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EFFECTS OF MOLYBDENUM ON GROWTH AND FRUIT QUALITY OF SMALL FRUIT MELON (*Cucumis melo* L.) CULTIVATED UNDER HIGH-TEMPERATURE STRESS

Meng Li [1, 2], Hong yan Wang [3], Ahmad Abdul Kareem Najm [2], Babul Airianah Othman [2], Douglas Law [4, 5]✉

[1] Xinyang Agriculture and Forestry University, College of Horticulture, Xinyang, Henan 464000, China

[2] University Kebangsaan Malaysia, Faculty of Science and Technology, Department of Food Sciences, Bangi, Selangor 43600, Malaysia

[3] Huazhong Agricultural University, College of Horticulture and Forestry, Wuhan 430070, China

[4] INTI International University, Faculty of Health and Life Sciences, Nilai, Negeri Sembilan 71800, Malaysia

[5] ENIAC, Centro Universitario de Excelencia. R. Força Pública, 89, Centro Guarulhos-SP, Brazil, 07012-030

ABSTRACT

Recurrent and prolonged heat waves during summer have significantly impacted the growth and quality of cultivated melons in China. Molybdenum (Mo), a trace element crucial for the plant's photosynthesis process under normal planting conditions, is posited to not only improve plant stress tolerance but also enhance fruit quality and nutritional content. In this study, melon cv. 'Japanese Sweet Treasure' was used as the experimental material. Various concentrations of ammonium molybdate solution (0, 0.05, 0.1, 0.2, 0.4 mg·L^{-1}) were foliar sprayed to examine their impact on the growth, photosynthetic characteristics, carbohydrate metabolism, and fruit quality of melons under high-temperature stress. The results indicated that plants sprayed with Mo exhibited enhanced plant parameters, including height, stem diameter, root volume, root activity, and physiological characteristics of melons under high-temperature stress, in comparison to the control (CK). The most significant improvements were observed in plants treated with 0.1 mg·L^{-1} Mo (T2). This treatment also showed higher improvement in melon net photosynthetic rate (*P*n), transpiration rate (*T*r) and total chlorophyll relative to other treatments. It also significantly promotes carbohydrate metabolism in melon plant leaves under high-temperature stress, enhancing their antioxidant enzyme activity. Melon plants exhibit a respective increase in sucrose, soluble sugars, superoxide dismutase (SOD), and peroxidase (POD) compared to the control. Melon sprayed with 0.1 mg·L^{-1} Mo showed significantly higher levels of vitamin C, soluble proteins, and soluble solids in fruits compared to other treatments, with a respective increase of 27.9% in individual fruit weight and 20.1% in per-plant yield compared to the CK. In conclusion, spraying 0.1 mg·L^{-1} Mo effectively mitigates damage caused by high-temperature stress during melon cultivation. It enhances the photosynthetic capacity of melon leaves, promotes carbohydrate metabolism in plant leaves, and thereby strengthens stress resistance. This comprehensive improvement leads to enhanced quality and yield of melon fruits.

Keywords: ammonium molybdate, antioxidant, heat damage, photosynthetic properties, yield

✉ douglas.law@newinti.edu.my

INTRODUCTION

The escalating occurrence of extreme weather patterns due to global warming, notably persistent high temperatures, has critically impeded agricultural progress [Ali et al. 2020]. China has witnessed frequent extreme weather events, especially prolonged heat waves during summer [Jahan et al. 2021, Hua et al. 2023]. Elevated temperatures inflict substantial damage by inducing extensive water loss, metabolic imbalances, and a decline in photosynthesis rates, severely impacting the growth of cash crops like melons [Arnao and Hernández-Ruiz 2020]. Melons display various heat-related symptoms, such as wilting, yellowing leaves, and decreased flower and fruit production when exposed to excessive external heat. Moreover, the disruption of melon carbon metabolism due to the accumulation of metabolites, including sugars and alcohols resulting from altered enzyme activity and protein structure at high temperatures, significantly hampers their growth and development, affecting the fruit quality [Amarasinghe et al. 2021]. Melon quality was determined by its flavor profile, which is a result of a delicate fusion of taste and aroma. Its taste is intricately linked to sugars and organic acids, while its aroma is contingent on a multitude of volatile compounds. Studies report at least 240 volatiles present in melons, predominantly esterified in aromatic varieties, while non-aromatic varieties showcase aldehydes and alcohols as their primary volatiles [Kavi Kishor et al. 2022, Zafar et al. 2022].

In China, melons stand as one of the principal cultivated crops, boasting a short cultivation cycle, high input-output ratio, and substantial income potential [Maresca et al. 2017]. Considered an industry with distinctive Chinese characteristics, melon cultivation holds a pivotal role in uplifting fruit farmers from poverty [Cheevitsopon and Sirisomboon 2018]. Over recent years, China's melon market has been growing rapidly, with the cultivation area steadily expanding. Melons, with a harvested area of 14 million ha and a yield of 45 million tons, are an important export crop of China, significantly shaping China's agricultural landscape and contributing to rural revitalization [Wen et al. 2022]. However, in recent years, the increasingly extreme hot weather has adversely impacted the growth and quality of cultivated melons, significantly affecting the income of farmers [Yang et al. 2022].

Molybdenum (Mo) is a trace element crucial for plant growth. The essential role extends to controlling physiological metabolic processes like nitrogen and carbon uptake in plants [Kareem et al. 2017, Rihan et al. 2014]. Its absence leads to altered leaf coloration, impacting crucial enzymatic quantities and subsequently disrupting redox reactions and nitrogen metabolism while also decreasing chlorophyll levels in plant cells [Asgher et al. 2017, Kareem et al. 2017]. Studies demonstrate that sodium molybdate application during flowering and fruiting stages significantly increases melon leaf chlorophyll content, reduces nitrate nitrogen accumulation, and promotes its transformation and utilization in melon plants, ultimately boosting fruit yield [Lopez-Zaplana et al. 2020]. Foliar application of molybdenum enhances wheat seed dormancy and vitality, supporting wheat growth and development [Ahsin et al. 2020, Imran et al. 2019]. Additionally, introducing molybdenum into the fertilization program alleviates plant stress, such as salinity stress in crested wheatgrass [Babenko et al. 2015], cold stress in peach trees [Gao et al. 2019], and in wheat [Al-Issawi et al. 2016]. However, research on high-temperature stress in melons remains limited to studies in individual cultivation facilities.

Thus, the primary objective of this study was to explore the influence of ammonium molybdate on melon growth, leaf antioxidant enzyme activity, carbohydrate metabolism, fruit quality, and yield under high-temperature stress. The aim was to determine the optimal concentration of ammonium molybdate that can effectively alleviate high-temperature stress in melons. The findings of this research serve as a theoretical foundation for the judicious utilization of the nutrient element molybdenum and the formulation of stress-resistant cultivation practices for melons.

MATERIAL AND METHOD

Materials. The melon (*Cucumis melo* L.) variety 'Japanese Sweet Treasure' was purchased from Fuzhou Jinmarriott Technology Co., Ltd., China. The substrates used in the experiment were peat, vermiculite, and perlite, purchased from Zhengzhou Lvzhiwo

Agricultural Technology Co., Ltd., China. Ammonium molybdate ($(NH_4)_6Mo_7O_{24}4H_2O$ content greater than 99%) was purchased from Jiaozuo Xin'an Technology Co., Ltd, China.

Cultivation parameters. The study was conducted in the greenhouse of the Internet of Things in Xinyang Agriculture and Forestry University Intelligent Horticulture Experimental Base from March to September 2023. The experimental site is located at 114°7'3" E and 32°9'51" N, with an elevation of about 114.35 m, belonging to the transition climate from subtropical to northern temperate zone. The average day/night temperatures inside the greenhouse were 22–28°C/16–18°C, the light intensity was between 800~1000 μmol·m^{-2}·s^{-1}, and the photoperiod was between 10–12 hours, relative humidity was maintained at 60%–70% during cultivation. The melon seeds were germinated in a mixture of peat:perlite at a volume ratio of 3:1 on March 5, 2023. The seeds of melon were cultivated in a 50-hole substrate tray and irrigated twice daily until seedlings were produced. Subsequently, at the three-leaf stage, approximately five weeks (on April 10, 2023) after seed planting, the seedlings were transplanted into cultivation barrels (with a capacity of 10 L, an upper mouth diameter of 34 cm, a lower mouth diameter of 22 cm, and a height of 28 cm) filled with mixed substrates, the cultivated substrate is peat:vermiculite:perlite with a volume ratio of 3:1:1. After the average plant height of the melons exceeded 20 cm and the first fruits were set (on June 13, 2023), strong, uniformly sized plants with thick stems, free from pests and diseases, were selected and transplanted into pots in an artificial climate chamber (TPG1160, China) for temperature control experiments. The temperature of the artificial climate chamber was set at 42 ±1°C during the day and 30 ±1°C during the night. The relative humidity was set at 70%, and light intensity at 800 μmol·m^{-2}·s^{-1}. After 14 days of high-temperature treatment, a return to room temperature (the temperature of the artificial climate chamber was set at 28 ±1°C during the day and 18 ±1°C during the night; other conditions remained the same) was applied. After two days of recovery, all the plants were moved into the greenhouse (the plant was planted at a spacing of 30 cm, the row spacing of 50 cm, ten plants were planted per square meter), with spraying water as control CK (0 mg·L^{-1} ammonium molybdate), the other treatments were T1 (0.05 mg·L^{-1} ammonium molybdate), T2 (0.1 mg·L^{-1} ammonium molybdate), T3 (0.2 mg·L^{-1} ammonium molybdate), and T4 (0.4 mg·L^{-1} ammonium molybdate). The concentrations of ammonium molybdate were set based on a pre-experiment, five groups of treatments were tested, and each treatment was repeated three times. Fifteen plants were tested in each treatment. The plant in each treatment was sprayed with 50 mL ammonium molybdate every two days, and the total was sprayed six times. The average day/night temperatures inside the greenhouse were 22–28°C/16–18°C, the light intensity was between 760–820 μmol·m^{-2}·s^{-1}, and the photoperiod was between 10–12 hours, relative humidity was maintained at 60%–70% during cultivation. During the full growth cycle, 1.0~1.5 L of Hoagland nutrient solution was applied daily to each melon plant. The pH and electrical conductivity (EC) of the nutrient solution were monitored daily to ensure an average pH value between 6.2 and 6.4, regulated with hydrochloric acid (HCL, Huabo Ltd, China). Furthermore, the EC was maintained within the range of 1500–3000 μS·cm^{-1}. Five days after all ammonium molybdate spraying was completed, samples were taken from the melon plant, and relevant indicators were measured to assess their physiological and biochemical characteristics. The melons were harvested (from August 27 to September 10, 2023) when they were greyish-white, smooth with yellow lines, had a strong fragrance, and showed slight softness at the blossom end. After harvesting, the fruits were stored at a temperature of 4–10°C and a relative humidity of 85–90%.

Plant growth determination. Three plants were selected randomly from each replication for all treatments. Plant height and root length were measured with a tape meter. The stem diameter was measured with a vernier caliper (Mitutoyo CD-15APX, Japan). Leaf area was measured by a leaf area meter (LI-3000C, USA), and root volume was measured using the water displacement method. The root activity of seedlings was assessed using the tetrazolium chloride (TTC) method [Li et al. 2021a]. Root segments were immersed in a 0.6% TTC solution and incubated in the dark at 30°C for 2–4 hours. The roots were then crushed, and the color was extracted using 95%

ethanol. The absorbance of the extract was measured at 485 nm using a spectrophotometer (Diones 4X250, USA), and the seedling index was measured by the method described by Li et al. [2021a]. Plant fresh and dry weight were also measured at the end of experiments by analytical balance precision 0.001 (Isvart CXE-1, USA). The plant material was dried in an oven (Nabertherm TR 1050, Germany) at 60°C for 72 hours.

Heat damage index, leaf water content and relative conductivity determination. The heat damage index (HDI) and water content of plant leaves were determined according to the method described by Li et al. [2023]. In short, the leaf pieces were immersed in a test tube containing a known volume of distilled water and incubated at 45°C for 30 minutes to simulate heat stress. After incubation, the test tubes were cooled to room temperature, and measurements of the initial electrical conductivity (EC1) of the solution were made using a conductivity meter (DDS-11A, China). The test tubes were then autoclaved at 121°C for 20 minutes to completely kill the leaf tissue and release all electrolytes. The repeated measurements of final electrical conductivity (EC2) were made after cooling the solution to room temperature. Heat damage index (HDI) was calculated according to the formula: HDI = (EC1/EC2) × 100%. Relative conductivity was determined using a method described by Chapin et al. [2014].

Chlorophyll content determination. Chlorophyll was analyzed using the ethanol and acetone mixture method [Li et al. 2021b]. Briefly, the first fully expanded functional leaf under the growth point of each treatment was selected. Leaves were first cut into pieces, after which a vein was removed. Samples were then weighed, and a 0.1 g sample was put into a 25 mL volumetric flask, mixed with 10 mL of mixed extractive solution, and stored in the dark. After the leaves were turned white, samples were mixed with an extraction reagent to a constant volume of 25 mL. The extraction reagent was used as blank, and a spectrophotometer (Diones 4X250, USA) was used for colorimetric determination at the wavelengths of 663, 646, and 470 nm, respectively. Each treatment was repeated three times.

Determination of photosynthetic properties. The third fully expanded functional leaf under the growth point of each treatment was selected, and the photosynthetic gas exchange parameters, including net photosynthetic rate (*P*n), stomatal conductance (*G*s), intercellular CO_2 concentration (*C*i) and transpiration rate (*T*r), were measured by a portable photosynthesis measurement system (Li-6400, USA) at 9:00~11:00 am [Zhao et al. 2020]. The photosynthesis conditions were set as follows: light intensity of 1500 μmol·m^{-2}·s^{-1}, CO_2 concentration of 400 μmol·mol^{-1}, leaf area of 6 cm^2, airflow of 500 μmol·s^{-1}, and temperature of 30°C, three plants were determined for each treatment.

Antioxidant activity determination. The superoxide dismutase (SOD), peroxidase (POD), catalase (CAT) activity, and malondialdehyde (MDA) content were determined according to the method described by Prie et al. [2016], hydrogen peroxide content was determined according to the method described by Kumar et al. [2014].

Carbohydrate content and carbon metabolism enzyme activity determination. The first fully expanded functional leaf under the growth point of each treatment was selected, and the sucrose and starch were measured according to the method described by Zhai et al. [2023], while the soluble total sugar was measured using the method described by Sharma et al. [2011], the sucrose synthase, sucrose phosphate synthase and acid invertase were determined using the method described by Li et al. [2021a].

Melon fruit quality and yield measurement. The soluble solid of the fruit was measured by LH-B55 saccharimeter (Lu Heng Biological Co. Ltd, China). Vitamin C was determined using 2,6-dichloroindophenol titration [Nerdy, 2018], the soluble protein was determined by Coomassie brilliant blue G-250 staining [Said-Fernández et al., 1990], acid content was determined according to the method described by Zhai et al. [2023], nitrate was determined by the method described by Li et al. [2021c]. A Vernier caliper (Mitutoyo CD-15APX, Japan) was used to measure the transverse and longitudinal diameter of the fruit. The fruit shape index was calculated using the following formula: longitudinal diameter/transverse diameter, the weight per fruit and yield per plant were measured by electronic balance (China and Avionics Technology Co., Ltd, China).

Data processing. Differences among means were assessed using one-way analysis of variance (ANO-

VA) in SPSS 23.0 (IBM SPSS, Armonk, NY: IBM Corp., USA), and graphing was performed using Origin2021 (OriginLab Corp., USA). Duncan's multiple range test was employed for multiple comparisons. The results were presented as means and standard error (SE). Statistical significance was set at a *p*-value <0.05. All measurements were conducted in triplicate.

RESULTS

Effects of different concentrations of ammonium molybdate solution on the growth of melon plants under high-temperature stress

Metrics such as plant height, stem diameter, and leaf area varied among melon plants under molybdenum treatments (Tab. 1). The use of molybdenum in concentrations of 0.05 mg L^{-1} (T1) and 0.1 mg L^{-1} (T2) resulted in an increase in the plant height, stem diameter, total leaf area, fresh weight and dry weight in comparison to CK. Plants from the T2 combination achieved the highest values of all the above parameters. Higher molybdenum doses of 0.2 mg L^{-1} (T3) and 0.4 mg L^{-1} (T4) negatively affected shoot width and total leaf area, and T4 negatively affected the dry weight of the plants.

Melon plants under T2 exhibited greater root volume (10.42 cm^3) and root activity (113.87 $\mu g \cdot g^{-1} \cdot h^{-1}$) as compared to all other treatments (Tab. 2). The heat damage index and relative conductivity of the leaves from the T2 treatment were the lowest, decreasing by 36.6% and 9.0%, respectively, compared to the CK. Moreover, leaf water content was highest with T2, followed by T3 and T1 treatments (Fig. 1).

Table 1. Effect of different concentrations of ammonium molybdate solution on melon growth under high-temperature stress

Treatment*	Plant height (cm)	Stem diameter (mm)	Fresh weight (g)	Dry weight (g)	Total leaf area (cm^2)
CK	149.52 ±2.35 c	8.61 ±0.14 b	273.36 ±21.36 b	31.28 ±1.03 bc	209.15 ±1.36 b
T1	153.07 ±2.48 ab	8.84 ±0.15 ab	329.63 ±13.45 a	35.30 ±1.02 b	229.11 ±1.08 a
T2	153.95 ±3.38 a	9.19 ±0.17 a	338.12 ±11.69 a	37.31 ±1.31 a	230.75 ±2.01 a
T3	152.09 ±2.61 b	8.43 ±0.12 c	331.33 ±21.35 a	34.32 ±1.22 b	195.25 ±1.69 c
T4	148.43 ±1.78 c	8.41 ±0.11 c	266.56 ±17.21 b	29.26 ±1.13 c	191.23 ±1.25 c

*Ammonium molybdate concentration (mg L^{-1}): CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04. The mean values ± standard errors in the same column with the same letter are not significantly different at $p < 0.05$, Duncan's multiple range test

Table 2. Effect of different concentrations of ammonium molybdate solution on root growth of melon under high-temperature stress

Treatment	Root length (mm)	Root volume (cm^3)	Root activity ($\mu g \cdot g^{-1} \cdot h^{-1}$)
CK	109.09 ±3.75 a	7.32 ±1.02 d	98.31 ±5.86 c
T1	109.53 ±3.10 a	9.38 ±1.01 b	108.37 ±6.95 b
T2	109.96 ±3.14 a	10.42 ±1.03 a	113.87 ±6.90 a
T3	108.83 ±3.61 a	9.16 ±2.04 bc	105.59 ±5.83 b
T4	108.74 ±3.31 a	8.31 ±1.02 cd	97.36 ±6.05 c

*Ammonium molybdate concentration (mg L^{-1}): CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04. The mean values ± standard errors in the same column with the same letter are not significantly different at $p < 0.05$, Duncan's multiple range test

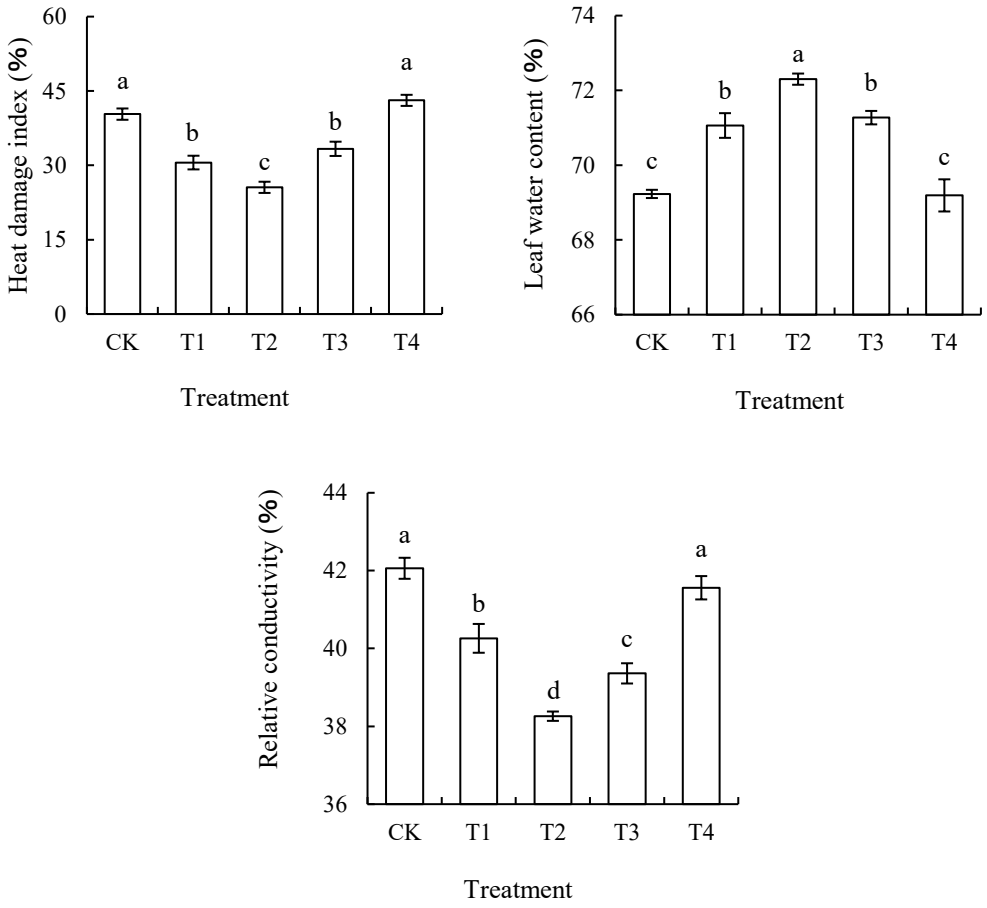

Fig. 1. Effects of different concentrations of ammonium molybdate solution: CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04 mg L^{-1} on heat damage index and leaf water content of melon under high-temperature stress. Bars followed by the same letter are not significantly different at $P < 0.05$, Duncan's multiple range test

Effects of different concentrations of ammonium molybdate solution on the photosynthetic properties, antioxidant activity and carbohydrate metabolism of melon leaves under high-temperature stress

Melon plants treated with T2 showed the highest levels of chlorophyll a, chlorophyll b, carotenoids, and total chlorophyll, measuring 8.63 mg·g^{-1}, 3.72 mg·g^{-1}, 2.37 mg·g^{-1}, and 14.72 mg·g^{-1}, respectively. Increased chlorophyll a, b, and total chlorophyll content was also noted in the leaves from T1 treatment. The highest concentration of molybdenum (T4) had no significant effect on the level of analyzed pigments or caused a decrease in their content compared to the control plants (Tab. 3).

Additionally, as ammonium molybdate concentration increased, the net photosynthetic rate (*P*n), stomatal conductance (*G*s), and transpiration rate (*T*r) also rose. At 0.1 mg·L^{-1}, these parameters increased by 12.6%, while the intercellular CO_2 concentration (*C*i) was lowest in T2-treated plants at 453.62 µmol·mol^{-1}, a 1.1% decrease compared to CK. This indicates that optimal ammonium molybdate concentrations can enhance photosynthesis, thereby boosting melon growth and development (Fig. 2).

The activities of SOD, POD, CAT and the levels of MDA and H_2O_2 in melon plant leaves varied with different concentrations of ammonium molybdate (Tab. 4). T2 treatment led to the highest SOD

Table 3. Effect of different concentrations of ammonium molybdate solution on photosynthetic pigment content in melon leaves under high-temperature stress

Treatment	Chlorophyll a content ($mg \cdot g^{-1}$)	Chlorophyll b content ($mg \cdot g^{-1}$)	Carotenoid content ($mg \cdot g^{-1}$)	Total chlorophyll content ($mg \cdot g^{-1}$)
CK	6.65 ±0.23 cd	2.47 ±0.17 c	1.53 ±0.13 b	10.65 ±0.26 c
T1	8.01 ±0.12 b	3.11 ±0.13 b	1.74 ±0.11 b	12.86 ±0.12 b
T2	8.63 ±0.25 a	3.72 ±0.19 a	2.37 ±0.15 a	14.72 ±0.26 a
T3	7.96 ±0.16 bc	2.98 ±0.17 b	1.62 ±0.19 b	12.56 ±0.28 b
T4	6.52 ±0.19 d	2.39 ±0.16 c	1.26 ±0.13 c	10.17 ±0.17 d

*Ammonium molybdate concentration (mg L^{-1}): CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04. The mean values ± standard errors in the same column with the same letter are not significantly different at $p < 0.05$, Duncan's multiple range test

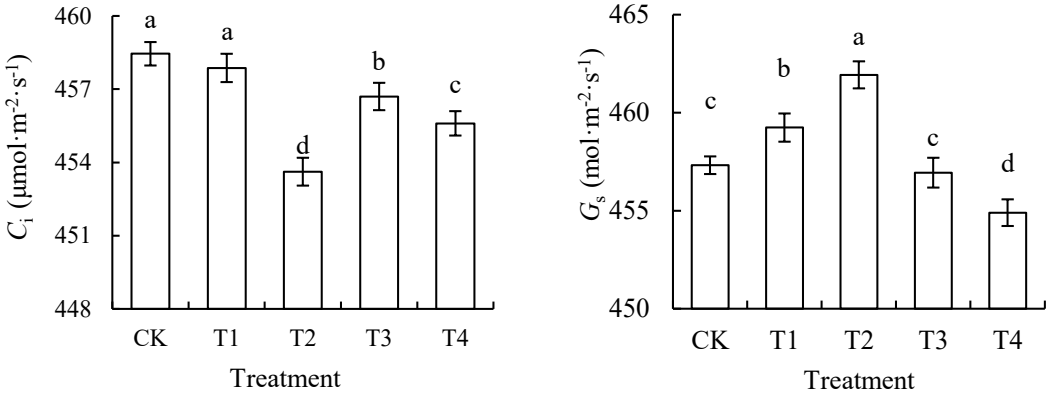

Fig. 2. Effects of different concentrations of ammonium molybdate solution CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04 mg L^{-1} on the photosynthetic properties of melon under high-temperature stress. *P*n – net photosynthetic rate; *G*s – stomatal conductance; *C*i – intercellular CO_2 concentration; *T*r – transpiration rate. Bars followed by the same letter are not significantly different at $P < 0.05$, Duncan's multiple range test

(41.86 U·FW·g^{-1}, 20.5% higher than CK) and POD (55.06 U·FW·g^{-1}) activities, while CAT activity peaked in T3-treated plants (32.57 U·FW·g^{-1}). In T2-treated plants, the lowest MDA (6.44 μmol·g^{-1}) and H_2O_2 (9.74 mmol·g^{-1}) levels were measured (Tab. 4). T2 treatment resulted in the highest soluble sugar (42.33 mg·g^{-1}) and sucrose (32.52 mg·g^{-1}) contents, as well as the highest activities of sucrose synthase (82.48 nmol·mg^{-1}) and sucrose phosphate synthase (131.69 nmol·mg^{-1}) in leaves. However, starch content (1.52 mg·g^{-1}) and acid invertase activity (53.22 nmol·mg^{-1}) were lowest in T2-treated plants (Tab. 5).

Effect of ammonium molybdate solution on melon fruit quality and yield under high-temperature stress

Melon fruits from T2-treated plants showed the highest vitamin C (325.78 mg·g^{-1}) and soluble protein content (0.556 mg·g^{-1}) compared to other treatments. Soluble solids were also elevated in T1 and T2 treat-

Table 4. Effects of different concentrations of ammonium molybdate solution on antioxidant activity of melon plants under high-temperature stress

Treatment	SOD ($U \cdot FW \cdot g^{-1}$)	POD ($U \cdot FW \cdot g^{-1}$)	CAT ($U \cdot FW \cdot g^{-1}$)	MDA ($\mu mol \cdot g^{-1}$)	H_2O_2 ($mmol \cdot g^{-1}$)
CK	34.73 ±1.08 cd	51.78 ±0.70 b	29.64 ±0.25 d	10.22 ±0.69 a	12.58 ±0.07 a
T1	38.59 ±1.26 b	53.96 ±0.38 a	31.08 ±0.30 c	7.59 ±0.40 c	11.09 ±0.06 b
T2	41.86 ±0.59 a	55.06 ±0.61 a	31.90 ±0.17 b	6.44 ±0.37 d	9.74 ±0.09 d
T3	36.38 ±0.88 c	52.13 ±0.82 b	32.57 ±0.18 a	8.33 ±0.46 bc	10.53 ±0.18 c
T4	32.84 ±0.62 d	50.89 ±0.62 b	29.58 ±0.28 d	8.79 ±0.28 b	11.07 ±0.03 b

*Ammonium molybdate concentration (mg L^{-1}): CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04. The mean values ± standard errors in the same column with the same letter are not significantly different at $p < 0.05$, Duncan's multiple range test

Table 5. Effects of different concentrations of ammonium molybdate solution on carbohydrate metabolism in leaves of melon plants under high-temperature stress

Treatment	Soluble total sugar content ($mg \cdot g^{-1}$)	Sucrose content ($mg \cdot g^{-1}$)	Starch content ($mg \cdot g^{-1}$)	Sucrose synthase activity ($nmol \cdot mg^{-1}$)	Sucrose phosphate synthase activity ($nmol \cdot mg^{-1}$)	Acid convertase activity ($nmol \cdot mg^{-1}$)
CK	38.70 ±0.60 b	27.78 ±0.77 c	2.04 ±0.19 a	77.43 ±0.93 bc	127.07 ±0.52 c	57.67 ±0.53 a
T1	41.03 ±0.85 a	30.41 ±0.62 b	1.87 ±0.16 ab	79.28 ±0.54 b	129.16 ±0.42 b	56.11 ±0.84 bc
T2	42.33 ±0.47 a	32.52 ±0.71 a	1.52 ±0.10 c	82.48 ±0.72 a	131.69 ±0.32 a	53.22 ±0.29 d
T3	36.56 ±0.51 c	28.97 ±0.86 bc	1.76 ±0.11 b	78.12 ±0.70 bc	125.68 ±0.88 c	55.78 ±0.45 b
T4	35.77 ±0.57 c	25.91 ±0.40 d	1.77 ±0.14 b	77.15 ±0.78 c	125.83 ±0.81 c	54.73 ±0.58 c

*Ammonium molybdate concentration (mg L^{-1}): CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04. The mean values ± standard errors in the same column with the same letter are not significantly different at $p < 0.05$, Duncan's multiple range test

Table 6. Effects of different concentrations of ammonium molybdate solution on the quality of melon fruit quality under high-temperature stress

Treatment	Vitamin C content ($mg \cdot g^{-1}$)	Soluble protein content ($mg \cdot g^{-1}$)	Acid content (%)	Soluble solids content ($mg \cdot g^{-1}$)	Nitrate content ($mg \cdot g^{-1}$)
CK	320.53 ±13.36 c	0.525 ±0.02 b	0.812 ±0.03 a	13.24 ±0.11 c	1.17 ±0.05 a
T1	322.56 ±11.65 b	0.531 ±0.01 b	0.781 ±0.02 ab	16.15 ±0.28 a	1.09 ±0.03 bc
T2	325.78 ±19.34 a	0.556 ±0.01 a	0.653 ±0.04 c	16.54 ±0.16 a	1.01 ±0.07 d
T3	321.92 ±9.83 bc	0.505 ±0.03 bc	0.764 ±0.02 b	14.56 ±0.21 b	1.06 ±0.02 cd
T4	318.27 ±15.48 d	0.494 ±0.01 c	0.766 ±0.04 b	12.43 ±0.18 d	1.12 ±0.01 b

*Ammonium molybdate concentration (mg L^{-1}): CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04. The mean values ± standard errors in the same column with the same letter are not significantly different at $p < 0.05$, Duncan's multiple range test

Table 7. Effects of different concentrations of ammonium molybdate solution on melon fruit yield under high-temperature stress

	Transverse diameter (cm)	Longitudinal diameter (cm)	Fruit index	Single fruit weight (kg)	Single plant yield (kg)
CK	7.84 ±0.14 c	20.74 ±1.03 c	2.64 ±0.05 a	0.43 ±0.02 c	1.39 ±0.12 e
T1	8.22 ±0.18 b	21.62 ±1.32 b	2.63 ±0.03 a	0.48 ±0.01 b	1.61 ±0.23 b
T2	8.58 ±0.15 a	23.31 ±2.05 a	2.72 ±0.07 a	0.55 ±0.05 a	1.67 ±0.15 a
T3	7.88 ±0.34 c	21.64 ±1.24 b	2.75 ±0.08 a	0.41 ±0.02 c	1.54 ±0.11 c
T4	7.64 ±0.32 d	19.84 ±1.17 d	2.60 ±0.11 a	0.40 ±0.04 c	1.51 ±0.21 d

*Ammonium molybdate concentration (mg L^{-1}): CK 0, T1 0.05, T2 0.01, T3 0.02, T4 0.04. The mean values ± standard errors in the same column with the same letter are not significantly different at $p < 0.05$, Duncan's multiple range test

Table 8. Correlation analysis of the growth indexes and characteristic indexes of melon plants

Index	PLH	SD	DW	LS	RL	RV	TCC	HDI	LWC	SFW	SPY
SOD	0.512	0.422	0.356	0.603	0.132	0.271	0.946**	–0.760**	0.179	0.146	0.225
POD	0.493	0.371	0.474	0.540	0.265	0.374	0.855**	–0.742**	0.366	0.259	0.101
CAT	0.209	0.469	0.392	0.543	0.435	0.402	0.912**	–0.747**	0.446	0.331	0.247
MDA	–0.314	–0.422	–0.545*	–0.710**	–0.212	–0.231	0.669	0.586*	–0.304	0.139	0.382
Pn	0.396	0.548*	0.481	0.783**	0.462	0.346	0.667*	0.219	0.616*	0.201	0.228
*G*s	0.501	0.346	0.260	0.873**	0.331	0.265	0.603*	–0.546*	0.583*	0.390	0.310
SC	0.426	0.241	0.691**	0.362	0.894**	0.631*	0.738**	–0.288	0.395	0.254	0.256
SSC	0.322	0.369	0.567*	0.671*	0.229	0.656**	0.799**	–0.394	0.283	0.229	0.122
SHC	–0.143	–0.456	–0.475	–0.487	–0.638*	–0.568*	–0.566*	0.161	–0.492	0.140	0.139
SSA	0.205	0.801**	0.715**	0.205	0.421	0.489	0.729**	–0.736**	0.240	0.261	0.110
SPSA	0.321	0.833**	0.643**	0.424	0.267	0.352	0.898**	–0.779**	0.358	0.117	0.255
ACA	–0.362	–0.339	–0.290	–0.161	–0.419	–0.279	–0.378	0.179	–0.191	0.303	0.170
VC	0.460	0.312	0.266	0.366	0.202	0.115	0.133	–0.357	0.212	–0.591*	–0.588*
SS	0.260	0.249	0.305	0.432	0.449	0.332	0.195	–0.269	0.453	–0.601*	–0.592*

PLH – plant height; SD – stem diameter; DW – dry weight of the whole plant; LS – leaf surface; RL – root length; RV – root volume; TCC – total chlorophyll content; HDI – heat damage index; LWC – leaf water content; SFW – single fruit weight; SPY – single plant yield; SOD – superoxide dismutase activity; POD – peroxidase activity; CAT – catalase activity; MDA – malondialdehyde content; *Pn* – net photosynthetic rate; *G*s – stomatal conductance; SC – sucrose content; SSC – soluble sugar content; SHC – starch content; SSA – sucrose synthase activity; SPSA – sucrose phosphate synthase activity; ACA – acid convertase activity; VC – vitamin C content; SS – soluble solid content

* remarkable correlation at $P < 0.05$ standard

** extremely remarkable correlation at $P < 0.01$ standard

ments, indicating 16.15 mg·g^{-1} and 16.54 mg·g^{-1}, respectively, representing increases of 22.0% and 24.9% over CK. Fruits from the T2 combination had the lowest acid (0.653%) and nitrate content (1.01 mg·g^{-1}) (Tab. 6).

Fruit measurements indicated that transverse diameter, longitudinal diameter, single fruit weight, and yield increased from T1 to T2 treatments, peaking with T2 at 8.58 cm, 23.31 cm, 0.55 kg, and 1.67 kg, respectively. Higher molybdenum doses had no significant effect on T3 treatment or negatively affected (T4) fruit diameter and yield (Tab. 7).

Correlation analysis of growth indexes and characteristic indexes of melon plants

Melon plant growth was significantly influenced by factors such as antioxidant enzyme activity, photosynthetic properties, and carbohydrate metabolism. SOD, POD, and CAT activities showed strong positive correlations with total chlorophyll and negative correlations with the heat damage index, MDA content, and leaf area (Tab. 8). These results emphasize the role of antioxidant enzymes in promoting growth and reducing heat damage. The net photosynthetic rate and stomatal conductance were positively correlated with total chlorophyll, leaf water content, single fruit weight, and leaf area, suggesting their contribution to improved plant growth.

In carbohydrate metabolism, sucrose content correlated positively with dry weight, root length, total chlorophyll, and root volume, while starch content was negatively correlated with these growth indicators. Sucrose synthase and sucrose phosphate synthetase activities were positively associated with stem diameters, dry weight, and total chlorophyll and negatively correlated with the heat damage index and acid invertase activity. Additionally, vitamin C and soluble solids content were significantly linked to single fruit weight and yield, indicating their importance in enhancing fruit quality and production (Tab. 8).

DISCUSSION

Molybdenum is a crucial micronutrient for plant growth and development, playing a significant role in various physiological and biochemical processes. Molybdenum-dependent enzymes, such as nitrate reductase, are essential for nitrogen assimilation in plants, a process vital for protein synthesis and overall plant growth. Molybdenum deficiency can impair nitrogen metabolism, thereby affecting plant growth and development [Dhaliwal et al. 2019]. Additionally, molybdenum influences carbon metabolism by impacting the synthesis and transport of carbohydrates. In molybdenum-deficient plants, chlorophyll content and photosynthetic efficiency are reduced, leading to lower carbohydrate production and transport to reproductive organs, ultimately affecting fruit quality [Oliveira et al. 2022].

Plant height, stem thickness, and leaf area are indicative of the plant's growth potential [Hu et al. 2017]. The dry and fresh weight of seedlings, influenced by photosynthesis and root absorption efficiency, serve as crucial indicators for assessing plant growth and development [Kučerová et al. 2019]. Root systems play a pivotal role in activating soil nutrients and facilitating essential plant nutrient absorption [Fang et al. 2013, Lo Presti et al. 2021]. The activity of roots significantly impacts a plant's nutrient acquisition ability. Previous research by Li et al. [2015] demonstrated that introducing molybdenum fertilizer under normal planting conditions for cucumber plants greatly enhanced leaf area and dry quality in seedlings, promoting root system development. A study by Tao et al. [2021] highlighted that molybdenum application effectively promotes root growth in wild apple trees and enhances their root vitality. In the current study, melon plants treated with 0.1 mg·L^{-1} ammonium molybdate exhibited the highest plant height, stem diameter, root activities, and dry weight, suggesting that an appropriate concentration of ammonium molybdate solution can stimulate melon plant growth and mitigate damage to melon roots under high-temperature stress.

Plant stress resilience and physiological responses are critical considerations in understanding high-temperature stress effects. Studies by Punia et al. [2011] highlighted leaf water content and heat damage index as crucial markers for plant heat resistance. Notably, in the current study, the application of molybdenum-based solutions demonstrated efficacy in reducing heat damage index and relative conductivity in melons under high-temperature stress. The application of molybdenum-based solutions also boosted leaf water content, alleviating membrane lipid destruction.

Similar findings align with research on salicylic acid's impact on heat tolerance in red grapes [Jahan et al. 2019]. The photosynthetic response and chlorophyll content, indicative of photosynthetic capacity, notably increased in melon leaves with ammonium molybdate application under high-temperature stress. The T2 treatment (0.1 mg·L^{-1} ammonium molybdate), in particular, fostered robust growth due to enhanced organic matter accumulation. Furthermore, molybdenum-based solutions, such as ammonium molybdate, have shown the ability to influence stomatal and non-stomatal conductance, facilitating CO_2 absorption and utilization, resulting in increased photosynthesis rates, akin to exogenous nitric oxide effects previously shown in vegetable bean seedling photosynthesis characteristics under high-temperature stress [Song et al. 2013]. This was also shown in studies on maize conducted by Slafer and Savin [2018], who found that increasing nitrogen levels led to elevated chlorophyll content in maize leaves under high-temperature stress, resulting in an increased photosynthesis rate.

Under high-temperature stress, the production of ROS poses a threat to plant growth. Studies indicate that molybdenum enhances the activity of antioxidant enzymes, reducing ROS production and oxidative damage [Imran et al. 2019]. In line with this, the current study shows that ammonium molybdate application in melon leaves under high-temperature stress increased SOD, POD, and CAT activity while decreasing MDA and H_2O_2 content, thereby fortifying ROS removal and safeguarding the plant's biofilm system, also noted by Liu et al. [2023]. Moreover, high-temperature stress often disrupts carbohydrate metabolism, in which it plays an important role in maintaining the normal physiological activities of plants [Hawrylak-Nowak et al., 2018]. In the current study, ammonium molybdate treatment led to increased sucrose and soluble sugar content, coupled with reduced starch accumulation in melon leaves, aiding in osmotic regulation and impeding the destruction of photosynthetic cell structures. Additionally, ammonium molybdate treatment in the current study notably enhanced sucrose synthase and sucrose phosphate synthetase activity while reducing acid invertase activity, improving carbohydrate metabolism levels and stress resistance, especially in plants treated with 0.1 mg·L^{-1} ammonium molybdate.

Vitamin C, soluble sugar, and soluble solid content serve as pivotal indicators of plant quality, with research indicating the impact of molybdenum spraying on plant quality. In a study by Marasek-Ciolakowska et al. [2019], exogenous molybdenum spray resulted in a significant increase in fruit vitamin C, soluble protein, and solid soluble content, while titratable acid and nitrate content also experienced notable changes. Adhikary et al. [2010] found that the application of molybdenum fertilizer can effectively mitigate the hindrance of waterlogging stress on corn growth, promoting corn dry matter accumulation and enhancing its overall quality. In the current study, the application of ammonium molybdate solution led to an increase in vitamin C content, soluble protein, and soluble solids in melon fruit under high-temperature stress. The T2 treatment exhibited the highest levels, underscoring the vital role of ammonium molybdate employment in regulating the improvement of melon fruit quality.

The application of molybdenum can improve fruit quality by enhancing nutritional content and overall yield. For example, in potatoes, molybdenum has been shown to increase leaf area and photosynthetic efficiency, leading to higher yields and better-quality seeds. Molybdenum interacts with other nutrients, such as phosphorus and nitrogen, enhancing their uptake and utilization [Al-juthery and Al-Maamouri 2020]. This synergistic effect can further improve plant growth and fruit quality. High-temperature stress poses a significant abiotic challenge to melon fruit production. The fruit shape index, determined by the ratio of melon fruit's transverse and longitudinal diameter, is a crucial metric. Jiang et al. [2020] demonstrated that the application of exogenous melatonin substantially increased tomato fruit yield under drought stress. In the current experiment, the injection of ammonium molybdate significantly boosted both the single fruit weight and overall yield per plant of melon fruit under high-temperature stress, reaching its peak in the melon plant planted using 0.1 mg·L^{-1} ammonium molybdate treatment. However, there was no significant difference in the fruit shape index among the treatments, indicating that ammonium molybdate injection did not notably impact the fruit shape index of melon fruit. This underscores that the spray concentration of ammonium molybdate solution effectively mitigates the inhibitory effects of high-temperature stress on melon growth and enhances melon yield.

CONCLUSION

Molybdenum, recognized as an essential trace element for plants, holds a pivotal role in the facilitation of plant growth and improving a plant's stress resistance. The findings of the study indicated that melons sprayed with 0.1 mg·L^{-1} ammonium molybdate exhibited enhanced physiological characteristics, demonstrating a more substantial improvement in net photosynthetic rate (*P*n), transpiration rate (*T*r), and total chlorophyll under high-temperature stress. Furthermore, this treatment significantly promotes the carbohydrate metabolism in melon plant leaves under high-temperature stress, enhancing their antioxidant enzyme activity. It also results in significantly higher levels of vitamin C, soluble proteins, and soluble solids in fruits compared to other treatments. In summary, spraying 0.1 mg·L^{-1} ammonium molybdate effectively alleviates damage caused by high-temperature stress during melon cultivation, leading to enhanced quality and yield of melon fruits. For future research endeavors, attention should be directed towards a deeper understanding of the mechanisms underlying molybdenum absorption and assimilation in plant organisms, along with the signal transduction processes regulated by molybdenum-containing enzymes. A priority lies in the cloning and identification of new molybdenum transport protein genes within plants and their correlation with plant stress resistance. Furthermore, exploring both common and distinctive mechanisms through which molybdenum regulates plant stress resistance will be of paramount importance.

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