stance	V1: BS-70	122.67a	39.06a	24.50a	2.50a	8.26c	2.23b	2496.3d
	V2: BS-15	116.73a	34.66a	23.66a	2.33a	13.53a	2.42ab	2481.0d
T2: UNR (30cm) No Stance	V1: BS-70	111.13b	36.86ab	20.83b	2.50a	11.26ab	2.50ab	5216.7a
	V2: BS-15	111.47b	36.20a	18.50c	2.17ab	8.66c	2.40ab	5074.7a
T3: UNR (30cm) Stance (20-day interval)	V1: BS-70	92.07c	31.40c	12.16d	1.66b	6.93c	3.03a	5135.0a
	V2: BS-15	90.06c	31.07b	10.00d	1.17c	7.60c	2.50a	4618.3b
T4: UNR (30cm) Stance (10-day interval)	V1: BS-70	71.80d	25.53d	8.33e	1.33bc	10.73b	2.98a	4498.3b
	V2: BS-15	73.87d	30.60b	6.50e	1.00c	8.00c	2.95ab	4136.3c

Table 1: Effects of row spacing and Mepiquat chloride (Stance) application on morphological and yield attributes of two cotton cultivars (BS-70 and BS-15).
Values within the same column followed by different letters are significantly different at P ≤ 0.05 based on Duncan's Multiple Range Test (DMRT) Least Significant Difference (LSD); UNR-Ultra Narrow Row.

Branching characteristics: The treatments had a strong effect on the number of sympodial branches. The highest number of sympodial branches was observed in the Control (24.08). The use of MC along with UNR spacing significantly reduces this number, and the lowest number of branches (7.41) was recorded in UNR (30 cm) + MC (with a duration of 10 days). Cultivar BS-70 generally showed the highest number of sympodial branches (16.45), while this number was less in BS-15 (14.67). These findings are in agreement with research showing that UNR influences branching patterns (Ali, 2014b; Mahdi, 2016) and the use of MC leads to a decrease in sympodial branches (Çopur et al., 2010; Yasmeen et al., 2016; Hussain et al., 2020). For monopodial branches, most branches (2.42) were observed in Control, which were equal to UNR (30 cm) without MC (2.33). The least number of monopodial branches (1.17) was recorded in UNR (30 cm) + MC (over 10 days). UNR systems have fewer monopodial branches due to greater competition for resources (Davis, 2021; Nawaz *et al.*, 2021; Lawton, 2023).

Yield components: The number of bolls per plant varied across treatments. While the overall mean for the Control (10.90) appeared highest, it was not significantly different from UNR (30cm) without MC (9.96). The UNR (30cm) with MC applications (both 20-day and 10-day intervals) resulted in a lower number of bolls (7.26 and 8.36, respectively). The interaction between cultivar BS-70 and UNR (30cm) without MC resulted in the highest number of bolls (11.26). While some studies suggest UNR may reduce boll numbers as reported by Siddiqui *et al.* (2007); Ahmad *et al.* (2009) and Ali (2014). Others indicate that MC application can increase boll quantity by translocating photo-assimilates to reproductive parts (Sawan *et al.*, 2006; Gonias *et al.*, 2012; Aslam *et al.*, 2020). Boll weight changed significantly with treatments (table 1). The heaviest bolls (2.96 g) were obtained after 10 days of MC in UNR (30 cm), followed by (2.76 g) after 20 days of MC in UNR (30 cm). Control and UNR without MC Boll weights were significantly lower (2.37 g and 2.45 g on a single basis). This suggests that UNR spacing and MC application result in heavier bolls, possibly due to less boll competition as the bursting process is less competitive for resources (Ali et al., 2009). These results are consistent with previous findings that MCs show a positive effect on boll weight, which is due to an enhancement of photosynthetic activity (Sawan *et al.*, 2006; Gwathmey and Clement, 2010; Ren *et al.*, 2013; Tung *et al.*, 2020). Seed cotton yield showed significant differences between treatments. The highest seed cotton yield (5145.7 kg ha) was produced under UNR (30 cm) without MC, which was statistically greater than UNR (30 cm) MC at 20-days (4876.7 kg ha). The lowest yield (2488.7 kg ha) was recorded under Control. Cultivar BS-70 (4336.6 kg ha) generally yielded more than BS-15 (4077.6 kg ha). Larger plant populations in UNR systems are associated with higher seed cotton yield (Darawsheh *et al.*, 2009; Brodrick *et al.*, 2013). Apart from this, MC application can improve seed cotton yield by shifting resources from vegetative to reproductive growth (Tung *et al.*, 2020; Abbas *et al.*, 2022; Murtza *et al.*, 2022).

Fiber quality traits: Fiber quality traits are summarized in table 2. In comparison, while significant effects were observed on the basic strength and productive parts of the plants, cotton fiber quality traits such as ginning outturn (GOT), fiber fineness (Micronaire), fiber length, and fiber strength were not significantly influenced by row spacing, MC application, or cultivar combinations (table 2). This indicates that, although treatments affected vegetative and reproductive growth, the genetic potential for fiber quality remained intact within these cultivars, or else the treatments did not

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impose sufficient stress to impair fiber development. This consistency in fiber quality is an important outcome, as it suggests that yield can be optimized through agronomic practices (UNR spacing and MC application) without compromising the marketable attributes of the fiber. This finding aligns with previous studies reporting a non-significant effect of UNR spacing (Hussain *et al.*, 2000; Boquet, 2005; Ahmad *et al.*, 2009; Iqbal and Khan, 2011; Sawan, 2013; Mahdi, 2016; Zhang *et al.*, 2016; Walelgn and Belete, 2020; Altundag and Karademir, 2021) and MC application (Karthikeyan and Jayakumar, 2001; Iqbal *et al.*, 2004; Ren *et al.*, 2013; Altundag and Karademir, 2021; Murtza *et al.*, 2022; Roche and Bange, 2022) on various cotton fiber quality parameters. The physiological mechanisms underlying this stability may be attributed to the fact that fiber development particularly traits like length and strength—is primarily genetically regulated and occurs post-anthesis during fiber elongation and secondary wall thickening phases, making it relatively resilient to moderate environmental or chemical perturbations that do not significantly impair overall photosynthesis or plant health (Huang *et al.*, 2021; Jiao *et al.*, 2025).

Row Spacing and Growth Inhibitor	Cultivar	Ginning outturn (GOT%)	Fiber fineness (micronaire)	Fiber length (mm)	Fiber strength(G/tex)
T1: Control (75cm) No Stance	V1: BS-70	28.83a	3.33b	30.33ab	26.76a
	V2: BS-15	33.63a	3.10b	30.56ab	26.26a
T2: UNR (30cm) No Stance	V1: BS-70	38.60a	3.63ab	34.23a	26.40a
	V2: BS-15	34.70a	3.40b	30.96ab	26.10a
T3: UNR (30cm) Stance (20-day interval)	V1: BS-70	37.00a	3.80a	32.83ab	26.66a
	V2: BS-15	34.06a	3.46b	23.20b	26.86a
T4: UNR (30cm) Stance (10-day interval)	V1: BS-70	31.56a	3.46ab	28.06b	26.20a
	V2: BS-15	33.50a	3.46b	29.16ab	26.03a

Table 2: Effects of row spacing and mepiquat chloride (stance) application on fiber quality attributes of two cotton cultivars (BS-70 and BS-15).

Values within the same column followed by different letters are significantly different at P ≤ 0.05 based on Duncan's Multiple Range Test (DMRT) Least Significant Difference (LSD); UNR-Ultra Narrow Row.

Reproductive traits: The interactive effects of cultivar, row spacing, and Mepiquat Chloride (MC) use significantly affected the reproductive phenology of cotton from square formation to complete boll development as presented in figure 1 (A-J). Often treatments showed a consistent time pattern where the numbers of reproductive structures (squares, flowers, and bolls) peaked at 90 to 120 days after sowing (DAS), after which the numbers decreased. This pattern reflects the natural progression of the cotton plant when the plant devotes resources to filling new reproductive sites rather than creating new reproductive sites.

The BS-70 cultivar (V1) grown in 75cm conventional row spacing (T1) recorded the most squares, flowers, and bolls per plant. For example, V1T1 produced approximately 14.0 squares (figure 1A) and 11.0 flowers (figure 1C) per plant. This superior performance is due to less competition for light, water, and nutrients in the wide row spacing, which allows each plant to fully express its genetic potential. The BS-70 cultivar showed greater inherent vigor under these ideal conditions than BS-15 (V2). These results are consistent with the current literature which has shown that high-density planting increases the number of plants in an area but reduces the reproductive output of each individual plant (Sher *et al.*, 2017; Khan *et al.*, 2019).

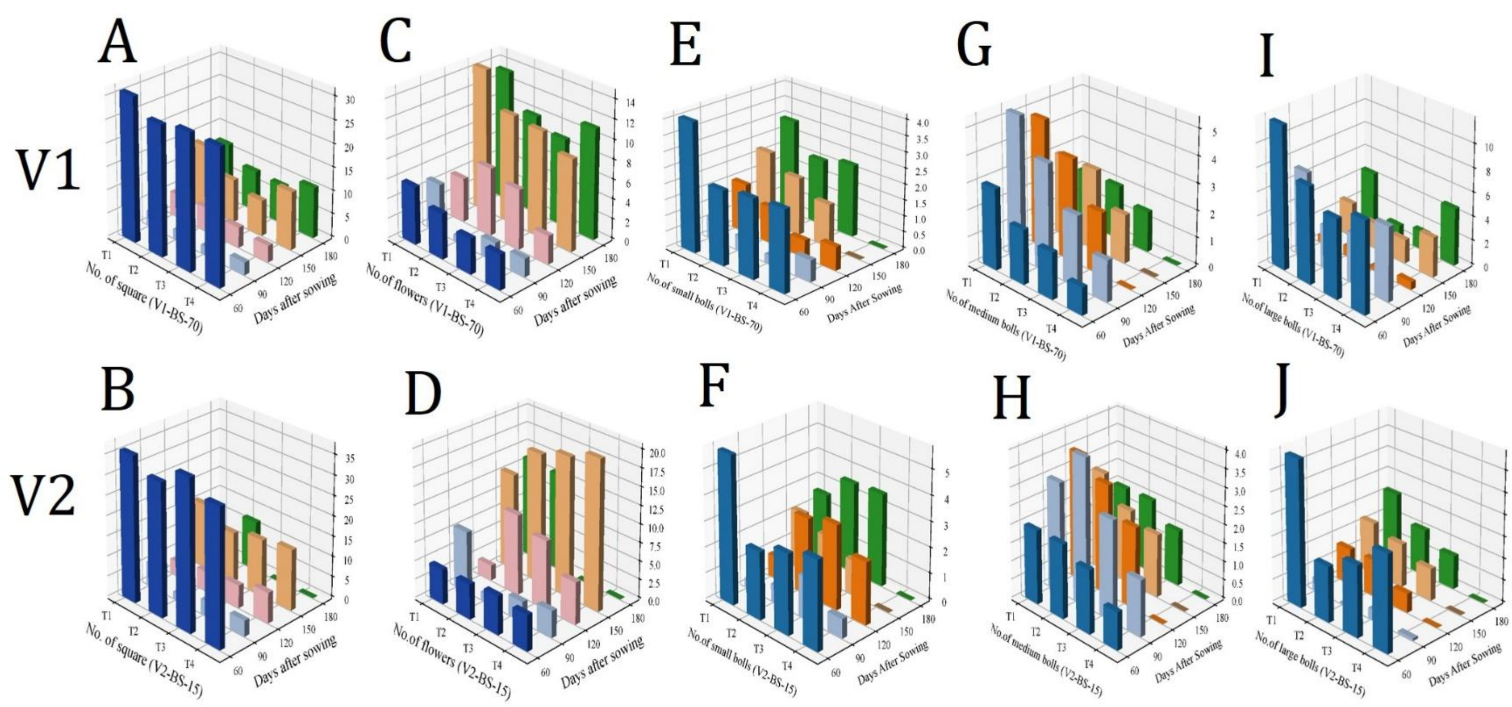

Figure 1:). Effect of ultra-narrow row spacing and Stance application on number of squares, number of flowers, and number of small, medium and large bolls in V1 (BS-70) and V2 (BS-15).

T1: Conventional row spacing at 75cm (control) ; T3: UNR 30cm with Stance application after 20 days interval

T2: UNR 30cm without Stance application ; T4: UNR 30cm with Stance application after 10 days

Small bolls: The formation of small bolls was significantly affected by both plant spacing and growth regulator (PGR) applications in both cultivars. In V1 (BS-70), the maximum number of small bolls (15.3 plant^{-1}) was recorded under 60 cm spacing with PGR applied at 20-day intervals, followed by 13.7 plant^{-1} with PGR applied at 30-day intervals as presented in figure 1E. The untreated control produced only 8.4 plant^{-1}. Similarly, in figure 3F exhibited that V2 (BS-15), the highest small boll retention (14.2 plant^{-1}) was observed under 60 cm × 20-day PGR application, compared to just 7.9 plant^{-1} in the control. These results emphasize that moderate spacing improves light interception and assimilate partitioning, while timely PGR use regulates vegetative reproductive balance to enhance boll initiation (Malik et al., 2021; Kavya et al., 2022).

Medium bolls: As bolls transitioned to medium size, clear treatment differences became evident. figure 1G&H demonstrated that in V1, 60 cm spacing with 20-day PGR intervals produced the highest medium bolls (12.8 plant^{-1}), followed by 11.5 plant^{-1} with 30-day PGR application. In contrast, only 6.7 plant^{-1} were retained in the control. V2 showed a similar trend, though with slightly lower counts (11.3 plant^{-1} under optimal treatment vs. 6.1 plant^{-1} in control). These findings highlight that V1 had greater retention capacity than V2, reflecting its adaptability to closer planting and frequent regulation. Enhanced medium boll retention under optimal treatments may be attributed to improved canopy architecture, efficient nutrient utilization, and balanced hormonal activity (Khan et al., 2019; Ahmed, 2022).

Large bolls: Large boll development also followed the same pattern. V1 recorded the highest large boll count (9.6 plant^{-1}) at 60 cm spacing with 20-day PGR application, compared to 8.1 plant^{-1} with 30-day intervals and just 4.5 plant^{-1} in control plots. V2 showed a maximum of 8.4 plant^{-1} under optimal conditions, while only 4.1 plant^{-1} were observed in untreated plants. Wider spacing (90 cm) without PGR application consistently reduced large boll formation in both cultivars as presented in figure 1 (I & J). This suggests that dense planting combined with regular growth regulation strengthens sink capacity, accelerates assimilate translocation, and minimizes boll abscission. These observations are in line with earlier studies reporting that closer spacing coupled with PGR improves boll maturation and yield potential (Reddy et al., 2017; Bashir *et al*., 2021).

In the ultra-narrow row (UNR) system, the application of MC was intended to manage vegetative growth and enhance the partitioning of assimilates towards reproductive structures. However, the results highlight the critical importance of application timing and frequency. While the UNR treatment without MC (T2) produced a moderate number of reproductive parts, the 20-day MC application interval (T3) resulted in a slight but consistent reduction in squares, flowers, and bolls per plant compared to the T2 control. This suggests that while the T3 schedule may have effectively controlled plant height, it imposed a mild suppressive effect on the reproductive capacity of individual plants, representing a trade-off between canopy management and per-plant yield components. The most striking result of this study was the severe negative impact of frequent MC application. The 10-day interval (T4) led to a complete and irreversible cessation of square, flower, and boll production after 90 DAS for both cultivars. This outcome indicates a phytotoxic response due to the accumulation of MC to supra-optimal levels within the plant tissue (Kumar *et al.*, 2020). Instead of beneficially regulating growth, repeated application significantly slowed development and likely arrested the function of apical meristems, thereby interrupting the formation of new reproductive organs. This observation serves as an important warning and supports previous studies warning of the risks of MC overdose. Overdose can disrupt basic physiological processes in the plant and lead to significant yield losses (Tung *et al.*, 2019; Wu *et al.*, 2023).

CONCLUSION: Ultra-narrow row spacing (30 cm), when combined with appropriate mepiquat chloride application, effectively regulated vegetative growth and improved cotton yield without impairing fiber quality. Cultivar BS-70 consistently outperformed BS-15 under UNR conditions, confirming its suitability for high-density planting. However, excessive MC use at 10-day intervals proved detrimental, highlighting the importance of optimal application timing. Overall, integrating UNR planting with carefully managed MC application represents a practical and sustainable approach to enhance cotton productivity, reduce production costs, and support resource-efficient crop management in cotton-growing regions.

Declaration: We hereby certify that the text of this review has neither been published elsewhere, nor is it under consideration elsewhere, and will not be submitted elsewhere.

Certify from authors and co-authors: We certify that all co-authors have been informed and agree with the submission of this paper.

Ethics approval: Not needed for this review.

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Conflict of interest: The authors declare that they do not have any personal relationships that can affect the work reported in this review.

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