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RESEARCH ARTICLE

Quantifying the impact of environmental conditions on the effectiveness of mepiquat chloride in modulating canopy architecture, yield, and quality of drought-stressed cotton (*Gossypium hirsutum* L.)

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ABSTRACT

This study, conducted in the semi-arid region of Turkey, during the 2022/23 cropping season, employed a split-split-plot design with three replications to evaluate the impact of Mepiquat chloride (MC) on the growth, yield, and quality of newly developed cotton varieties. The main plot comprised two cotton varieties, while the sub-plots represented two MC application timings and the sub-sub plots included four MC dosages. Although statistical analysis revealed that treatment differences were generally not significant for most parameters, notable trends were identified. In 2022, MC treatments delayed cotton development, whereas in 2023, they improved fiber quality. The highest fiber percentage was recorded under the control treatment in 2023, while in 2022, it peaked at a dosage of 400 mL•ha^{-1}. Among the varieties, Selin showed the highest fiber percentage when MC was applied during the bolling stage. Additionally, the shoot-root ratio reached its maximum at 400 mL•ha^{-1} during harvest in 2022 and at 0 mL•ha^{-1} during the reproductive stage in 2023. These results indicate that the effectiveness of MC in promoting physiological traits and alleviating drought stress appeared to be closely associated to weather variability, underscoring the necessity for site-specific management strategies to achieve optimal outcomes.

Keywords: Application time; cotton; fiber percent, maturity index, mepiquat chloride, shoot-root ratio.

INTRODUCTION

Cotton (*Gossypium* spp.) is an upright, perennial plant with a hermaphroditic growth habit, primarily grown as a cash crop by millions of farmers worldwide (Ashokkumar & Ravikesavan, 2011 & 2013; Ashokkumar et al., 2014). The precise centers of origin of cotton remain uncertain (Huckell, 1993). It is broadly adapted to temperate, sub-tropical, and tropical environments, but its growth and production face significant challenges due to the impacts of climate change (Fatima et al., 2024). Recent evidence and predictions indicate an increase in climate hazards, notably heat stress, drought, and extreme rainfall, in some of the highest cotton-producing countries, including China, India, the USA, Brazil, Pakistan, and Turkey (Çelik, 2023). Climate risks not only pose a threat to the cotton value chain but also impact the well-being of workers throughout the production cycle (Aslan et al., 2022). An increase in temperature can hamper productivity and threaten food security, a situation that can be further worsened when extreme temperature coincides with shifts in rainfall patterns (Shumate et al., 2024).

Cotton farmers encounter challenges in selecting the best management strategies to address the adverse effects of climate change, especially amidst rising production costs and unpredictable crop returns (Cakalogullari, 2023; Zafar et al., 2023). This difficulty arises despite the availability of various technologies, including the use of tolerant varieties, irrigation, optimal planting densities, and synthetic growth regulators, which have been developed and disseminated to mitigate the impacts of climate change (Bas & Killi, 2024; Khan et al., 2024; Lee et al., 2023). Among these techniques, the use of plant growth regulators holds paramount importance (Jia et al., 2024).

Mepiquat chloride, a widely used plant growth regulator, reduces excessive vegetative growth, yield, and fiber quality of cotton (Hu et al., 2023; YE et al., 2024). Moreover, it maintaining a vigorous crop stand, enhancing radiation-use efficiency, harmonizing plant canopy structure, better comfort of harvest, optimizing the source-sink relationship by regulating hormonal balance, and reducing the need for labor-intensive tasks, thereby mitigating costs (Luo et al., 2023; Meng et al., 2023; Wu et al., 2024). However, its efficiency depends on several factors, including crop size, variety, growth stage, crop management practices, environmental conditions, application dosage, methods and timing (Arekhi et al., 2023; Hu et al., 2023). Despite the documented benefits of Mepiquat Chloride in mitigating the effects of adverse climatic conditions by controlling excessive cell expansion, its impact on certain cotton varieties remains insufficiently understood (Bas & Killi, 2024; Müjdeci et al., 2024). To bridge this gap, this study was designed to investigate the efficacy of Mepiquat Chloride on newly developed cotton varieties in Turkey. The primary objectives were to identify the optimal dosage and application timing to improve canopy architecture, enhance yield, and boost fiber quality, specifically under the challenging conditions of Turkey's semiarid regions.

MATERIALS AND METHODS

Description of the study site

The experiments were conducted on a field of the Eastern Mediterranean Agricultural Research Institute (36° 5123 N, 35° 2048 E), Adana, Mediterranean region, Turkey, in 2022 and 2023. The Mediterranean region has average temperatures ranging between 17–20 °C. Winters typically have mean temperatures around 7–10 °C, while summers are warmer and mild, with mean temperatures between 26–29 °C. Annual precipitation generally ranges from 600 to 1,200 mm, consisting entirely of rainfall, with the average monthly rainfall during summer varying between 2.20 mm and 41.20 mm (Kızılsımsek et al., 2024; TSMS, 2023). During the 2022 growing season, the average temperature was 23.91°C, with an average wind speed of 2.38 $km \cdot h^{-1}$ and a mean rainfall of 170.20 mm (Table 1). In contrast, the 2023 season experienced an increase in all-weather parameters: the average temperature rose to 24.23°C, the average wind speed increased to 2.45 $km \cdot h^{-1}$, and the mean rainfall was 172.80 mm (Table 1) (TSMS, 2024). The weather profiles for 2022 indicate low mean rainfall, low moisture content, and low average temperature, which contrasted sharply with the more favourable conditions in 2023.

Table 1. Mean monthly rainfall, wind speed and temperature across two years studied.

		Months						
Climatic Trait	Year	May	June	July	August	September	October	November

Rainfall (mm)	2022	9.00	21.40	0.50	0.30	10.70	8.20	120.10
	2023	13.90	22.90	0.00	0.60	0.00	133.80	1.60
Temperature (°C)	2022	21.73	25.70	28.15	28.29	25.62	21.68	16.19
	2023	21.58	25.05	28.64	29.05	26.01	22.11	17.18
Wind speed (km·h^{-1})	2022	2.72	2.60	2.50	2.59	2.22	2.10	1.91
	2023	2.64	2.79	2.64	2.53	2.24	1.90	2.39

Experimental Design, Treatments and Field Management

The experiment was conducted in field plots measuring 0.3 m × 0.3 m, each consisting of four rows, and implemented within a split-split plot experimental design, arranged according to a randomized complete block design (RCBD) with three replications. The main plots were assigned to two cotton varieties: Sezener and Selin. The sub-plots were defined by two distinct application timings: one at the squaring stage (60 days after planting) and another during boll development (78 days after planting). The sub-sub plots were assigned four Mepiquat Chloride dosages, which were applied at the following rates: 0 mL·ha^{-1} (T_0), 400 mL·ha^{-1} (T_1), 400 + 400 mL·ha^{-1} (T_2), and 800 mL·ha^{-1} (T_3).

The planting configuration involved row spacing of 0.7 m and intra-row spacing of 0.2 m, resulting in a plant density of 142,857 plants·ha^{-1}. Cotton was sown following wheat harvest. The cotton varieties and Mepiquat Chloride were sourced from the Eastern Mediterranean Agricultural Research Institute. Throughout the growing season, recommended agronomic practices were adhered to. Both cotton varieties are early-maturing, requiring between 130 and 150 days to reach physiological maturity.

Prior to sowing, the field was plowed using a tractor to improve soil structure, mitigate capillary rise, and level the field. Crop residues from the previous wheat crop were cleared. Phosphorus fertilizer was applied at a rate of 8 kg·ha^{-1} prior to sowing. The cotton seeds used were mechanically sown, ensuring the use of clean, healthy, and mature seeds, with a seeding density of four seeds per planting hole. In 2022, sowing took place on May 26, and in 2023, on June 12. Following emergence, manual weeding was performed, and thinning was carried out to maintain two plants per hole.

Fertilization with ammonium nitrate (20-20-0) occurred in two stages: 16 kg N·ha^{-1} was applied pre-sowing, followed by 26 kg N·ha^{-1} at the squaring stage during the first irrigation. A total of four irrigation events were applied throughout the growing season to ensure adequate soil moisture. Pest management was carried out using specific chemical treatments: Movento (150 mL·ha^{-1}) for aphid and *Empoasca* spp. control, Mosplan 20 SP (60 g·ha^{-1}) for whitefly management, and Neemarin (60 g·ha^{-1}) for green caterpillar control. Harvesting was conducted upon reaching physiological maturity of the plants, which occurred on October 22, 2022, and November 13, 2023, respectively. All procedures were conducted in accordance with the local agronomic guidelines and environmental regulations to ensure the accuracy and reproducibility of the results.

Data Collection

Canopy architecture

Three (3) plants from each plot were selected randomly and brought to Ondokuz Mayis University for measurements. The samples were collected at three different growth stages (i.e. vegetative, reproductive and harvest). The collected samples were dived into to their above- and belowground parts at the boundary between the root and stem, and then dried in a forced-air-circulation oven at 65°C for 72 hours. The dried biomass was weighed using electronic 0.001 g weighing balance and averaged to assess their shoot-root biomass ratios.

Fiber percent

Seed cotton was handpicked from the two inner rows (4.2 m^2) of each plot and cautiously labeled. The collected seed cotton was then sun-dried for a month and weighed using an electronic weighing balance, and subsequently, was ginned to separate fiber, seeds and trash. Fiber percentage was calculated using the following formula:

[100 × fiber weight (g)] / [weight of seed cotton (g)]   (1)

Fiber quality

The ginned cotton from each plot was sent to the quality analysis department of the Eastern Mediterranean Agricultural Research Institute for high-volume instrument (HVI-900, USTER) analysis of fiber properties, typically, maturity index (%).

Statistical Analysis

The collected data were analysed using SPSS 17 computer software (https://www.ibm.com/support/pages/downloading-ibm-spss-modeler-170), and trial data were subjected to analysis of variance (ANOVA) fitting for the experimental design. Significant differences between treatment means were determined using the Duncan multiple comparison procedure at a significance level of $P \leq 0.05$ (Stern, 1986). Tables and graphs were drawn with Microsoft Excel 2019.

RESULTS

Outcome of Mepiquat Chloride on Shoot-root ratio at different growth stages

In 2022, the application of Mepiquat chloride to cotton varieties revealed that the shoot-root ratio was significantly ($p \leq 0.05$) highest during the harvesting stage, reaching 6.76 with 400 mL·ha^{-1}, compared to 5.08 with 0 mL·ha^{-1} at the same stage (Figure 1). The Sezener variety exhibited a significantly ($p \leq 0.05$) higher shoot-root ratio of 6.57 at the reproductive stage, outperforming the Selin variety (Figure 2). Mepiquat chloride application at the bolling stage resulted in the highest shoot-root ratio of 6.54 when measured at the reproductive stage, whereas the lowest ratio of 5.73 was recorded with Mepiquat chloride application at the squaring stage and measured at vegetative (Figure 2).

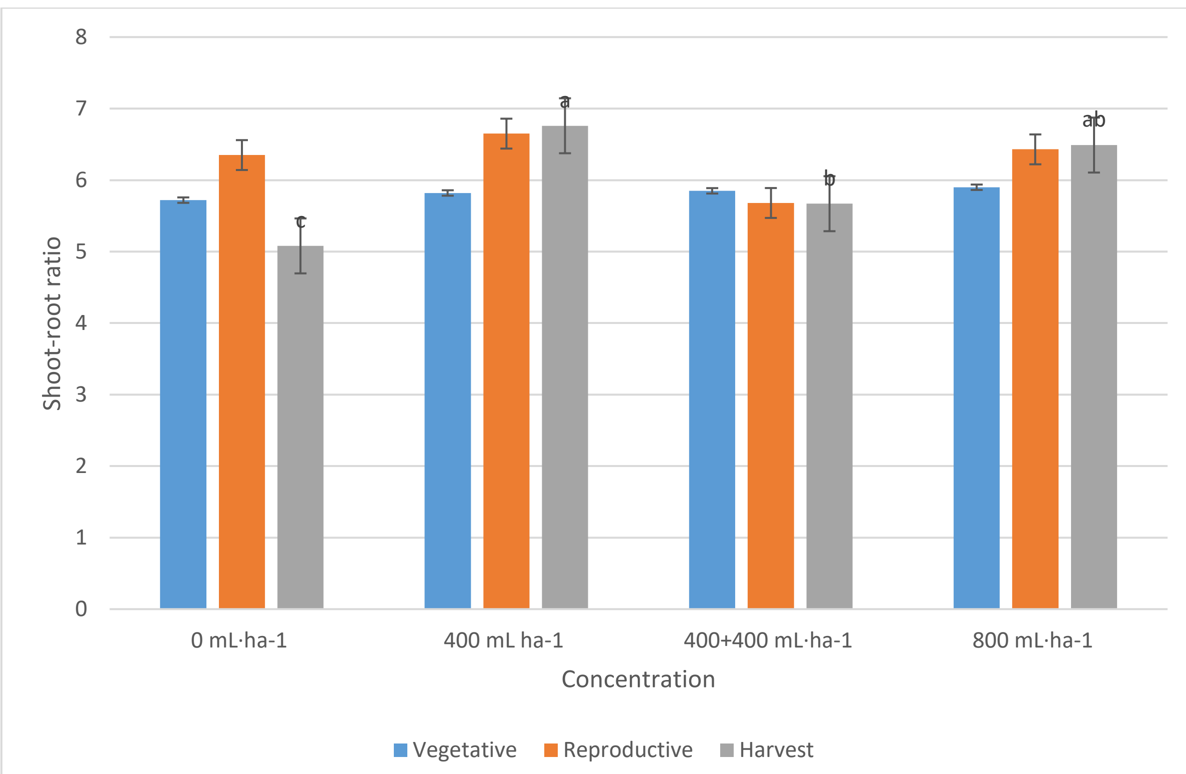

Figure 1. Effect of Mepiquat Chloride concentrations on shoot-root ratio at different growth stages in 2022. Values followed by different letters at the harvest stage are statistically different at $P \leq 0.05$.

In 2023, the application of Mepiquat chloride to cotton varieties revealed that the shoot-root ratio was highest during the reproductive stage, reaching 14.32 with 0 mL·ha^{-1}, compared to 5.57 with 400+400 mL·ha^{-}

[1] at the vegetative stage (Figure 3). The Selin variety demonstrated a superior shoot-root ratio of 14.65 at the reproductive stage (Figure 4), and Mepiquat chloride application at the squaring stage produced the highest ratio of 14.63 at the same stage (Figure 4).

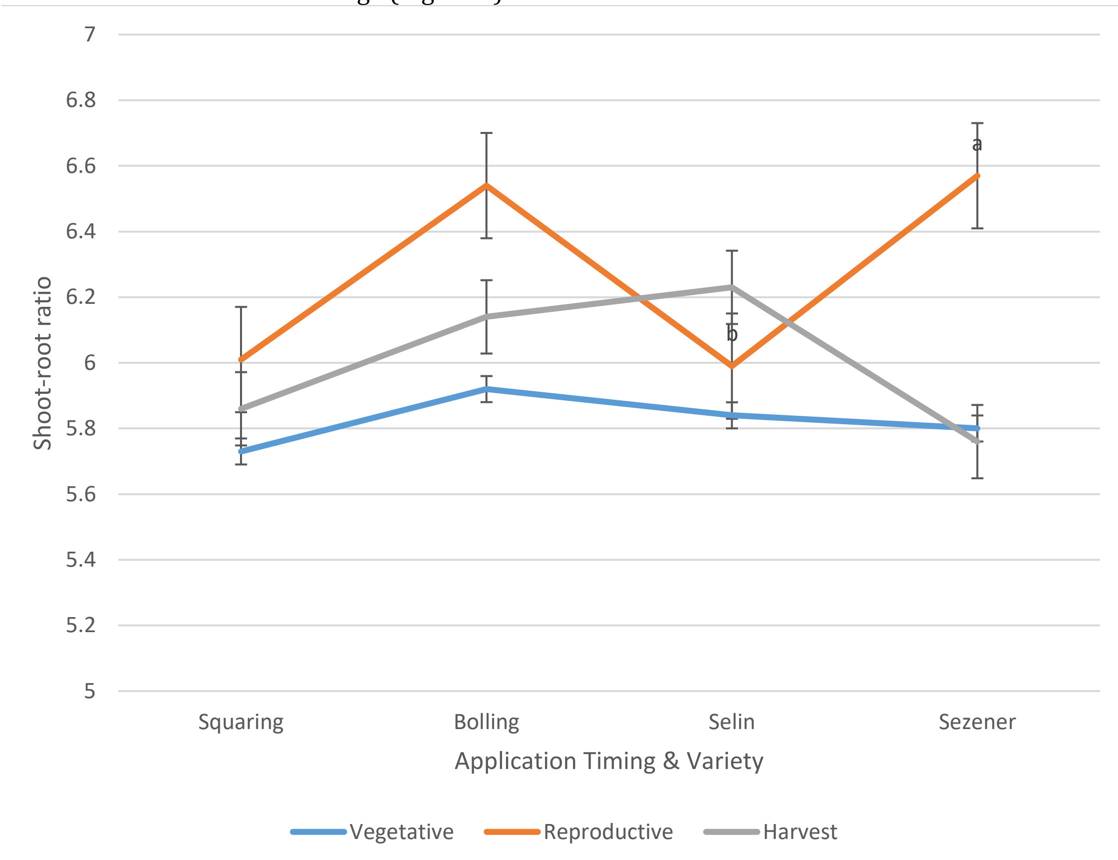

Figure 2. Effect of different Mepiquat Chloride application timing on shoot-root ratio of cotton varieties at different growth stages in 2022. Values followed by different letters at the reproductive stage are statistically different at P ≤ 0.05.

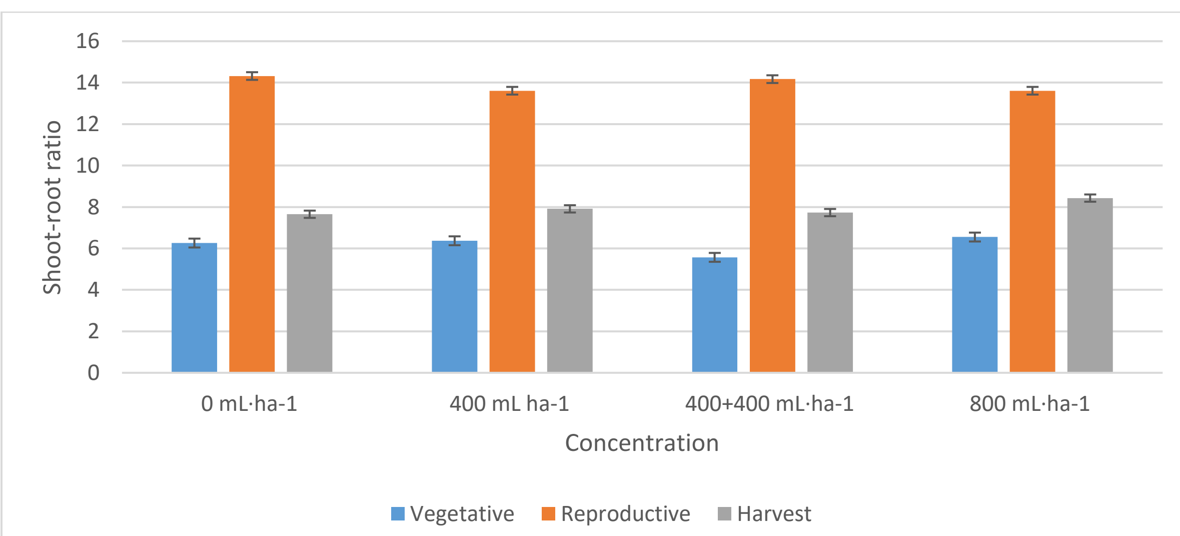

Figure 3. Effect of Mepiquat Chloride concentrations on shoot-root ratio at different growth stages in 2023. The significance level was p > .05 ("ns") at all growth stages.

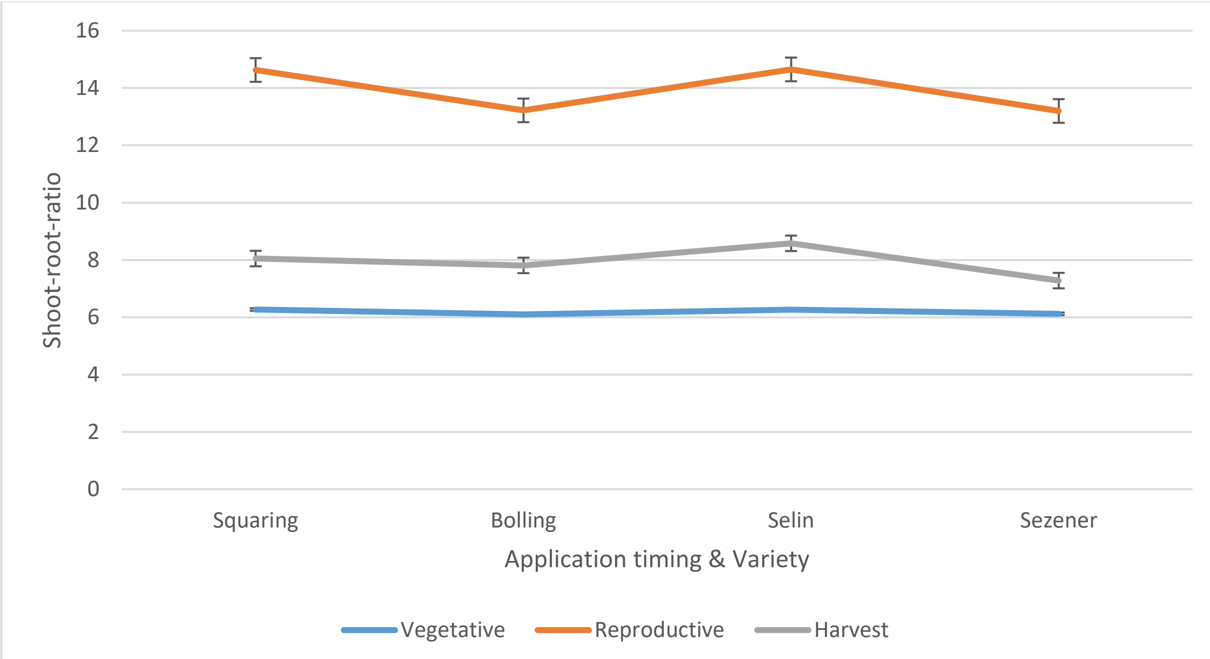

Figure 4. Effect of different Mepiquat Chloride application timing on shoot-root ratio of cotton varieties at different growth stages in 2023. The significance level was p > .05 ("ns") at all growth stages.

Outcome of Mepiquat Chloride on fiber percent

In 2022, the application of Mepiquat Chloride at squaring stage and the Selin variety resulted in the highest fiber percent, with 61.53% and 61.49%, respectively (Figure 5). Conversely, Sezener variety had a lower fiber percent (55.06%) with the application of 400 $mL{\cdot}ha^{-1}$ at bolling stage (Table 2). Fascinatingly, the control treatment (0 $mL{\cdot}ha^{-1}$) recorded the highest fiber percent (64.60%) in the Selin variety when Mepiquat Chloride was applied at squaring stage (Table 2).

Table 2. Interaction of different Mepiquat chloride concentrations and scheduling time on fiber percent and maturity index of cotton varieties across two growing seasons.

Sources of variations			2022		2023	
			Fiber percent (%)	Maturity index (%)	Fiber percent (%)	Maturity index (%)
Variety	App. T	Conc.				
Selin	Squaring	T_0	64.60 ± 1.11ns	83.33 ± 0.33ns	71.65 ± 3.16ns	87.88 ± 0.17ns
		T_1	61.73 ± 2.06ns	83.67 ± 0.33ns	70.54 ± 0.92ns	87.50 ± 0.51ns
		T_2	60.31 ± 1.21ns	84.00 ± 0.58ns	72.26 ± 0.77ns	88.02 ± 0.24ns
		T_3	58.29 ± 3.00ns	84.33 ± 0.33ns	72.86 ± 2.13ns	87.95 ± 0.10ns
	Bolling	T_0	60.77 ± 2.64ns	83.67 ± 0.21ns	76.36 ± 0.78ns	87.96 ± 0.28ns
		T_1	66.29 ± 4.16ns	84.33 ± 0.33ns	74.74 ± 2.66ns	88.00 ± 0.21ns
		T_2	55.66 ± 3.12ns	84.33 ± 0.33ns	74.57 ± 1.36ns	87.32 ± 0.36ns
		T_3	64.30 ± 4.22ns	84.00 ± 0.58ns	72.48 ± 2.28ns	88.06 ± 0.04ns
Sezener	Squaring	T_0	62.76 ± 4.10ns	84.00 ± 0.58ns	71.62 ± 3.66ns	87.37 ± 0.66ns

	T_1	60.39 ± 3.06ns	84.33 ± 0.33ns	70.19 ± 2.59ns	88.25 ± 0.59ns
	T_2	59.61 ± 4.19ns	83.67 ± 0.33ns	73.87 ± 1.76ns	88.65 ± 0.42ns
	T_3	64.52 ± 2.62ns	84.33 ± 0.33ns	69.34 ± 1.87ns	87.79 ± 0.37ns
Bolling	T_0	62.05 ± 4.34ns	84.33 ± 0.67ns	72.49 ± 1.06ns	86.89 ± 0.68ns
	T_1	55.06 ± 1.19ns	84.17 ± 0.17ns	72.67 ± 4.03ns	87.94 ± 0.35ns
	T_2	60.65 ± 2.56ns	84.00 ± 0.58ns	68.42 ± 1.26ns	87.79 ± 0.41ns
	T_3	62.11 ± 1.97ns	84.33 ± 0.33ns	69.88 ± 1.05ns	88.07 ± 0.62ns
Grand Mean		61.194	84.063	72.122	87.84
SE		5.311	0.665	3.774	0.725
CV (%)		8.678	0.792	5.233	0.825

Values represent mean ± SD. T_0 = 0 mL·ha^{-1}, T_1 = 400 mL·ha^{-1}, T_2 = 400+400 mL·ha^{-1}, T_3 = 800 mL·ha^{-1}, Conc = Concentration, App. T = Application Time, SD = standard deviation, CV Coefficient of variation. The significance level "ns" represents p > 0 .05.

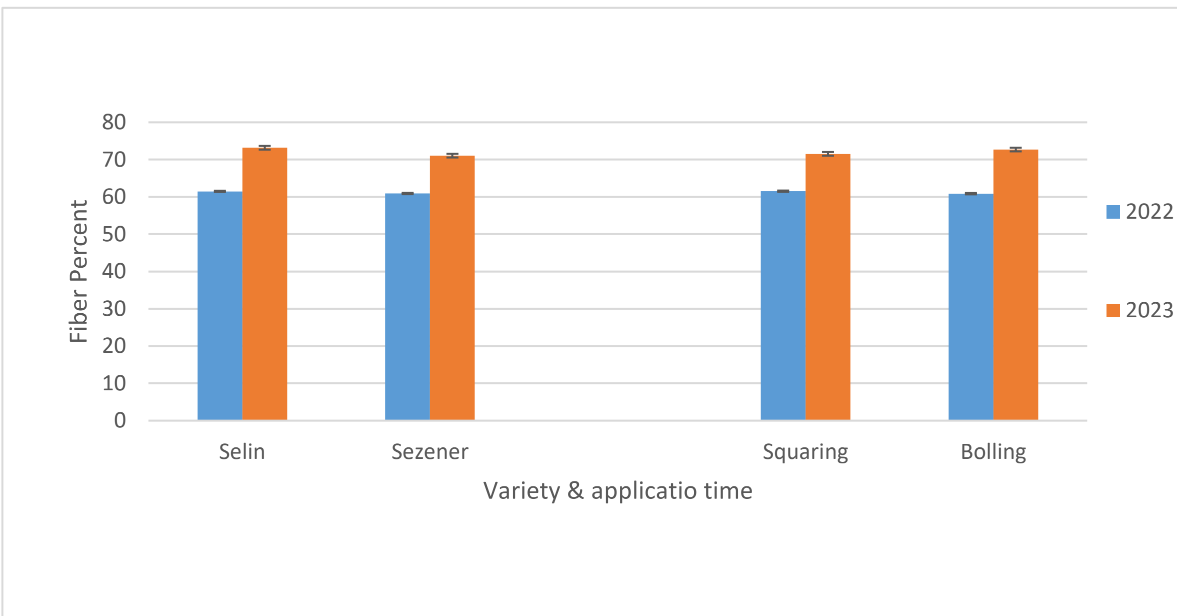

Figure 5. Effect of Mepiquat Chloride application on fiber percent of different cotton varieties under different application intervals (2022– 2023). The significance level was p > .05 ("ns").

In 2023, the highest fiber percent (72.70%) was detected with the application of Mepiquat Chloride at bolling stage (Figure 5). The Selin variety consistently outperformed the Sezener variety in fiber percent, reaching 73.18% compared to 71.06% (Figure 5). Additionally, the lowest fiber percent (68.42%) in the Sezener variety was recorded with Mepiquat Chloride spritzing at 400+400 mL·ha^{-1} at bolling stage, while the control treatment (0 mL·ha^{-1}) yielded the highest fiber percent (76.36%) in the Selin variety at bolling stage (Table 2).

Outcome of Mepiquat Chloride on maturity index

In 2022, the highest maturity index (84.17%) was recognized when Mepiquat Chloride was applied at bolling stage (Figure 6). The Sezener variety recorded the highest maturity index (84.13%), exceeding the Selin variety

(84.00%) (Figure 6). Additionally, the findings discovered the lowest maturity index (83.33%) in the Selin variety with control treatment (0 mL·ha^{-1}) (Table 2).

In 2023, the mean maturity index of two cotton varieties did not vary significantly, with both recording 84.87% (Figure 6). Application time of Mepiquat Chloride showed discrepancies in maturity index, with the highest percentage (87.93%) found at squaring stage, and the lowest percentage (87.75%) achieved at bolling stage (Figure 6). Spraying Mepiquat Chloride at a concentration of 400+400 mL·ha^{-1} during the squaring stage led to the highest maturity index (88.65%), whereas applying it at 0 mL·ha^{-1} resulted in the lowest maturity index (86.89%) for the Sezener variety (Table 2).

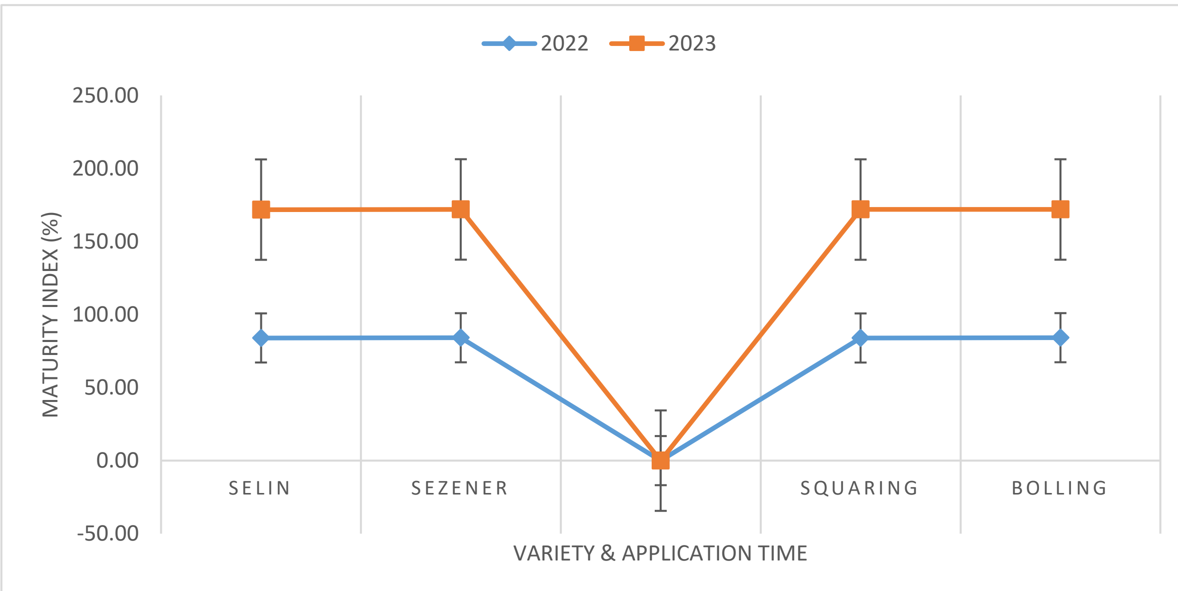

Figure 6. Effect of Mepiquat Chloride application on maturity index of different cotton varieties under different application intervals (2022– 2023). The significance level was p > .05 ("ns").

DISCUSSION

The Effect of the Mepiquat chloride doses and Timing on the Shoot root ratio, Fiber Yield and Maturity Index

Shoot-root ratio is a key morphological character used to assess numerous physiological processes, counting osmotic rates, transpiration, gas exchange rates, cell wall elasticity, water-use efficiency, and, ultimately, the photosynthesis rate (Hessini et al., 2009). A low shoot-root ratio indicates a dominance of root biomass compared to leaf surface area, suggesting the plant is less likely to experience excessive water stress, and vice versa. In 2022, a higher shoot-root ratio was observed when Mepiquat Chloride was applied at the bolling stage compared to the squaring stage (Figure 2). Delayed defoliation boosted plant height, carbon assimilation, and the allocation of photosynthates toward boll development, leading to increased dry above-ground biomass (Priyadarshini et al., 2023). However, the shoot-root ratio did not follow a consistent pattern with different Mepiquat Chloride concentrations (Figures 1 and 3). For example, in 2023, the highest shoot-root ratio was observed in the control treatment (0 mL·ha^{-1}) at the reproductive stage (Figure 3), while in 2022, the control treatment resulted in the lowest shoot-root ratio across all growth stages (Figure 1). This inconsistency may be due to varying weather conditions between the two years (Table 1). The decline in shoot-root ratio with increasing Mepiquat chloride concentrations could be attributed to reduced plant height, internode length, number of nodes, height-to-node ratio, and disruptions in the source-to-sink relationship (Kenanoğlu et al., 2023; Müjdeci et al., 2024).

Mepiquat chloride has shown uneven effects on fiber percent, as our findings designate that the highest fiber percentage was detected with the control treatment (Table 2). In 2022, the increase fiber percent might be due to the presence of abundant roots, which can effectively seek out, absorb, and transport water and dissolved minerals from the soil to the plant for photosynthesis. Conversely, in 2023, the decline in fiber percent with Mepiquat Chloride application could be attributed to reduced chlorophyll synthesis in plants, which is essential for carbon assimilation, carbohydrate synthesis, and protein and sugar formation (Arekhi et al., 2023; Sravanthi et al., 2022). Furthermore, each variety reacted slightly differently to the application timing of Mepiquat chloride on fiber percent (Figure 5). The differences could be ascribed to heterogeneity in plant genetic characteristics for mepiquat chloride requirement, as a result, differencing in fiber percent. The genotypic discrepancy in fiber percent in response to Mepiquat Chloride application has been documented by prior researchers (Khamdullaev et al., 2021; Sravanthi et al., 2022; Wang et al., 2023).

Maturity index is a qualitative parameter for assessing the degree of cell wall thickness, which in turn affects various aspects of the spinning process, yarn evenness, yarn appearance, fabric drape, and yarn brightness (Shahat et al., 2022a; Yasar & Karademir, 2021). Maturity index is categorized as follows: low if ≤75%, immature: 75 to 85%, mature/premium: 86 to 95% and very mature ≥95% (Shahat et al., 2022b). The maturity index varied across the two years studied, being low in 2022 and in the premium range in 2023 (Table 2). Across the two years studied, the lowest numerical values were recorded in control treatment (0 $mL \cdot ha^{-1}$) (Table 2). This exemplify that Mepiquat chloride might be more suitable for producing high-quality yarn and fabric by reducing excessively vegetative growth in cotton plants, which is accomplished through the inhibition of gibberellin hormone. This inhibition resulted in earlier maturity due to enhanced partitioning of assimilates into upper canopy bolls, which subsequently matured more rapidly (Abbas et al., 2022; Chalise et al., 2022; QI et al., 2022).

The Effect of weather conditions on the effectiveness of Mepiquat chloride applications in cotton

Under low temperature conditions, cotton growth was severely reduced irrespective of Mepiquat chloride (MC) application, as indicated by decreased dry matter yields. The reduction in dry matter production is due to the suppressive effect of Mepiquat chloride on extensive cell elongation (Seif & Arafa, 2021). The ideal temperature for vegetative growth ranges around 32/27 °C (day/night) (Ramachandra et al., 1996). However, under supra or infra optimum temperature conditions, the effect of Mepiquat chloride on plant growth may be counteracted (Rosolem et al., 2013). As observed in this study, the highest/lowest temperatures of 24.23/23.91 °C did not fall within the optimal range for Mepiquat chloride to effectively enhance cotton growth, which is supported by our results.

A good vegetative/reproductive balance in cotton is usually observed when the average temperature is around 25 °C (Pettigrew, 2010). As observed in the findings, the average temperature in 2023 (24.23 °C) falls closely within the optimal range for Mepiquat chloride to express its effects on maximum dry matter accumulation and fruit retention, which ultimately leads to the highest fiber yield. The results accord with the investigations of (De Souza & Rosolem, 2007), who recognized changes in reproductive branches development in cotton under high-temperature conditions with the application of Mepiquat chloride. Furthermore, (Gwathmey & Clement, 2010), reported an increase of fiber yield as well as fiber quality-related traits in cotton under high-temperature conditions, following the application of Mepiquat chloride. The performance is linked to enzymatic activities of a particular genotype that help balance vegetative and reproductive growth stages for photoassimilates (Zafar et al., 2022).

CONCLUSION

The results indicated that the efficiency of Mepiquat chloride applied at different scheduling times depends on the weather-related conditions of a particular area. Our findings revealed an inconsistent trend for the shoot-root ratio, fiber percent, and maturity index across all treatments, including variety, application timing, and concentration across the two years examined. Our results showed a good vegetative/reproductive balance in cotton when Mepiquat chloride was applied at high temperatures. When the temperature regime was within the optimal range, the response to Mepiquat chloride was maximal, with optimal plant growth, including leaf area, dry matter, fruiting branches, yield, quality, and minimal shedding. Ultimately, there was an increase in the shoot-root ratio, fiber percent, and maturity index in cotton varieties. From a financial perspective, relying solely on Mepiquat chloride application may lead to economic losses. Hence, further research is needed to explore the benefits of integrating various Mepiquat chloride formulations, sources, meteorological data, and Mepiquat chloride within the cotton agroecology zones, which is significantly affected by the negative impacts of climate change.

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AUTHORS CONTRIBUTIONS

M.M: Conceptualization, Methodology, Validation, investigation, data curation, visualization, writing—original draft. O.K: Conceptualization, visualization, supervision, project administration, funding acquisition, Methodology. M.S.H: Software Validation, formal analysis, investigation. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable

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