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Yttrium nitrate improves the longevity of campanula cut flowers through strengthening the enzymatic antioxidant system and maintaining water balance

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Abstract: We explored the role of yttrium nitrate ($Y(NO_3)_3$) in extending the longevity of campanula cut flowers. The results showed that $Y(NO_3)_3$ significantly enhanced the enzymatic antioxidant system, including the superoxide dismutase, peroxidase, ascorbate peroxidase, dehydroascorbate reductase, monodehydroascorbate reductase, glutathione reductase, glutathione peroxidase, and glutathione S-transferase. In this way, $Y(NO_3)_3$ increased the DPPH scavenging activity and decreased the malondialdehyde content and electrolyte leakage, which implied that $Y(NO_3)_3$ strengthened the antioxidant capacity. Meanwhile, $Y(NO_3)_3$ significantly improved the production of the soluble sugars, proline, and soluble protein, relative water content, average fresh weight change rate, and average water balance value, which indicated that $Y(NO_3)_3$ could maintain the water balance. Besides, $Y(NO_3)_3$ dramatically increased the flower diameter and extended the longevity. Our current research demonstrated that $Y(NO_3)_3$ improved the longevity by reinforcing the enzymatic antioxidant system and water balance, which added new information and a supportive base for the utilisation of $Y(NO_3)_3$ in the preservation of campanula cut flowers.

Keywords: *Eustoma grandiflorum*; rare-earth element; vase life; enzymatic activity; osmolytes

Campanula (*Eustoma grandiflorum*) is an herbaceous plant belonging to the Gentianaceae family, typically reaching 1 to 2 years of age. It is commonly utilised as a cut flower material in our daily lives. However, the longevity of this kind of cut flower is short, which seriously restricts its market value. Therefore, it is important to explore the corresponding measures to extend the longevity of campanula cut flowers. Some researchers have found that exogenous chemicals could extend the longevity of campanula cut flowers (Bahrami et al. 2013; Fatima et al. 2022; Lu et al. 2022). Bahrami et al. (2013) showed that salicylic acid (SA) could improve the longevity of campanula cut flowers by improving the antioxidant capacity and maintaining the water balance of the petals. Lu et al. (2022) demonstrated that sodium selenite also could prolong the longevity of campanula cut flowers through the same ways. Accordingly, it will be a useful measure to utilise corresponding exogenous chemicals to extend the longevity of campanula cut flowers by improving the antioxidant capacity and maintaining the water balance.

Rare earth elements (REEs) are a kind of resource with an important use. More and more studies have shown that REEs could increase the chlorophyll content and enhance the photosynthesis, promote root development and seed germination, improve seedling growth, and enhance the stress tolerance (Dai, Shan 2019; Jahani et al. 2019; Gelioli Salgado et al. 2020; Lu et al. 2020; Luo et al. 2021; Zhu et al. 2021; Iguchi et al. 2023; Jiao et al. 2023; Li et al. 2023).

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For cut flowers, an increasing number of research studies have documented that REEs lanthanum (La), cerium (Ce), neodymium (Nd), and praseodymium (Pr) showed important roles in extending the longevity of cut flowers through strengthening the antioxidant capacity and maintaining the water balance, including that for lilies (Lilium), carnations (Dianthus), and streliteelas (Strelitzia), etc. (Shan, Zhao 2015; Zheng, Guo 2018, 2019; Azarhoosh et al. 2021; Zhang et al. 2023). Yttrium (Y) is another important REE. Wu et al. (2016) reported that Y showed beneficial effects in regulating the growth and physiological characteristics of *Microcystis aeruginosa* through enhancing the antioxidant capacity. Lyu et al. (2019) revealed that Y also enhanced the nickel tolerance of *Potamogeton crispus* by strengthening the antioxidant capacity. However, the effect of Y on the enzymatic antioxidant system and water balance of campanula cut flowers has still not been reported. Hereby, it will be meaningful to investigate this part of work, which can add new information for the utilisation of these kind of REEs in the campanula cut flower industry.

Increasing research studies have revealed that there are close relationships between the cut flowers' longevity and the enzymatic antioxidant system (Hou et al. 2018; Zhou 2023). Previous research manifested that REEs improved the longevity of cut flowers by reinforcing the enzymatic antioxidant system via the corresponding antioxidases (Zheng, Guo 2018, 2019; Azarhoosh et al. 2021; Zhang et al. 2023). Previous research revealed that La enhanced the ascorbate peroxidase (APX), peroxidase (POD), and glutathione reductase (GR) activities in cut lilies (Shan, Zhao 2015), and Nd enhanced the APX, superoxide dismutase (SOD), catalase (CAT), POD, GR, and glutathione peroxidase (GPX) activities in cut lilies (Zheng, Guo 2019). Azarhoosh et al. (2021) showed that Ce reinforced the enzymatic antioxidant system of cut streliteelas via the corresponding antioxidases. Zhang et al. (2023) reported that Pr improved the POD, CAT, APX, GR, dehydroascorbate reductase (DHAR), and monodehydroascorbate reductase (MDHAR) activities in cut lilies. However, whether the REE Y could enhance the enzymatic antioxidant system of campanula cut flowers is still unclear.

Meanwhile, many researchers have also revealed that there is close relationship between the water balance and the osmolyte contents, mainly including soluble sugars (SSs), proline (PRO), and soluble proteins (SPs) (Zheng, Guo 2019; Gómez-Merino et al. 2020a; Zhou 2023). Hou et al. (2018) revealed that Ce maintained the water balance through increasing the SS and SP contents in the petals of cut lilies. Zheng, Guo (2019) found that Nd increased the SS, PRO, and SP contents in the petals of cut lilies, thereby reinforcing the water balance and improving the longevity. Gómez-Merino et al. (2020a) uncovered that La promoted water uptake through increasing the SS and SP contents in the petals of tulip (Tulipa) cut flowers. Zhang et al. (2023) found that Pr also promoted water uptake by increasing the SS and PRO contents in the petals of cut lilies. However, whether the REE Y could enhance the water balance of campanula cut flowers is still unclear.

The ornamental value of cut flowers had a close relationship with the flower diameter and the longevity (Lu et al. 2022; Zhou 2023). For campanula cut flowers, Lu et al. (2022) showed that sodium selenite could increase the flower diameter, which further improved the ornamental value. Whereas, whether the REE Y affects the flower diameter of this kind of cut flower is still unknown. Moreover, increasing research has shown that the REEs La, Ce, Pr, and Nd all extended the corresponding cut flowers' longevity (Shan, Zhao 2015; Wang et al. 2017; Zheng, Guo 2019; Zhang et al. 2023). Whereas, it is still unclear if Y has an effect on the longevity of campanula cut flowers. For this research, we hypothesised that Y could extend the longevity of campanula cut flowers through reinforcing the enzymatic antioxidant system and maintaining the water balance. In order to verify the correctness of this hypothesis, we studied the roles of yttrium nitrate ($Y(NO_3)_3$) in modulating the longevity, the activities of the corresponding antioxidases, the contents of the common osmoregulatory substances SP, SS and PRO, the 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity, malondialdehyde (MDA) content, electrolyte leakage (EL), relative water content (RWC), average fresh weight change rate (AFWCR), average water balance value (AWBV), and flower diameter. Therefore, our purpose was to clarify the physiological mechanism of $Y(NO_3)_3$ in extending the longevity of campanula cut flowers.

MATERIAL AND METHODS

Plant materials and treatments. Campanula cut flowers of the Rosita variety with a green colour at the tight bud stage were purchased from a fresh cut flower producer in Yuxi city, Yunnan Province. During the cultivation process of the flowers, normal water

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and fertiliser management treatments were carried out without any special treatment. The producer harvested the cut flowers 1 day previously and only transported and stored them in distilled water and did not apply any post-harvest treatment. Cut flowers with five buds of a similar size were selected for the current study. To avoid an air embolism, we used the underwater cutting method to cut all the stems. Namely, we immersed all the stems of the cut flowers in distilled water and then cut them into 30 cm in length. After cutting, all the stems were still immersed in distilled water for 20 minutes to ensure that all the stems absorbed a sufficient amount of water, which can further avoid an air embolism. Then, the cut flowers were immediately treated by immersing the base of the stems in 500 mL of distilled water (Control), 1.0, 3.0, and 9.0 mg/L $Y(NO_3)_3$. All the cut flowers treated as above were then placed into a climatic chamber under the following conditions: 28 °C/15 °C (day/night), 60% relative humidity, 300 μmol/m^2/s light intensity, and a 12 hours photoperiod. All the treatments were repeated four times. For each time period, two cut flowers with five buds were used as the material. To supply the consumed solutions, we added different treatment solutions to 500 mL each day. The petals of the first open flowers were sampled and taken to determine the corresponding indices after 4 days of treatment. The cut flowers lost their ornamental value when 80% of the cut flowers withered, and then we recorded their longevity.

Enzymatic activities of the antioxidases. After 4 days of treatment, the activities of the antioxidases were analysed by the method of Lu et al. (2020), including the SOD, POD, CAT, APX, DHAR, MDHAR, and GR. The enzymatic activities of GPX and glutathione S-transferase (GST) were analysed according to the instruction manual of the GPX and GST detection kits (Solarbio Technology Co., Ltd., Beijing, China). The GPX and GST activity were assayed spectrophotometrically at 348 nm and 340 nm, respectively. For each treatment, four repetitions were conducted for the above enzymatic antioxidants.

DPPH scavenging activity. The total antioxidant activity was determined by using 2,2-diphenyl-1-picrylhydrazyl (DPPH) as a free radical (Kalisz et al. 2020).

Malondialdehyde content (MDA) and electrolyte leakage (EL). After 4 days of treatment, the MDA content was tested according to Hodges et al. (1999). The EL was tested according to Zhao et al. (2004). For each treatment, four repetitions were conducted for the MDA and EL.

Osmolyte contents. After 4 days of treatment, the SP content was estimated by using the Bradford method (Bradford 1976). The SS content was tested according to Wei (2009) by using the anthrone-sulfuric acid method. The PRO content was tested by using the acidic-ninhydrin method (Bates et al. 1973). For each treatment, four repetitions were conducted for the above three osmolytes.

Relative water content (RWC). After 4 days of treatment, the RWC was determined following the equation below. For each treatment, four repetitions were conducted.

RWC = [(fresh weight (FW) – dry weight (DW)) / (saturated weight (SW) – DW)] × 100%.

Longevity. For each treatment, the longevity was determined from the time when the cut flowers were placed in the flasks to the time when the petals of 80% of the cut flowers withered.

Flower diameter. The flower diameter was measured by digital callipers every 2 days. For each treatment, the east-west and north-south distances between the outermost petals of the first open flower were measured and the average value was taken as the flower diameter.

Average fresh weight change rate (AFWCR) and average water balance value (AWBV). The total weight of the cut flower, treatment solution and flask (TW_1) and the total weight of the treatment solution and flask (TW_2) were recorded every other day by using an electronic balance. The difference between them was the FW of the cut flowers. The FWCR was calculated following the equation below. FWCR = (FW – initial fresh weight (FWi)) ÷ FWi × 100%. From 0 to 10 days of treatment, the AFWCR was the mean value of the FWCR.

Meanwhile, the water loss (WL) and water absorption (WA) were determined every other day. The WL was expressed as the difference of TW_1 in two adjacent days. The WA was expressed as the difference of TW_2 in two adjacent days. The WBV was the difference between the WA and WL. From 0 to 10 days of treatment, the AWBV was the mean value of the WBV.

Statistical analysis. The data were the mean of four replicates. All the data are collected with Microsoft Excel software version 2007. SPSS Statistics 25.0 was used to compare all the data by a one-way analysis of variance (ANOVA) and Duncan's test at a 0.05 level of significance.

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RESULTS

Effects of yttrium nitrate (Y) on the the 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity and the activities of the antioxidases. Compared to the control group, $Y(NO_3)_3$ significantly enhanced the DPPH scavenging activity and the enzymatic activities of POD, SOD, GPX, and GST in the petals (Figure 1). Among three concentrations, 3.0 mg/L $Y(NO_3)_3$ had a more positive influence on these indicators. In comparison with the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$ increased the POD activity by 16.16, 53.49, and 34.69%, respectively. At concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, the SOD activity increased by 18.35, 50.26, and 27.34%, respectively. The GPX activity also showed significant enhancements of 33.33, 93.33, and 53.33% at concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, respectively. Additionally, the GST activity increased by 20.00, 113.33, and 66.66% at concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, respectively. Meanwhile, 1.0, 3.0, and 9.0 mg/L $Y(NO_3)_3$ increased the DPPH scavenging activity by 41.79, 108.46, and 73.01%, respectively. These results clearly demonstrate that a suitable concentration of $Y(NO_3)_3$ could effectively enhance the antioxidant capacity by reinforcing the above antioxidases.

Effects of yttrium nitrate (Y) on the ascorbate peroxidase (APX), dehydroascorbate reductase (DHAR), monodehydroascorbate reductase (MDHAR), and glutathione reductase (GR) activities. Compared to the control, $Y(NO_3)_3$ dramatically increased the enzymatic activities of APX, GR, DHAR, and MDHAR (Figure 2). When compared to the other concentrations, 3.0 mg/L of $Y(NO_3)_3$ had a more positive influence on the above antioxidases. In comparison with the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$ enhanced the APX activity by 23.15, 66.31, and 43.15%, respectively. At concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, the GR activity increased by 19.04, 66.66, and 30.95%, respectively. The DHAR activity also showed significant enhancements of 33.33, 110.00, and 60.00% at concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, respectively. Additionally, the MDHAR activity increased by 29.41, 76.47, and 17.64% at concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, respectively. The above results demonstrated that a suitable concentration of $Y(NO_3)_3$ could also effectively enhance the antioxidant capacity by reinforcing the activities of the antioxidases in the ascorbate-glutathione cycle.

Effects of yttrium nitrate (Y) on the malondialdehyde (MDA) content and electrolyte leakage (EL). Compared with the control group, $Y(NO_3)_3$ dramatically reduced the MDA content and EL (Figure 3). Among the three concentrations, 3.0 mg/L of $Y(NO_3)_3$ also had a more positive influence on the lipid peroxidation by lowering the MDA content and EL. In comparison with the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$ decreased the MDA content by 18.57, 42.85, and 28.57%, respectively. At concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, the EL decreased by 18.61, 46.80, and 30.85%, respectively. These results clearly demonstrated that a suitable concentration of $Y(NO_3)_3$ could effectively reduce the level of lipid peroxidation in the petals.

Effects of yttrium nitrate (Y) on the osmolytes and relative water content (RWC). Compared to the control, $Y(NO_3)_3$ dramatically increased the levels of osmolytes, SS and PRO, thereby improving the RWC. (Figure 4). Among the three concentrations, 3.0 mg/L of $Y(NO_3)_3$ had a more positive influence on the osmolyte levels and RWC. In comparison with the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$ improved the SS content by 21.50, 66.00, and 43.30%, respectively. At concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, the PRO content improved by 25.00, 102.77, and 52.77%, respectively. The RWC increased by 6.17, 14.81, and 9.87% at concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, respectively. These results clearly showed that a suitable concentration of $Y(NO_3)_3$ could effectively improve the RWC by enhancing the accumulation of the osmolytes, SS and PRO, in the petals.

Effects of yttrium nitrate (Y) on the average fresh weight change rate (AFWCR) and average water balance value (AWBV). Compared to the control group, $Y(NO_3)_3$ markedly increased the AFWCR and AWBV (Figure 5). Among the three concentrations, 3.0 mg/L of $Y(NO_3)_3$ showed a more positive influence on the AFWCR and AWBV. In comparison with the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$ improved the AFWCR by 27.77, 71.11, and 44.44%, respectively. At concentrations of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, the AWBV improved by 23.07, 58.97, and 38.46%, respectively. The above results further indicated that a suitable concentration of $Y(NO_3)_3$ could effectively maintain the water balance of campanula cut flowers.

Effects of Y on the flower diameter and longevity. Compared to the control group, all the concentrations

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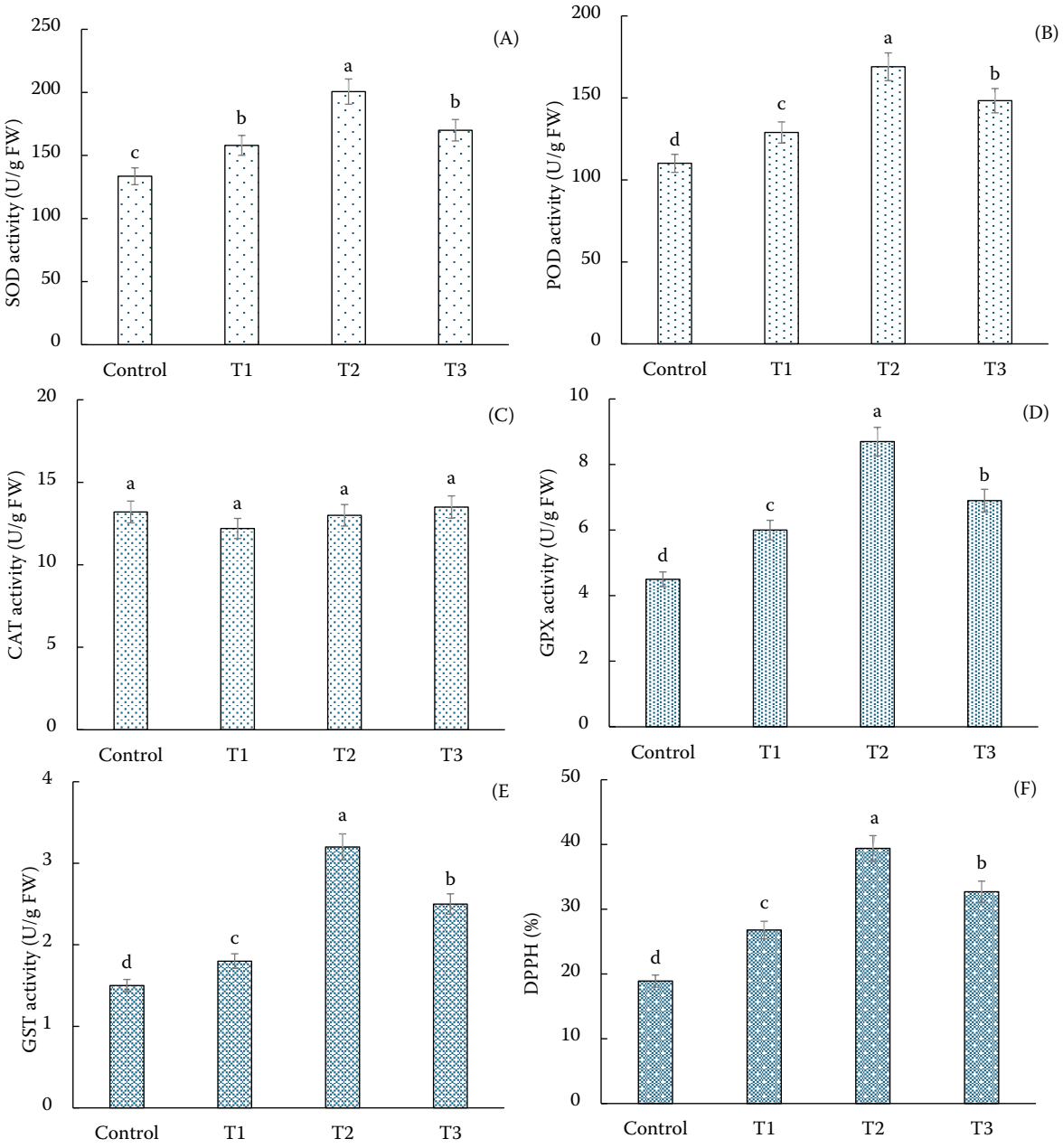

Figure 1. Effects of Y on the DPPH scavenging activity and enzymatic activities of superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione peroxidase (GPX), and glutathione S-transferase (GST) based on the fresh weight (FW). The cut flowers were treated as: Control, distilled water; T1, 1.0 mg/L of $Y(NO_3)_3$; T2, 3.0 mg/L of $Y(NO_3)_3$; T3, 9.0 mg/L of $Y(NO_3)_3$

The values represent the mean ± standard deviations (SD) (n = 4); different letters indicate a statistical difference at $P < 0.05$

of $Y(NO_3)_3$ dramatically increased the flower diameter and longevity (Figures 6 and 7). For all the treatments, the flower diameter gradually increased from 0 to 6 days of treatment and reached a maximum value at 6 days of treatment. After 6 days of treatment, the flower diameter of all the cut flowers gradually decreased. The maximum values of the flower diameter were 50.22, 57.00, 66.77, and 59.42 mm under the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, respectively. The applications of 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$ all dramatically increased the flower diameter than the control group. Meanwhile, the longevity was 9.0, 10.2, 13.0, and 11.5 d under the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$, respectively. When compared to the control, 1.0, 3.0, and 9.0 mg/L of $Y(NO_3)_3$ extended the longevity by 13.33, 44.44,

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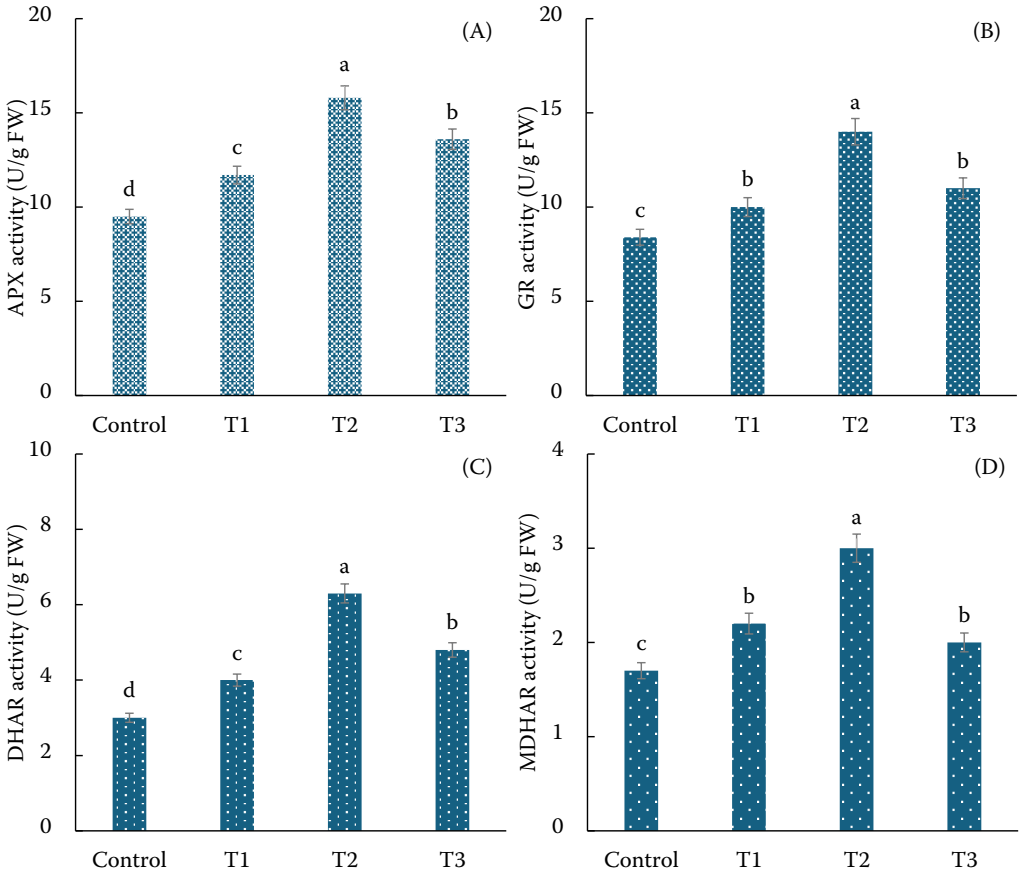

Figure 2. Effects of Y on the enzymatic activities of ascorbate peroxidase (APX), glutathione reductase (GR), dehydroascorbate reductase (DHAR), and monodehydroascorbate reductase (MDHAR) based on the fresh weight (FW). The cut flowers were treated as: Control, distilled water; T1, 1.0 mg/L of $Y(NO_3)_3$; T2, 3.0 mg/L of $Y(NO_3)_3$; T3, 9.0 mg/L of $Y(NO_3)_3$

The values represent the mean ± standard deviations (SD) (n = 4); different letters indicate a statistical difference at $P < 0.05$

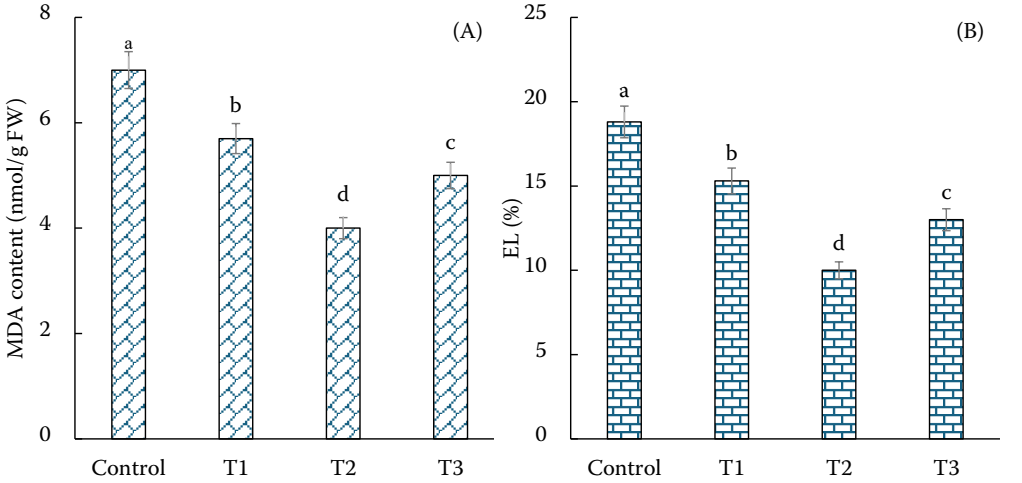

Figure 3. Effects of Y on the malondialdehyde (MDA) content and electrolyte leakage (EL). The MDA content was calculated based on the fresh weight (FW). The cut flowers were treated as: Control, distilled water; T1, 1.0 mg/L of $Y(NO_3)_3$; T2, 3.0 mg/L of $Y(NO_3)_3$; T3, 9.0 mg/L of $Y(NO_3)_3$

The values represent the mean ± standard deviations (SD) (n = 4); different letters indicate a statistical difference at $P < 0.05$

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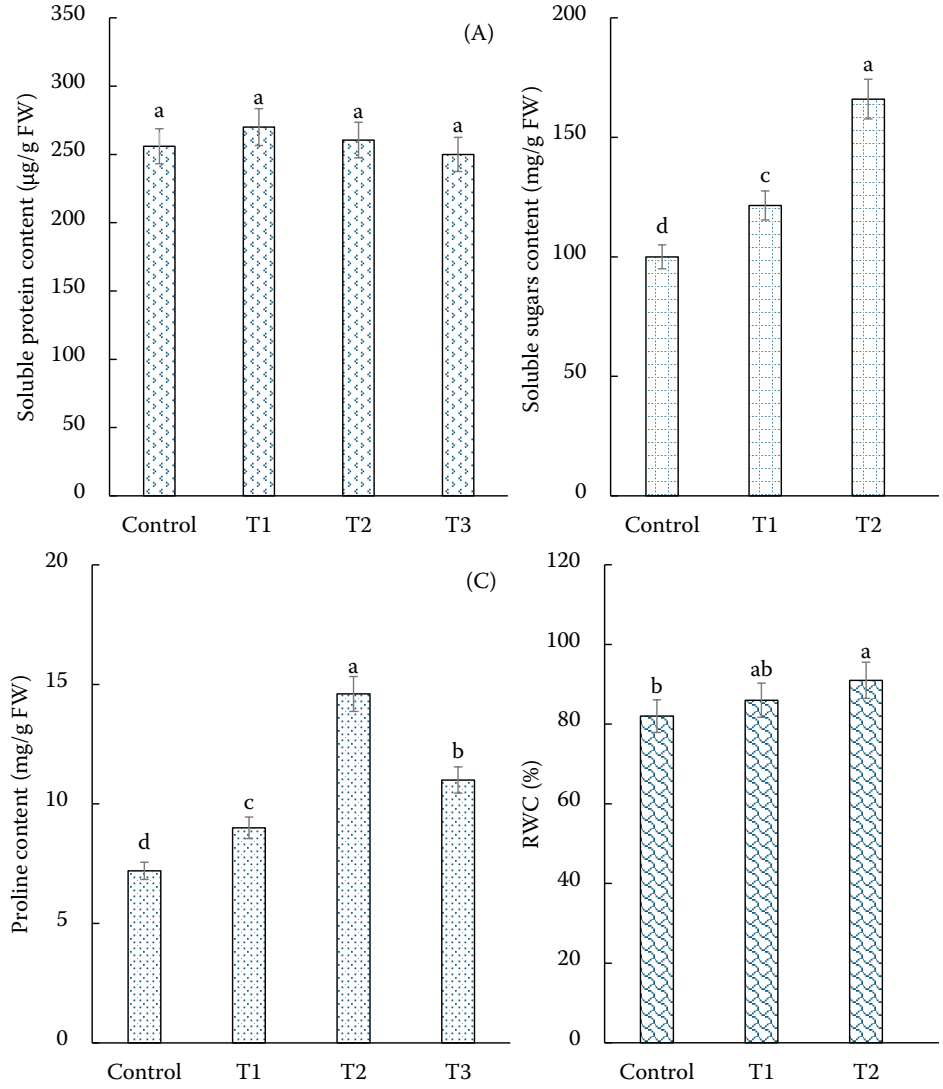

Figure 4. Effects of Y on the relative water content (RWC) and osmolyte contents. The osmolyte contents were all calculated based on the fresh weight (FW). The cut flowers were treated as: Control, distilled water; T1, 1.0 mg/L of $Y(NO_3)_3$; T2, 3.0 mg/L of $Y(NO_3)_3$; T3, 9.0 mg/L of $Y(NO_3)_3$

The values represent the mean ± standard deviations (SD) (n = 4); different letters indicate a statistical difference at $P < 0.05$

and 27.77%, respectively. Among the three concentrations, 3.0 mg/L $Y(NO_3)_3$ had a more positive influence on the above two indices. These results suggested that a suitable concentration of $Y(NO_3)_3$ could effectively improve the flower diameter and longevity of campanula cut flowers.

DISCUSSION

MDA and EL are two meaningful indices to judge the level of the membrane lipid peroxidation of plants (Lu et al. 2020). During the ageing process of cut flowers, the level of the membrane lipid peroxidation of petals is an important factor affecting the longevity. Researchers have demonstrated that the REEs La, Ce, Pr, and Nd all could mitigate the membrane lipid peroxidation of cut lilies, roses (Rosa), and carnations, which further prolonged their longevity (Shan, Zhao 2015; Wang et al. 2017; Zheng, Guo 2018, 2019; Zhang et al. 2023). The current research indicated that $Y(NO_3)_3$ also mitigated the membrane lipid peroxidation of campanula cut flowers by decreasing the MDA content and EL, which agreed with previous results regarding other REEs (Shan, Zhao 2015; Azarhoosh et al. 2021; Zhang et al. 2023).

Previous reports indicated that La, Ce, Pr, and Nd alleviated the membrane lipid peroxidation of cut lil-

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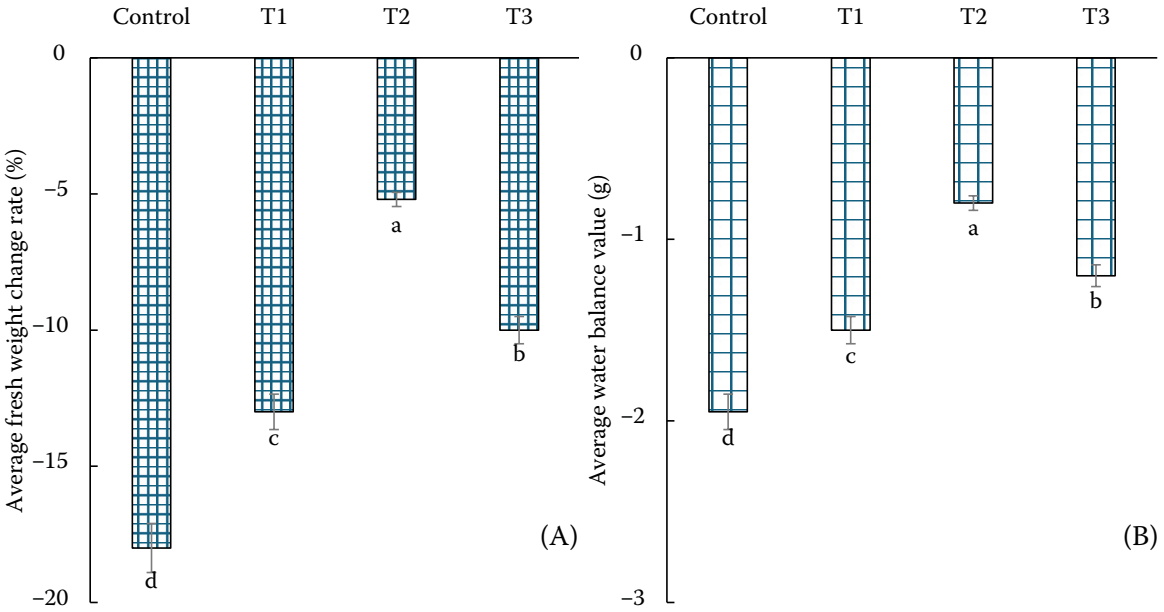

Figure 5. Effects of Y on the average fresh weight change rate and average water balance value. The cut flowers were treated as: Control, distilled water; T1, 1.0 mg/L of $Y(NO_3)_3$; T2, 3.0 mg/L of $Y(NO_3)_3$; T3, 9.0 mg/L of $Y(NO_3)_3$
The values represent the mean ± standard deviations (SD) (n = 4); different letters indicate a statistical difference at $P < 0.05$.

ies, roses, and carnations by enhancing the enzymatic activities of the antioxidases in the petals (Shan, Zhao 2015; Wang et al. 2017; Zheng, Guo 2018, 2019; Zhang et al. 2023). For cut lilies, Shan, Zhao (2015) revealed that La enhanced the POD, APX, GPX, and GR activities. Another study showed that Nd also strengthened the SOD, POD, CAT, GPX, APX, and GR activities (Zheng, Guo 2019). Zhang et al. (2023) found that Pr improved the POD, CAT, APX, GR, DHAR, and MDHAR activities. For cut roses, Wang et al. (2017) uncovered that Ce strengthened the SOD, POD, CAT, GPX, GST, APX, and GR activities. This research showed that Y strengthened the POD, SOD, GPX, APX, GR, DHAR, and MDHAR activities, which agreed with previous results regarding other REEs. However, the current results revealed that Y showed no obvious influence on the CAT activity, which was not in agreement with the effect of Ce on cut roses (Wang et al. 2017) and Nd and Pr on cut lilies (Zheng, Guo 2019; Zhang et al. 2023). This difference is perhaps owing to the difference in REEs and/or the species of the cut flowers. As is well known, the above antioxidases form the enzymatic antioxidant system and play a part in the first line of the defence against membrane peroxidation induced by the over-production of active oxygen spe-

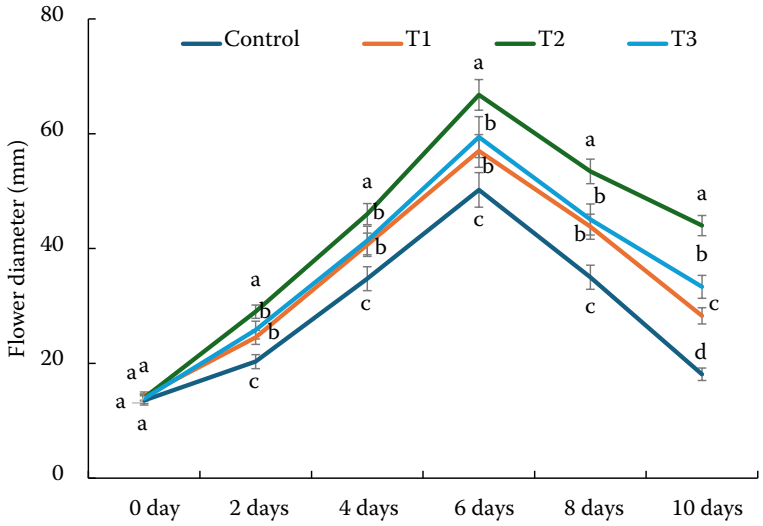

Figure 6. Effects of Y on the changes in the flower diameter. The cut flowers were treated as: Control, distilled water; T1, 1.0 mg/L of $Y(NO_3)_3$; T2, 3.0 mg/L of $Y(NO_3)_3$; T3, 9.0 mg/L of $Y(NO_3)_3$
The values represent the mean ± standard deviations (SD) (n = 4); different letters indicate a statistical difference at $P < 0.05$

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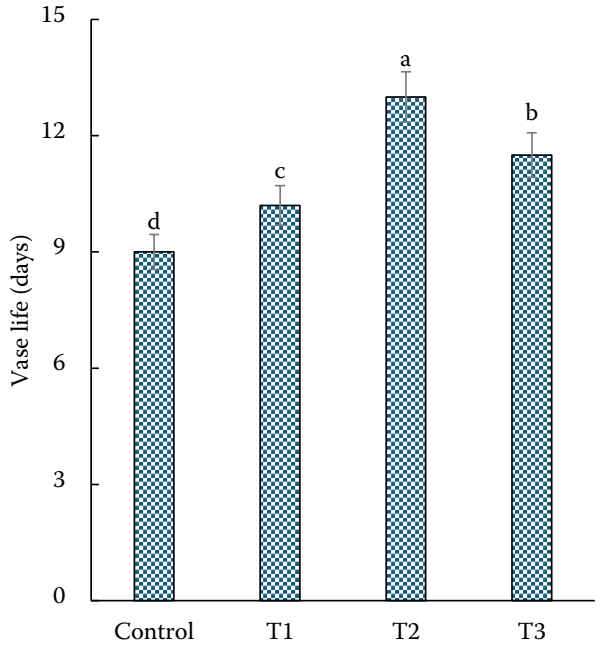

Figure 7. Effects of Y on the longevity. The cut flowers were treated as: Control, distilled water; T1, 1.0 mg/L of $Y(NO_3)_3$; T2, 3.0 mg/L of $Y(NO_3)_3$; T3, 9.0 mg/L of $Y(NO_3)_3$

The values represent the mean ± standard deviations (SD) (n = 4); different letters indicate a statistical difference at $P < 0.05$

cies. Through this system, plants can control the level of the membrane lipid peroxidation. Meanwhile, we also found that $Y(NO_3)_3$ could improve the DPPH scavenging activity of campanula cut flowers. Therefore, our findings clearly demonstrated that $Y(NO_3)_3$ reduced the membrane lipid peroxidation of the petals through the whole enzymatic antioxidant system.

Osmolytes play vital roles in preserving the water balance, such as SP, SS, and PRO (Lu et al. 2020; Gómez-Merino et al. 2020a, 2020b; Zhang et al. 2023). Shan, Zhao (2015) indicated that the REE La increased the SP, SS, and PRO contents, which further improved the RWC and extended the longevity of cut lilies. Zheng, Guo (2019) showed that Nd increased the above three osmolyte contents, which further improved the RWC and extended the longevity of cut lilies. Gómez-Merino et al. (2020a) demonstrated that La improved the SS and SP contents in cut tulips. Zhang et al. (2023) reported that Pr increased the PRO and SS contents, which further maintained the water balance and improved the longevity of cut lilies. For this research, we found that Y increased the SS and PRO contents, thereby improving the RWC and prolonging the longevity of campanula cut flowers. Accordingly, Y showed the same influence as the REEs La, Pr, and Nd on the SS and PRO contents in cut flowers. However, we found that Y showed no significant effect on the SP content. This difference was also probably due to the difference in the REEs and/or the species of cut flowers. Moreover, we uncovered that Y dramatically improved the AFWCR and AWBV, which implied that Y had a meaningful role in preserving the water balance of campanula cut flowers.

The flower diameter is used as a common index to evaluate the ornamental value. The REE La increased the bud length and diameter of cut tulips (Gómez-Merino et al. 2020b). While, the influence of Y on the opening degree of cut flowers is still unclear. For the current research, we revealed that Y dramatically improved the opening degree of *E. grandiflorum* cut flowers by increasing the flower diameter. In addition, Y dramatically increased the flower diameter at 6 days of treatment. Meanwhile, we found that Y prolonged the longevity of campanula cut flowers. These results also showed that Y improved the ornamental value of campanula cut flowers.

In the current research, we revealed that different Y concentrations had different influences on the antioxidase activities, DPPH scavenging activity, osmolyte contents, RWC, AFWCR, AWBV, flower opening degree, and longevity. Among the three concentrations, 3.0 mg/L of $Y(NO_3)_3$ had a more positive influence on the above indices. High or low concentrations of Y were not beneficial to the extension of the longevity of campanula cut flowers. Similar phenomena also existed in other research studies regarding the influence of other REEs on the longevity of cut flowers, such as La, Ce, Pr, and Nd (Shan, Zhao 2015; Wang et al. 2017; Lu et al. 2020; Zhang et al. 2023). Our study and other research studies all implied that we should select a suitable concentration of REEs to apply in the fresh-keeping of cut flowers.

Phytohormones showed important an influence on the longevity of cut flowers, especially for ethylene (ETH) (Ji et al. 2023; Xu et al. 2023). Wongjunta et al. (2021) found that ETH participated in the post-harvest aging process of *Mokara* orchid cut flowers. Meanwhile, Darvish et al. (2021) demonstrated that exogenous substance 24-epibrassinolide could prolong the longevity of campanula cut flowers by decreasing the ACC oxidase (ACO) activity, a key enzyme for the ETH biosynthesis. The results of Darvish et al. (2021) implied that 24-epibrassinolide could extend the longevity

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of campanula cut flowers by inhibiting the ETH biosynthesis. However, it is still unclear whether Y could modulate the ETH biosynthesis in modulating the longevity of campanula cut flowers. Hereby, it is meaningful to study the influence of Y on the key enzymes of ETH biosynthesis, including ACO and ACC synthase (ACS), which can add new information on the understanding of the regulatory mechanism of Y in modulating the longevity of campanula cut flowers.

CONCLUSIONS

To sum up, our findings obviously uncovered that Y could extend the longevity of campanula cut flowers by reinforcing the enzymatic antioxidant system and maintaining the water balance. Meanwhile, we also revealed that a suitable concentration of Y had a more positive influence on the longevity of campanula cut flowers. Thus, our study demonstrated that a suitable concentration of Y could be used as a regulator to prolong the longevity, which was an effective strategy to promote the post-harvest performance of campanula cut flowers.

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