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Effects of mepiquat chloride (MC) spraying on the lodging resistance and yield characteristics of soybean**

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A b s t r a c t. Soybean lodging exerts a significant impact on yield, and the application of growth regulators represents a crucial approach to mitigate soybean lodging. In this study, we investigated the impact of spraying mepiquat chloride on soybean lodging resistance and yield. We also assessed the relationship between soybean stem characteristics (breaking force, stem bending, semi-cellulose content), stem length, and dry weight and lodging resistance parameters. Additionally, we examined the correlation between pod number, 100 seed weight, and yield. The findings showed that applying mepiquat chloride spray effectively improved soybean's lodging resistance by increasing stem breaking force and reducing plant height. The present study investigates the impact of mepiquat chloride on soybean growth, bridging the knowledge gap regarding the influence of the plant growth regulator – mepiquat chloride on soybean production. The research results show that spraying 200 mg L^{-1} mepiquat chloride during the three-leaf stage and early flowering stage of soybeans has the best effect on balancing soybean lodging resistance and yield. Compared with HN44CK, the 200 mg L^{-1} treatment increased the yield by 25.5 g/4 plants. Furthermore, it offers theoretical support and a scientific foundation for enhancing soybean yield and lodging resistance.

K e y w o r d s: yield, soybean, lodging resistance, breaking force

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1. INTRODUCTION

Soybean is the primary oilseed crop in Northeast China and is vulnerable to strong winds throughout its growth cycle (Konno and Homma, 2023). The occurrence of typhoons in Heilongjiang Province, China, over the past 60 years indicates a seasonal tendency for typhoon activity between July and September (Li *et al.*, 2023). In the world, the climate of Heilongjiang Province in China is similar to that of central Canada and the Russian Far East (Littleboy *et al.*, 2024). July to September is the critical growing period for soybeans (Hassankhah *et al.*, 2020; Tan *et al.*, 2021). Soybean yield can be affected by the occurrence of strong winds or typhoon disasters. Furthermore, variations in lodging severity and growth stages of soybean plants have distinct impacts on crop productivity (Cheng *et al.*, 2015). Enhancing lodging resistance in soybean has emerged as a pivotal research focus (Su *et al.*, 2024), owing to the significance of lodging during the early flowering stage and the seed filling phase in reducing soybean yield (Futi Xie *et al.*, 1994).

The lodging resistance coefficient is a comprehensive evaluation index of crop stem lodging resistance. The lodging of soybean is characterized by varying degrees of stem bending or tilting, typically resulting from excessive aboveground biomass and plant height (Qin *et al.*, 2023).

The lodging incidence of crop is directly proportional to the aboveground biomass and stem length (Muhammad *et al.*, 2020). The lodging of soybeans is also correlated with the basal stem's breaking force (Zhao *et al.*, 2023). The stem's thickness positively correlates with a decrease in internode length and an increase in stem breaking force. Similarly, the content of semi-cellulose, which can give fiber elasticity and enhance plant toughness, in the plant exhibits a strong association with stem breaking force (Mengistie and Mcdonald, 2023). There is a substantial abundance of semi-cellulose present in soybean stems, primarily distributed within the cell wall. Currently, an increasing body of evidence indicates that the predominant role of semi-cellulose in stems lies in its resistance to fracture and flexure (Bai *et al.*, 2023).

Currently, the plant lodging rate can be reduced by adjusting the planting density or applying specific growth inhibitors, such as mepiquat chloride (MC) and Chlormequat (Wang *et al.*, 2022). Compared to Chlormequat, MC exhibits a higher level of environmental friendliness. As an exogenous plant growth retardant, it effectively inhibits cell elongation and induces dwarfism in plants. The application of MC through spraying represents a viable approach for enhancing soybean lodging resistance (Song *et al.*, 2023). Previous studies have demonstrated that MC has the potential to mitigate maize lodging and enhance maize yield by promoting an increase in the basal internode diameter and reduction in basal internode elongation (Kamran *et al.*, 2018). Moreover, the application of MC has been demonstrated to significantly enhance dry matter accumulation and yield in soybean cultivation (Jaidka *et al.*, 2020). The MC agent applied in cotton enhanced lodging resistance and yield by reducing the internode distance at the stem base, increasing the stem diameter, and augmenting the cellulose and semi-cellulose content within the internodes (Qi *et al.*, 2023; Tung *et al.*, 2020).

The investigation into the impact of MC spraying on soybean's lodging resistance and yield characteristics remains to be conducted. Therefore, the soil basin method was used in this experiment, and Heinong 44 (HN44) and Heinong 65 (HN65) were used as test materials. The effects of MC on lodging resistance and yield of soybean were investigated by studying the effects of MC on semi-cellulose, stalk breaking force, stem bending, dry matter accumulation, 100 seed weight, and pod number. Ultimately, this experiment aims to enhance soybean lodging resistance using low-toxicity and environmentally friendly regulators, providing theoretical support for further improvements in soybean yield while addressing the issue of lodging-induced grain yield reduction.

2. MATERIALS AND METHODS

2.1. Plant materials

Previous studies have shown that MC can improve the drought tolerance of Heinong(HN44) and Heinong(HN65) (Wang *et al.*, 2022). To better supplement the effect of MC application on soybeans, HN44 and HN65 were selected as seeds in this experiment. The selected varieties are all soybean varieties bred by the Research Institute of Heilongjiang Academy of Agricultural Sciences. HN44 is characterized by its round leaf shape, while HN65 exhibits a sharp leaf structure. The experiment was conducted at the experimental station of Northeast Agricultural University in China.

2.2. Test design

The soil culture technique was employed in the experiment. The barrel had dimensions of 35 cm in diameter, 22 cm in width, and 30 cm in height. Each pot was filled with a uniform amount of surface soil weighing 16 kg, and eight soybean seeds of consistent size were sown in each pot. When sowing, the soil temperature should be kept stable at 80ºC at a depth of 5 cm. The seed surface was coated with fludioxonil for treatment. The seedlings were separated upon the emergence of the first compound leaf, and four seedlings exhibiting similar growth vigor were retained in each barrel. Irrigation was carried out once every 3 days, and the excess water was allowed to flow out through the round hole at the bottom of the bucket to keep the soil moisture at around 20%.

The first application of Mepiquat Chloride (MC) was administered at the fourth compound leaf stage (the sum of average temperatures greater than or equal to 10℃ is approximately 470℃), followed by a second application at the flowering stage (the sum of average temperatures greater than or equal to 10℃ is approximately 710℃). MC was sprayed until leaves were non-dripping. The spraying procedure provided about 75 ml per pot during the seedling stage and about 200 ml per pot during the flowering stage. The sprayer used was Hasdick HKW5 (Shanghai, China) to ensure that both the front and back of each leaf were sprayed. The spray was started from the upper leaves of the plant to the lower leaves of the plant in sequence. The treatments included CK – 0, M1 – 50, M2 –100, M3 – 200, and M4 – 400 mg L^{-1} MC, respcetively.

The sampling was conducted from 7:00 to 8:00 a.m. on the 3rd, 6th, 9th, 12th, 15th, and 18th days following the second application of the MC solution. Immediately after the sampling, the stalk breaking force test was performed. Subsequently, it was deactivated at a temperature of 105°C for 30 minutes and dried at a constant weight in controlled conditions at a temperature of 65°C. The soybean crop was harvested and air-dried upon reaching maturity. The experimental soil was selected from the surface soil of Harbin, Heilongjiang Province, China, where the total content of the soil was: nitrogen 1.12 g kg^{-1}, phosphorus 0.67 g kg^{-1}, and potassium 17.90 g kg^{-1}. The experiment was repeated three times, with each pot being one repeat.

2.3. Determination method

2.3.1. Determination of mechanical properties of stalk

The stalk breaking force was measured using a soybean stalk breaking force measuring instrument (S-type force sensor, manufacturer: Chengying, China). The sensor was mailed back to the factory for calibration every month. The determination method employed was Xu *et al.* (2017). The thrust sensor, denoted as F, is utilized to measure the applied thrust by slowly oscillating the measuring handle. The sensor provides real-time feedback on the current thrust value, which becomes stable when indicating stalk breaking force (F). Stem bending refers to the maximum horizontal offset angle of the stem. The thrust sensor employed in this study was manufactured by Wenzhou Haibao Instrument Co., Ltd., with a model designation of HG-100.

Lodging resistance coefficient $Q = \frac{2FL}{MgH}$ (Weiguo *et al.*, 2016). In the formula, H – plant stem length, F – stalk breaking force, L – distance between the thrust action point and the upper fulcrum. In this experiment, L = 4 cm; M – plant dry weight, g = 9.8 m s^{-2} (Weiguo *et al.*, 2016).

2.3.2. Determination of semi-cellulose content in stalk

The sample was dried to constant weight, fully ground in the mortar, and passed through a 40-mesh sieve. 0.05 g samples were weighed and placed in a centrifuge tube with addition of 1000 μL of an 80% ethanol solution, kept in a 90°C water bath for 10 min, 25°C, and centrifuged at 8 000 g for 10 min to discard the supernatant and retain the precipitate. The precipitate was washed with distilled water three times and dried to constant weight. After drying, the measurement was performed according to a method described elsewhere (Meng *et al.*, 2023). An ultraviolet spectrophotometer (Hitachi High – Technologies SERIAL No. 2227-002) was used, and the wavelength was adjusted to 540 nm for measurement.

2.3.3. Agronomic index determination

The soybean stem length (cotyledon scar to growth point) was measured 3 days after the first spraying of MC and measured every 5 days until the top flower produced a pod. The stem length was measured with a tape measure, and the stem diameter was measured with a vernier caliper. Dry matter mass was measured with an electronic scale. Three pots of plants were selected for harvesting (total of 12 plants). The bottom pod height was measured before harvesting, and the seeds were tested after harvesting. The number of one pod, two pods, three pods, and four pods were manually measured, and the samples were air-dried. The mass and 100 seed weight of the soybean seeds were measured with an electronic scale.

2.4. Ethical statement

The authors ensure that the research for this article was conducted in a fair and ethical manner.

3. DATA ANALYSIS

Microsoft Office 365 (Home edition) was used for writing. Microsoft Excel (2010) was used to calculate the deviation and the calculation function was stdev.P. IBM SPSS Statistics 27.0.1 (IBM Corporation, Armonk, NY, USA) performed significance analysis (Tukey's HSD test). All significance analyses were comparisons between different treatments of the same variety on the same day. Origin 2021 software was used for drawing.

4. RESULTS

4.1. Effect of MC on dry matter accumulation of soybean

The total dry matter accumulation of HN65 exhibited an initial increase followed by a subsequent decrease, as depicted in Fig. 1a, with the augmentation of the treatment concentration. With the extension of time, the dry matter accumulation rate in the M1, M3, and M4 treatments exhibited an increasing trend, characterized by an initial decrease followed by a subsequent increase in dry matter accumulation. At day 6, the dry matter accumulation of stems increased by 19.58, 20.36, 32.20, and 28.45% compared to HN65CK, while the dry matter accumulation of leaves increased by 12.90, 42.51, 36.21, and 34.10%.

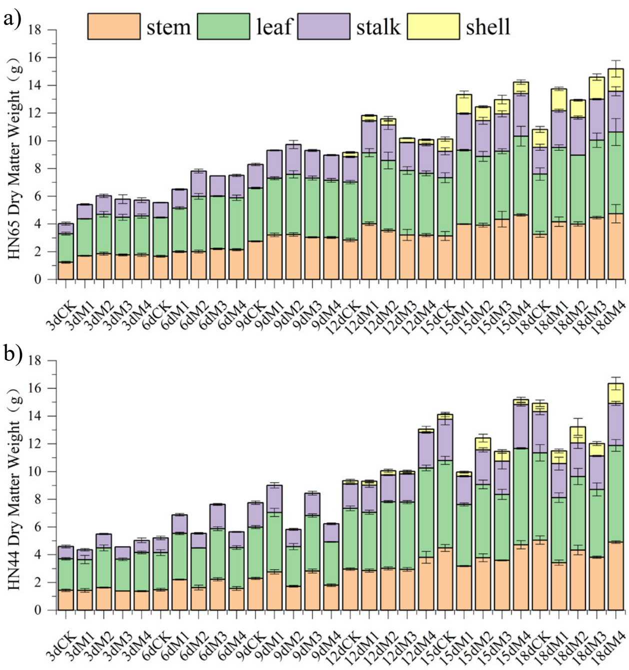

Fig. 1. Mepiquat chloride enhanced the change of dry matter accumulation during soybean lodging resistance: a) variety HN65 and b) variety HN44 dry matter accumulation changes. The values (mean ± SE) are the averages of three independent experiments (n = 15).

Additionally, the dry matter accumulation of stalks showed an increase of 24.59, 69.09, 35.19, and 49.95%. At day 18, the proportion of leaf dry matter in the treatment group was higher than that in the control group by a margin of 2.28, 1.39, 28.10, and 3.53%, respectively (Fig. 1a).

The total dry matter accumulation of HN44 exhibited distinct growth patterns under the different concentrations of the MC treatment. Compared to the control, the dry matter accumulation of M2 increased by 13.91% at 3 d, and all the treatments showed higher dry matter accumulation than the control at 6 d, with increases of 49.28, 10.70, 50.86, and 6.17%, respectively. At 12 d, there was a gradual increase in plant dry matter quality with the increasing spraying concentration. At both 15 d and 18 d, the dry matter quality of M1, M2, and M3 was lower than that of HN44CK; however, the dry matter quality of M4 surpassed that of HN44CK (Fig. 1b).

In summary, the impact of MC on the total dry matter accumulation varied among the different soybean varieties. The application of MC enhanced the total dry matter accumulation in HN65, while in HN44, the low concentration of the MC spray reduced the plant dry matter accumulation whereas the high concentration exerted an opposite effect.

4.2. Effects of spraying MC on stem length of soybean

The impact of MC spraying on plant stem length is illustrated in Fig. 2. In comparison to the control, the HN65 soybean stem length decreased by -4.98, 9.28, 4.03, 3.58%, respectively, after a period of 27 days following the MC application. By constructing a regression equation, the slope indicated the trend of plant height growth, with HN65CK having a higher slope value (2.21) than that of the treatment group; M3 had the lowest slope value (1.94), indicating a slower growth trend (Fig. 2a).

Compared to the control group, the application of MC in HN44 for 27 days resulted in a significant increase in the soybean stem length by 6.29, 4.94, 8.93, and -1.05%, respectively (Fig. 2b). The slopes of each treatment in HN44 were found to be 2.05, 1.95, 2.24, 2.19, and 1.96, respectively.

In summary, the application of MC resulted in a reduction in the stem length of HN65. As the spraying concentration increased, the inhibitory effect of MC on stem length also increased, with the M4 treatment showing a rebound in the concentration. However, compared to HN65CK, the M1 treatment ultimately led to an increase in the stem length of HN65 after harvest, while the M2, M3, and M4 treatments reduced this parameter. The impact of MC on the stem length of HN44 exhibited an initial increase followed by a decrease trend; that is to say, the application of MC hindered the growth trend in plant height in both the M1 and M4 treatments. At final harvest, compared to HN44CK, the treatments with M1, M2, and M3 resulted in an increase in the stem length of HN44, whereas the treatment with M4 decreased its value.

4.3. Effect of spraying MC on semi-cellulose content of soybean

The change in the semi-cellulose content in the stem of HN65 after MC spraying is depicted in Fig. 3a. Over time, there was a gradual increase in the semi-cellulose content, and the trend in the parameter among the different treatments initially showed an upward trajectory followed by a decline, with a peak occurring in M3. At 3 d, the semi-cellulose content in the M1 treatment surpassed that of HN65CK, but its accumulation gradually decelerated as time progressed. Compared to HN65CK, the semi-cellulose content in M3 exhibited respective increases of 35.49, 33.83, 44.65, 54.85, 58.50, and 66.49% with the increasing time (Fig. 3a).

The change in the semi-cellulose content in the HN44 stems after MC spraying is illustrated in Fig. 3b. Over time, there was a gradual increase in the semi-cellulose content, and the trend in this parameter among the different treatments

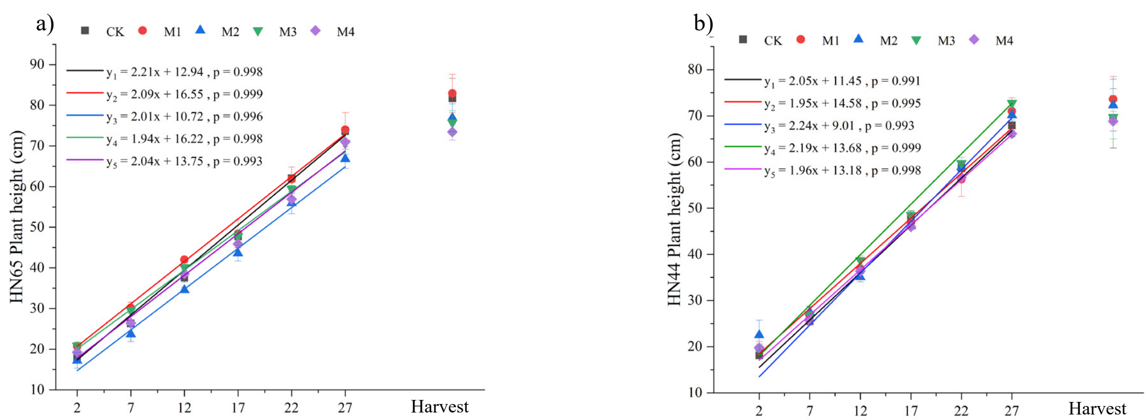

Fig. 2. Mepiquat chloride enhances the change of stem length during soybean lodging resistance: a) variety HN65 and b) variety HN44 stem length changes. The abscissa in the Figure represents the number of days, with 2 denoting the final three days of the initial application of MC, and 13 indicating the second application of MC. Measurements were taken at intervals of every five days to monitor their growth status. The values (mean ± SE) are the averages of three independent experiments (n = 15).

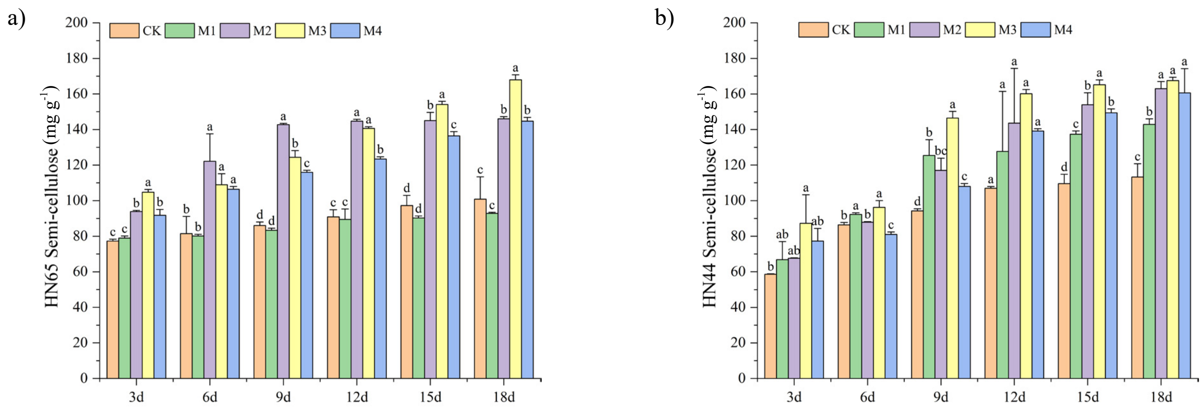

Fig. 3. Changes of semi-cellulose content in soybean stems during lodging resistance enhanced by mepiquat chloride changes of semi-cellulose content in stem of: a) HN65, b) HN44. The values (mean ± SE) are the averages of three independent experiments (n=15). Bars not sharing the same letters indicate statistically significant differences by Duncan's multiple range test (p < 005).

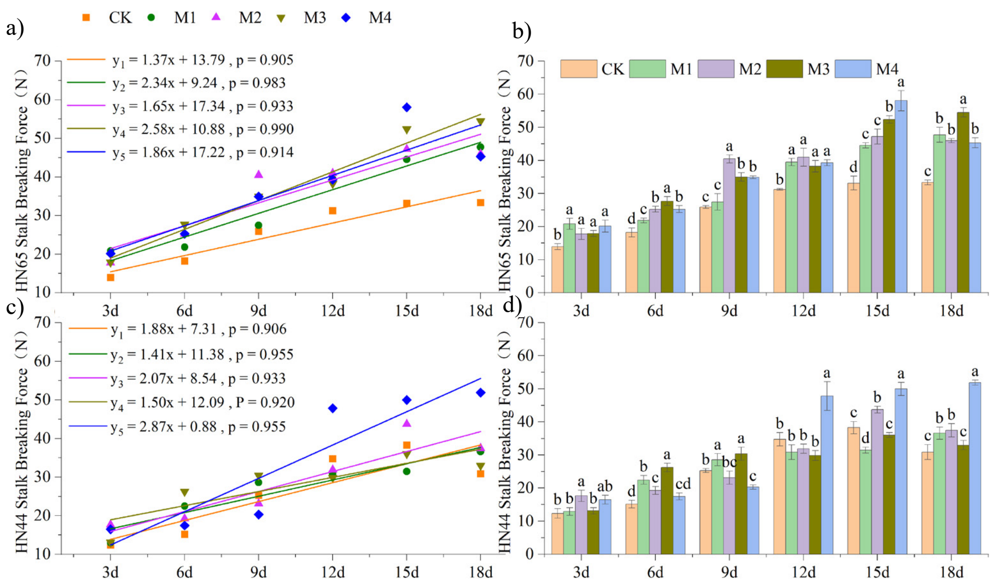

Fig. 4. Mepiquat chloride enhances the change of Stalk Breaking Force during soybean lodging resistance: a) variety HN65 and b) variety HN44 stalk breaking force content changes. Other explanations as on Fig. 3.

initially increased and then declined, with a peak observed in the M3 treatment. Compared to HN44CK, at 3 d, each treatment showed an increase of 13.93, 15.22, 48.87, and 31.72%, respectively, in the semi-cellulose content. At 18 d, compared to HN44CK, there was an increase of 26, 43.92, 47.89, and 41.75%, respectively, in the semi-cellulose content for each treatment tested hereafter mentioned as M1-M4 treatments accordingly (Fig. 3b).

In summary, the M1 treatment reduced the semi-cellulose content in the soybean stems, and the M2, M3, and M4 treatments increased this parameter in the soybean stems.

4.4. Effect of MC on soybean stalk breaking force

The impact of MC on soybean stalk breaking force is illustrated in Fig. 4. The application of MC resulted in an increase in the flexural resistance of the base of soybean stems. The stalk breaking force in the HN65CK M1, and M3 treatments of HN65 increased with time but initially increased and then decreased over time in the M2 and M4 treatments. Compared to the control group, the treatment groups exhibited a respective increase of 42.04, 46.47, 64.20, and 75.22% in stalk breaking force on the 15th day. By constructing regression equations, slopes were determined as follows: HN65CK (1.37), M1 (2.34), M2 (1.65), M3 (2.58), and M4 (1.86). Notably, the slopes for the treatment groups were higher than those observed for the control group (Fig. 4a, b).

The stalk breaking force in the M1 and M4 treatments of HN44 exhibited an increasing trend with the passage of time. Conversely, the stalk breaking force of the HN44CK, M2, and M3 treatments initially increased but subsequently decreased as days progressed. Notably, compared to the HN44CK treatment, the stalk breaking force showed respective increments of 11.35, 18.05, 3.12, and 18.23% at day 18 (Fig. 4c, d).

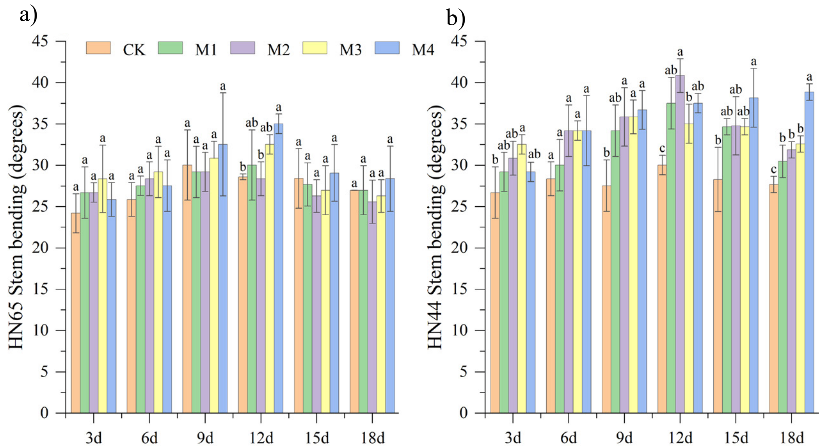

Fig. 5. Mepiquat chloride enhances the change of Stem bending during soybean lodging resistance: a) variety HN65 and b) variety HN44 stem bending changes. Other explanations as on Fig. 3.

In summary, the application of the MC spray can enhance the flexural strength of the soybean stem base. By establishing a regression equation, the slopes for HN44CK, M1, M2, M3, and M4 were determined as 1.88, 1.41, 2.07, 1.5, and 2.87, respectively. Spraying MC can increase the stalk breaking force of soybean, and enhance the increasing trend of HN65 stalk breaking force and the increasing trend of M2 and M4 stalk breaking force of HN44 varieties.

4.5. Effect of spraying MC on stem bending of soybean

The application of the MC spray generally resulted in an increase in soybean stem bending, with the trend of stem bending in HN65 showing an initial increase followed by a decrease over time. As the concentration of the MC spray increased, the soybean stem bending initially increased and then decreased. At 9 days, there was a gradual increase in stem bending. After 12 days, this parameter first decreased and then increased. Compared to the HN65CK, treatment M4 exhibited respective increases in stem bending by 6.89, 6.44, 8.32, 22.46, 2.36, and 5.18% as time progressed. The stem bending of HN44 initially increased and then decreased with the increasing spraying concentration for three days, reaching its peak value in treatment M3. At day 18, compared to HN44CK, treatments M1, M2, M3, and M4 showed respective increases in stem bending by 9.36,15.60, 21.84, and 9.36% (Fig. 5).

4.6. Effect of spraying MC on soybean lodging resistance index

After calculation, the lodging resistance index of HN65 and HN44 exhibited a declining trend over time. In the HN65 treatment group, the lodging resistance index initially decreased and subsequently increased with the increasing concentration on the 3rd day. With the passage of time, this trend gradually transformed into a pattern characterized by an initial increase followed by a subsequent decrease (indicating a gradual upward trajectory at 12 d), with the peak observed in the M3 treatment. At 18 d, each treatment exhibited significant increases of 4.02, 28.97, 32.63, and 7.26%, respectively, compared to HN65CK. The lodging resistance index for HN44 in the M4 treatment displayed superior lodging resistance at 3, 12, and 18 d, while the lodging resistance index for M1 showed maximum strength at 6, 9, and 15 d. The lodging resistance index in the M4 treatment exhibited a significant increase of 27.32, 22.23, 5.36, 8.23, 23.52, and 66.98%, compared to HN44CK, respectively. Compared to HN44CK, the lodging resistance index in the M1, M2, and M3 treatments showed substantial increases of 61.48, 52.82, and 39.57% at day 18. Overall, the application of the MC spray significantly enhanced the soybean lodging resistance index (Fig. 6).

4.7. Effects of spraying MC on soybean yield

4.7.1. Effects of spraying MC on soybean pod number

The MC spraying significantly influenced the pod number of the HN65 soybean. As the spraying concentration increased, the number of single-seed pods gradually increased, while the number of two-seed pods initially decreased and then increased. The number of three-seed pods exhibited a downward trend (with the M3 treatment slightly higher than M2 and M4), and the number of four-seed pods showed an initial increase followed by a decrease. Compared to plants with normal growth, the MC spraying reduced the number of effective pods in HN65. The effective pod numbers for M1, M2, M3, and M4 decreased by 6.87, 20.85, 15.40, and 31.28%, respectively compared to the control group. Additionally, MC spraying increased the number of ineffective pods in HN65 with each treatment showing an increase of 4, 2, 1, and 3 (per every 12 plants) compared to HN65CK (Fig. 7).

The application of the MC spray significantly influenced the pod number in the HN44 soybean. As the spraying concentration increased, the number of one-seed pods (M2 and M4) exceeded that of HN44CK. The number of two-seed pods initially increased and then decreased, while the number of three-seed pods showed an opposite

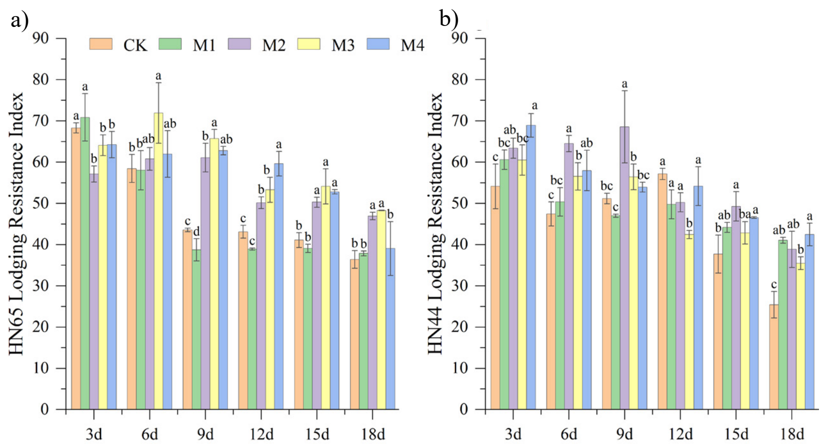

Fig. 6. Mepiquat chloride enhanced the change of lodging resistance index during soybean lodging resistance: a) variety HN65 and b) variety HN44 lodging resistance index change. Other explanations as on Fig. 3.

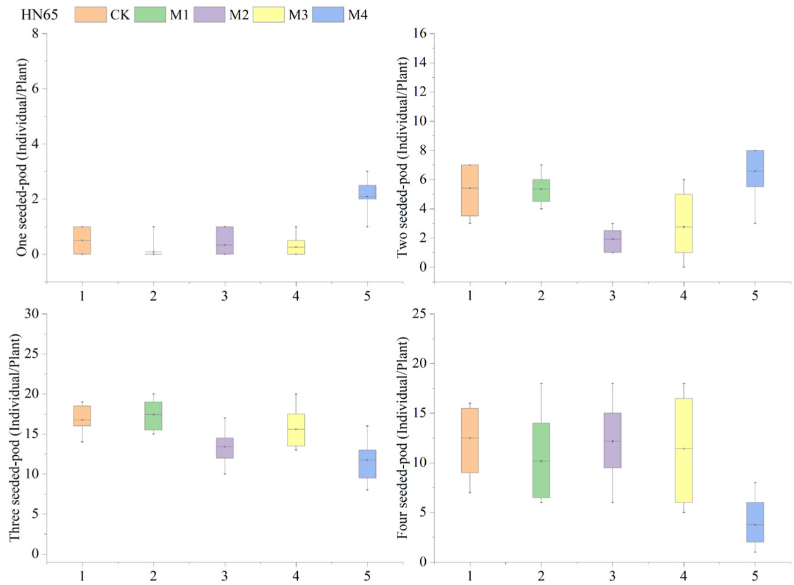

Fig. 7. Effect of spraying MC on pod number of HN65. The symbols 1, 2, 3, 4, and 5 correspond to CK, M1, M2, M3, and M4.

trend. Additionally, the number of four-seed pods first increased and then decreased. Compared to plants with normal growth, the MC spray reduced the effective pod count in the M1 treatment but enhanced it for the M2, M3, and M4 soybeans. Specifically, compared to HN44CK, there was a 1.51% decrease in the effective pod count for M1 but a 26.79, 24.91, and 33.21% increase for M2, M3, and M4, respectively. Furthermore, the MC spray led to an increase in invalid pods in HN44, with each treatment resulting in an additional 1, 1, 2, and 7 invalid pods per every twelve plants, respectively, compared to HN44CK (Fig. 8).

4.7.2. Effects of spraying MC on soybean harvest yield

The effects of MC on HN44 and HN65 differed significantly. In comparison to HN65CK, the yield in HN65 exhibited reductions of 9.20, 19.70, 10.90, and 30.20 g 4 plants, respectively. Additionally, the average weight of 100 seeds increased by -0.23, 3.02, 4.07, and -0.15% in each respective treatment. Compared to the control group, the M2, M3, and M4 treatments in HN44 exhibited a significant increase in yield by 26.20, 25.50, and 18.90 g respectively, while the M1 treatment showed a decrease in yield by 6.40 g. Additionally, there was a reduction of 23.77, 20.77, 20.37, and 21.77% in the weight of each hundred seeds in the respective treatments. The application of MC generally resulted in a decrease in the yield in the HN65 and HN44(M1) treatments, while it led to an increase in the yield of HN44 in the M2, M3, and M4 treatments. Moreover, it enhanced the 100-seed weight in the M2 and M3 treatments in HN65 but reduced it in the other varieties and treatments (Fig. 9).

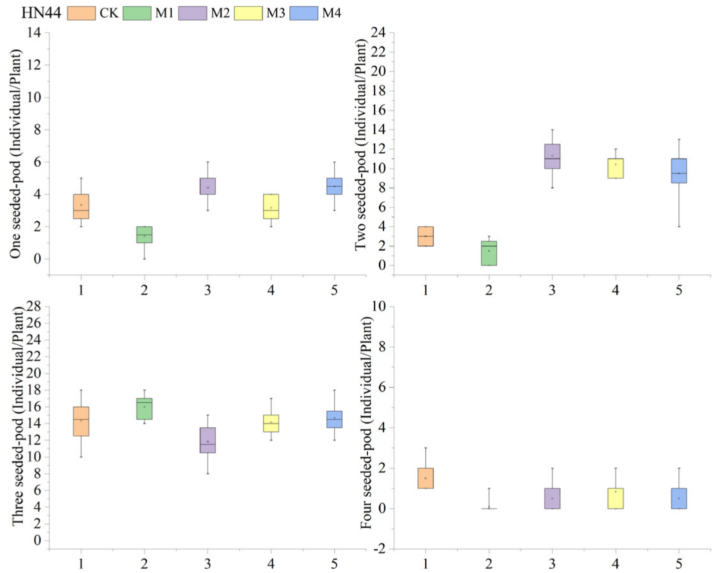

Fig. 8. Effects of spraying mepiquat chloride on pod number of HN44. The symbols 1, 2, 3, 4, and 5 correspond to CK, M1, M2, M3, and M4.

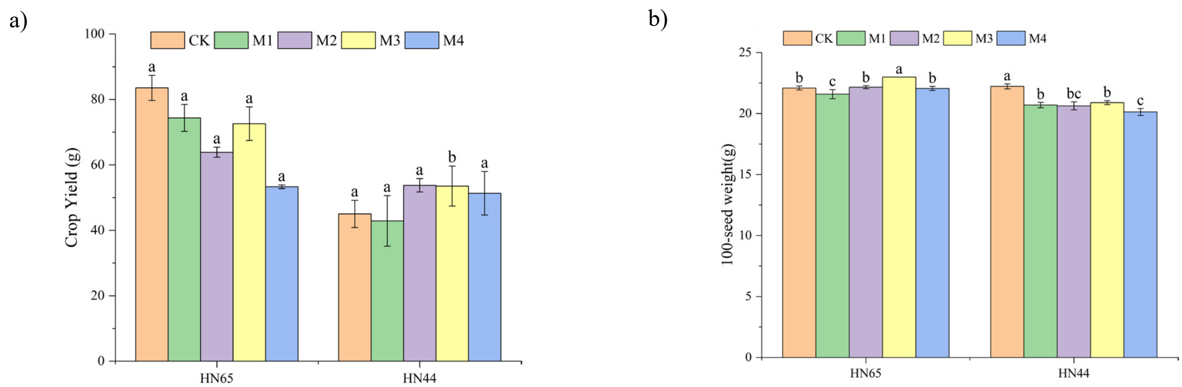

Fig. 9. Effect of mepiquat chloride on soybean yield: a) harvest yield change / 4 plants, b) 100-seed weight change.

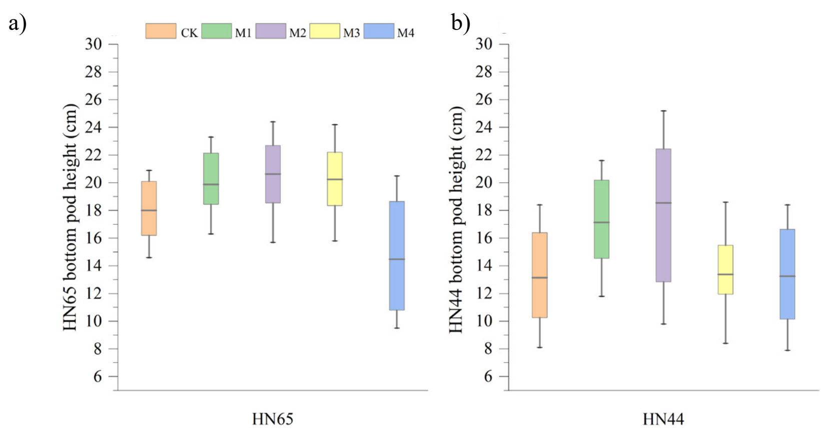

Fig. 10. Effect of MC on soybean bottom pod height: a) variety HN65 and b) variety HN44 bottom pod height change.

4.8. Effects of spraying MC on soybean bottom pod height

The application of the MC spray had varying effects on the bottom pod height of soybean after harvest, as depicted in Fig. 10. In HN65, there was an initial increase followed by a subsequent decrease in the bottom pod height. Compared to HN65CK, treatments M1, M2, and M3 exhibited respective increases of 10.46, 14.62, and 12.40% in bottom pod height. Conversely, treatment M4 resulted in a reduction in

HN65 bottom pod height. Similar trends were observed for both HN44 and HN65; however, it is noteworthy that all the treatments applied to HN44 displayed higher average bottom pod heights compared to HN44CK with increments of 30.44, 41.09, 1.81, and 0.82% (Fig. 10).

5. DISCUSSION

The application of MC as a plant growth regulator can enhance the lodging resistance of plants by augmenting the stalk breaking force and reducing plant length (Kamran *et al.*, 2018). This discovery enhances the resilience of soybeans in facing severe windy conditions during production, thereby mitigating the impact of natural disasters on food production. Additionally, MC can augment the lodging resistance index by promoting stem thickening and reducing internode elongation. Previous investigations have compared the lodging resistance index of soybean and suggested that it is influenced by stem length, stem diameter, and internode length (Ting *et al.*, 2016). This finding is in line with the outcomes of this experimental investigation indicating a high degree of consistency.

The application of the MC spray exerted a significant impact on the morphological characteristics of soybean. Specifically, in HN65, the stem length was reduced while the stem diameter increased. In HN44, both the M1 and M4 treatments resulted in a decreased stem length and an increased stem diameter. However, the increase in the stem length observed in the M2 and M3 treatments in HN44 may be attributed to their strong inhibitory effect on HN44, leading to compensatory growth during later stages and resulting in longer stems compared to the control group. Notably, when MC was sprayed on cotton plants, it effectively reduced their stem length (Cui *et al.*, 2014). The efficacy of MC spraying on soybean stems remains unverified. Firstly, the correlation analysis between soybean stem length, stem diameter, and GA3 revealed a positive association between soybean stem length and diameter with increasing GA3 content (Shan *et al.*, 2021). Furthermore, application of MC on soybean plants resulted in a significant elevation in the levels of GA1 and GA3 within soybean leaves (Wang *et al.*, 2023). The study revealed that gibberellin and the DEC1 gene exerted an influence on rice stem elongation (Nagai *et al.*, 2020). Therefore, by augmenting the gibberellin content in soybean plants, MC has the potential to enhance stem diameter and dry matter weight (Amin *et al.*, 2018). However, it is plausible that the reduction in stem length could be attributed to MC-induced upregulation of genes associated with stem elongation inhibition. Notably, this study did not assess GA levels; henceforth, future investigations should encompass an analysis of hormone metabolism.

The application of MC resulted in an increase in plant stalk breaking force, stem bending, and semi-cellulose content, thereby enhancing the soybean's lodging resistance capability (Xu *et al.*, 2017). The stem lodging resistance is positively correlated with both the stalk breaking force and stem bending, indicating that a stronger force and greater stem bending contribute to enhanced resistance. Recent research has indicated an association between semi-cellulose and stem lodging ability; however, the specific localization of a gene responsible for this trait remains unidentified (Li *et al.*, 2022). The hydrophilic nature of semi-cellulose facilitates water absorption and swelling of the cell wall, thereby enhancing elasticity and subsequently increasing plant lodging resistance (Farhat *et al.*, 2017). The relationship between the content of semi-cellulose in plant stems and the lodging resistance of plants has been previously established by several studies (Qingqin *et al.*, 2018). The application of the MC spray in this study resulted in an increase in the semi-cellulose content within plant stems as well as enhancement in stalk breaking force and stem bending.

The effect of MC on soybean yield was found to be influenced by the soybean variety and the concentration used for spraying. This experimental study demonstrates that a concentration of 200 is optimal for spraying on soybeans. Applying MC at an appropriate concentration can effectively increase the height of bottom pods in soybean plants, thereby facilitating harvest (Souza *et al.*, 2013). The soybean yield was influenced by the number of pods and the weight of 100 seeds. Application of MC spray can enhance both pod quantity and 100-seed weight (Jaidka *et al.*, 2020). This experiment demonstrated that spraying MC on soybean plants increased yield, consistent with the performance of HN44. However, the yield of HN65 decreased due to the reduction in effective pods and 100-seed weight caused by the MC application. This may be attributed to changes in material distribution resulting in increased dry matter accumulation in stems, leaves, and stalks. The effect of MC on soybean plant yield was found to be selective (Novakoski *et al.*, 2020), which is similar to our findings.

6. CONCLUSIONS

Spraying mepiquat chloride can enhance soybean's lodging resistance by reducing stem length, increasing stem diameter, stalk breaking force, stem bending, and semi-cellulose content. The impact of mepiquat chloride on soybean yield is varietal-specific with variations observed among different cultivars. The research findings indicate that spraying 200 mg L^{-1} mepiquat chloride at the three-leaf stage and early flowering stage of soybean has the most favorable effect on both lodging resistance and yield improvement.

Conflict of interest: The authors declare no conflict of interest.

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