

ARTICLE

Cerium (Ce) supply during the tulip production improves postharvest quality parameters

Oferta de cério (Ce) durante produção de tulipa melhora parâmetros de qualidade pós-colheita

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Abstract

Tulip (*Tulipa gesneriana* L.) is an ornamental species highly appreciated in international markets; however, it poses challenges at both the production and postharvest stages, which reduce the duration and quality of vase life. Inorganic biostimulation offers a viable alternative to face these constraints. This study aimed to evaluate the effect of Ce supplied in the irrigation nutrient solution during the production cycle on the postharvest quality and nutritional status of tulips cv. Jan van Nes. The Ce concentrations used were 0, 5, 15, and 25 μ M. For the evaluation of post-harvest quality, flower stems of tulips were used, harvested at 49 days after sowing (DAS). Plants treated with 25 μ M Ce exhibited significantly greater flower bud length throughout vase life, while the effect of 5 μ M Ce was significant only from day 2 onwards. Regarding flower bud diameter, only the 25 μ M Ce treatment outperformed the rest of the treatments evaluated, and this effect was observed exclusively on day 6 of vase life. In addition, they showed an increase in the contents of macronutrients, some micronutrients, and total soluble sugars in the flower. Although Ce did not increase vase life, and a dose of 25 μ M caused excessive stem elongation (an undesirable condition in postharvest), it did improve other quality indicators. Thus, Ce can be used as a novel inorganic biostimulant to improve postharvest quality in tulips.

Keywords: cut flowers, inorganic biostimulation, nutritional content, *Tulipa gesneriana*.

Resumo

A tulipa (*Tulipa gesneriana* L.) é uma espécie ornamental muito apreciada nos mercados internacionais, porém apresenta problemas tanto na produção quanto na pós-colheita, o que reduz a duração e a qualidade da vida de vaso. A bioestimulação inorgânica oferece uma alternativa viável para enfrentar essas restrições. O objetivo deste estudo foi avaliar o efeito do Ce fornecido na solução nutritiva de irrigação durante o ciclo de produção sobre a qualidade pós-colheita e o estado nutricional de tulipas cv. Jan van Nes. As concentrações de Ce utilizadas foram 0, 5, 15 e 25 μ M. Para a avaliação da qualidade pós-colheita, foram utilizadas hastes florais de tulipas, colhidas aos 49 dias após a semeadura (DAS). As plantas tratadas com 25 μ M de Ce apresentaram maior comprimento do botão floral durante todo o período de vida de vaso, enquanto o efeito de 5 μ M foi significativo apenas a partir do segundo dia. Em relação ao diâmetro do botão floral, somente o tratamento com 25 μ M foi superior ao controle, e esse efeito foi observado exclusivamente no sexto dia de vida de vaso. Além disso, apresentaram aumento nos teores de macronutrientes, alguns micronutrientes e açúcares solúveis totais na flor. Embora Ce não tenha aumentado a vida do vaso, e uma dose de 25 μ M tenha causado alongamento excessivo do caule (uma condição indesejável na pós-colheita), ele melhorou outros indicadores de qualidade. Assim, Ce pode ser usado como um novo bioestimulante inorgânico para melhorar a qualidade pós-colheita em tulipas.

Palavras-chave: bioestimulação inorgânica, conteúdo nutricional, flores de corte, *Tulipa gesneriana*.

Introduction

Tulip (*Tulipa gesneriana* L.) is an ornamental bulbous plant belonging to the Liliaceae family. This species is an economically important ornamental geophyte, with high national and international demand. It is positioned as the third most popular cut flower after roses (*Rosa hybrida* L.) and chrysanthemums (*Chrysanthemum morifolium* Ramat.) (MDF, 2025). They are appreciated for their beauty, elegance, and showy colors. The Netherlands is the main producer, followed by Japan, France, and the United States (BKD, 2023). In Latin America, Colombia and Ecuador stand out as producers of this species (MDF, 2025).

Although tulip is one of the most studied species among cut flowers, it still presents problems both in the production process and in post-harvest, which reduce the duration and quality of vase life. These last two aspects are of great relevance in cut flowers, since their value depends primarily on the vase life and the qualities of the stem during this period (MDF, 2025).

In the production process, the most common challenges are associated with nutritional issues that detract from commercial quality (Inkham et al., 2023). Among the macronutrients, N deficiency may lead to less vigorous plants, small leaves, early senescence of the foliage, and late flowering; P deficiency causes reduced flower and stem growth (Verma and Singh, 2021; Biliás et al., 2023); while Ca deficiency causes stem bending (tulip topple), flower bud abortion, and reduced root length and

leaf area (Inkham et al., 2023). Regarding micronutrients, B, Cu, Fe, Mn and Zn have been determined in different tulip plant tissues, with B being critical at determining the quality of flowers (Biliás et al., 2023; Alkaç and Güneş, 2024).

In postharvest, the main limitation is early senescence of tepals, followed by tepal abscission and rapid yellowing of leaves (Verma and Singh, 2021), which may be prevented by lanthanum applications (Gómez-Merino et al., 2020a), another rare earth element with similar properties to Cerium (Ce). In many cultivars, the internode of the upper stem shows a high rate of elongation during vase life, causing undesirable bending of the stem (van Doorn et al., 2011). Likewise, water relations, presence of fungi and bacteria, carbohydrate supply, and the internal status of hormones determine the useful life of the flower (Costa et al., 2021). Therefore, it is necessary to search for effective and sustainable methods such as inorganic biostimulation to improve the production and postproduction quality of tulip crops.

Biostimulation is a recent technology that allows improving the physiology and metabolism of plants through the application of products such as humic substances, amino acids, algae extracts, biopolymers, inorganic compounds, and beneficial microorganisms. Biostimulants based on inorganic compounds include phosphite salts and beneficial elements (Trejo-Téllez and Gómez-Merino, 2023). Beneficial elements are not essential for the plant but have a use *in planta*, such as stimulating

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growth and promoting development under certain adverse conditions, improving crop quality, increasing vase life, participating in the synthesis of secondary metabolites and inducing resistance or tolerance mechanisms to cope with abiotic stress factors, among other benefits. Since beneficial elements usually induce hormetic dose-response curves, their range of beneficial effects is usually at low to medium concentrations (Trejo-Téllez et al., 2023).

Cerium (Ce) is a beneficial element that has shown stimulating effects on plants by promoting the induction of floral initiation and increasing the number of flowers produced per plant (Feng et al., 2023); moreover, it may be involved in the assimilation of N and C, in increasing the efficiency of photosystem II (Pietrzak et al., 2024), and activating the expression of key enzymes for chlorophyll biosynthesis (Agathokleous et al., 2022; Li et al., 2023). Hence, Ce may increase the activity of antioxidant enzymes and chlorophyll content, and decrease the number of wilted flowers (Subbaramamma and Bhaskar, 2023).

In tulip, Gómez-Navor et al. (2021) reported that cerium applied during the production cycle at low concentrations (5 μM) stimulated bulb sprouting, advanced floral bud formation, and promoted early flowering, while higher concentrations (25 μM) delayed these processes.

In addition to cerium, other lanthanide elements have also shown promising effects on tulip. Gómez-Merino et al. (2020a) reported that lanthanum delayed senescence and improved postharvest quality in cut tulip flowers by increasing bud size, stem fresh weight, and solution uptake. Similarly, Gómez-Merino et al. (2020b) demonstrated that La prolonged vase life in 15 tulip cultivars by enhancing water consumption and the concentrations of sugars, proteins, and chlorophylls. Together, these studies support the potential role of rare earth elements in improving the growth, quality, and postharvest performance of tulip.

In another species of the Liliaceae family, the lily (*Lilium longiflorum* Thunb.), praseodymium (Pr), another lanthanide element, stimulated the activity of antioxidant enzymes such as peroxidase (POD), catalase (CAT), and those of the ascorbate–glutathione cycle, in addition to increasing the fresh weight change rate, water balance value, and the contents of osmolytes such as soluble sugars and proline. At the same time, it reduced the levels of malondialdehyde (MDA) and hydrogen peroxide (H_2O_2), resulting in an extended vase life (Zhang et al., 2022). Thus, the objective of the present study was to evaluate the influence of Ce applied during the production cycle on the postharvest quality and nutritional status of tulips cv. Jan van Nes.

Materials and Methods

Flower stems of tulips (*Tulipa gesneriana* L.) cultivar Jan van Nes were used, harvested at the commercial bud stage, with the tips of the tepals still closed [49 days after sowing (DAS)]. This cultivar has an intense yellow color. The bulbs were planted in 6.6 cm pots with a substrate consisting of tezontle (particle size 3 mm), perlite (Agrolita®, Gómez Palacio, Durango, Mexico), and peat (Promix® FLX, Saint-Lambert, Quebec, Canada) in a ratio of 70:20:10 (v:v:v), on December 7, 2018 (during the fall-winter cycle 2018), in Texcoco, Mexico. Before planting, the bulbs were cleaned and disinfested by immersion in a solution composed of 2 g L^{-1} Ridomil Bravo SC [metalaxyl-M (3.3%) + chlorothalonil (33%)] + 1 g L^{-1} Captán® [N-trichloromethylthio-4-cyclohexene-1,2-dicarboximide (50%)] for 15 min.

The experiment was conducted under 50% shade mesh conditions, with an average daytime temperature of 21.6 °C and a nighttime temperature of 7.1 °C, average daytime and nighttime relative humidity of 31.7% and 70.5%, respectively, and with average light intensity values of 70 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

The Steiner nutrient solution was used at 50%, which contained the following concentrations of macronutrient salts in g L^{-1} : 0.5313 $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (Meyer®, Mexico), 0.2464 $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ (Meyer®),

0.0680 KH_2PO_4 (J.T. Baker®), 0.1516 KNO_3 (Meyer®), and 0.1306 K_2SO_4 (Meyer®). It was supplemented with the commercial mixture of micronutrients that provided the following in mg L^{-1} : Fe 4.99, Mn 2.33, Zn 0.47, B 0.43, Cu 0.19, and Mo 0.17. The pH of the nutrient solution was adjusted to 5.3.

A completely randomized experimental design was used, employing four treatments with nine replicates each. The treatments evaluated were different doses of Ce: 0, 5, 15, and 25 μM , supplied from $\text{CeCl}_3 \cdot 7\text{H}_2\text{O}$ (Molecular mass: 372.58 g mol^{-1} ; Sigma-Aldrich®; USA), which were added to the Steiner nutrient solution and supplied through a drip irrigation system. Irrigation was carried out four times a day, each event lasting one minute and supplying an average volume of 80 mL. The treatments started on the day of planting and continued throughout the productive cycle until harvest, 49 days after sowing (DAS). The experimental unit was a pot with one tulip plant.

The flower stems, at harvest (49 DAS), were transferred to the laboratory, labeled by treatment, and placed in glass vases containing 250 mL of distilled water, for the evaluation of quality and postharvest life.

The stem length was measured with a 1 m ruler. Flower bud diameter and length were determined with a digital vernier caliper (Truper; China). Both variables were assessed at harvest (day 0) and at 2, 4, 6, and 8 days of vase life.

Water uptake was assessed every 48 h throughout vase life. Fresh biomass of the flower stem was determined during vase life (days 0, 2, 4, 6, and 8) using an analytical scale (Ohaus Adventurer® Pro; USA).

Vase life was determined by counting the number of days elapsed from placing the flower stems in the glass until they lost their ornamental value (more than 80% wilting and loss of tepal color). At the end of this period, the dry biomass of each organ (stem, leaf, and flower) was determined, as well as the dry biomass of the flower stem, calculated as the sum of all organs. The samples were dried in an oven with forced air circulation (Riossa HCF-125D; Mexico) at a temperature of 72 °C for 72 h (Rueda-López et al., 2025).

In each organ, nutrient concentration analysis was performed at the end of vase life. For total nitrogen, the semi-micro-Kjeldahl method was used with sulfuric-salicylic acid for digestion. For the determination of P, K, Ca, Mg, S, Fe, Cu, Zn, Mn, and B, a wet digestion was carried out with HNO_3 and HClO_4 . The extracts obtained after digestion were read in the inductively coupled plasma optical emission spectroscopy equipment (ICP-OES 725 Series, Agilent; USA). With the dry biomass data of each organ, the contents of the different nutrients were estimated.

The total soluble sugar content was measured at the end of vase life by the anthrone method, using sulfuric acid and 80% alcohol. We took 1000 mg of leaf or 250 mg of flower previously ground with liquid nitrogen to perform this assay. Glucose (Sigma-Aldrich®) was used to prepare the standard calibration curve. Absorbance was determined at a wavelength of 600 nm in a spectrophotometer (Jenway 6715 UV/Vis; UK).

With the data obtained, analysis of variance and mean comparison tests (Tukey, $p \leq 0.05$) were performed, using the SAS® software.

Results

Stem length

During vase life, flower stem length increased with the 15 and 25 μM Ce treatments. At this latter dose, stem length was 14.6%, 13.6%, 13.8%, and 14% longer on days 2, 4, 6, and 8 of vase life, respectively, compared to the control (Table 1).

Flower bud length and diameter

Flower bud length and diameter increased over time in all treatments; however, a slight decrease in these values was observed as senescence approached. No data were recorded on day 8 due to tepal abscission (Tables 2 and 3).

Table 1. Flower stem length (cm) of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes during vase life from plants treated with cerium (Ce) in the nutrient solution during the production cycle.

Ce (μM)	Days of vase life				
	0	2	4	6	8
0	26.40 ± 2.93 a	36.22 ± 3.08 b	39.38 ± 3.70 b	40.32 ± 3.33 b	41.00 ± 3.27 b
5	25.38 ± 2.57 a	38.02 ± 3.85 ab	41.36 ± 3.52 ab	43.42 ± 3.43 ab	43.60 ± 3.46 ab
15	27.86 ± 2.13 a	39.98 ± 2.06 a	43.00 ± 1.94 ab	45.16 ± 1.92 a	45.25 ± 1.57 a
25	28.07 ± 0.62 a	41.52 ± 1.06 a	44.72 ± 1.24 a	45.90 ± 1.26 a	46.72 ± 1.21 a

Means ± SD with different letters in the same column indicate significant statistical differences (Tukey, $p \leq 0.05$). n = 9.

Table 2. Flower bud length (mm) of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes during vase life from plants treated with cerium (Ce) in the nutrient solution during the production cycle.

Ce (μM)	Days of vase life			
	0	2	4	6
0	50.32 ± 2.14 bc	53.55 ± 3.36 b	60.43 ± 3.85 b	57.77 ± 3.37c
5	52.85 ± 4.11 ab	61.53 ± 6.22 a	67.86 ± 5.41 a	66.05 ± 6.22ab
15	48.35 ± 0.99 c	53.168 ± 1.79 b	60.68 ± 1.19 b	61.50 ± 2.17 bc
25	55.07 ± 1.84 a	62.36 ± 2.45 a	70.48 ± 2.21 a	69.41 ± 3.10 a

Means ± SD with different letters in the same column indicate significant statistical differences (Tukey, $p \leq 0.05$). n = 9.

Table 3. Flower bud diameter (mm) of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes during vase life from plants treated with cerium (Ce) in the nutrient solution during the production cycle.

Ce (μM)	Days of vase life			
	0	2	4	6
0	16.67 ± 1.51 a	60.22 ± 4.70 a	73.75 ± 6.37 a	56.57 ± 6.37 b
5	16.67 ± 0.96 a	52.45 ± 6.70 b	68.97 ± 7.17 a	56.60 ± 14.84 b
15	16.95 ± 0.89 a	52.67 ± 4.13 b	72.16 ± 5.06 a	56.45 ± 8.15 b
25	17.07 ± 1.10 a	48.75 ± 3.77 b	75.77 ± 3.41 a	70.81 ± 4.17 a

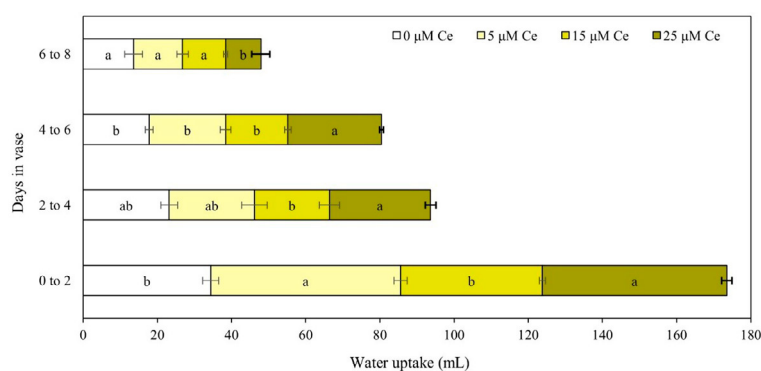
Means ± SD with different letters in the same column indicate significant statistical differences (Tukey, $p \leq 0.05$). n = 9.

At the time of cutting (day 0), the flower bud length of plants treated with 25 μM Ce was 9.4% greater than the control. Therefore, this treatment increased this variable by 16.5%, 16.6%, and 20.1% on days 2, 4, and 6 respectively, compared to the control (Table 2).

On day 2 of vase life, all Ce-treated plants exhibited a smaller flower bud diameter than the control. As compared to the control, the greatest reduction, 19.1%, was observed in the 25 μM Ce treatment. This trend was reversed on day 6, when the flower bud diameter in the 25 μM Ce treatment surpassed that of the control by 25.3%. (Table 3).

Water uptake by flower stems

The highest water uptake occurred in the first two days during vase life (Fig. 1). In the first two days, flower stems from plants treated with 5 and 25 μM Ce consumed more water compared to the control, with increases of 48.8% and 44.6% respectively; while, between days 4 and 6, flower stems from plants treated with 25 μM Ce surpassed the control by 41.9% in water uptake.

**Fig. 1.** Water uptake of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes flower stems during vase life from plants treated with cerium (Ce) in the nutrient solution during the production cycle. Means ± SD with different letters in each evaluation indicate significant statistical differences (Tukey, $p \leq 0.05$). n = 9.

Fresh biomass of the flower stem

In all treatments, the weight of fresh biomass of the flower stem increased between the beginning of the vase and day four; subsequently, it decreased (Fig. 2). The treatments with 5 and 25 μM Ce presented the highest weight of the flower stem, with the treatment with 25 μM Ce standing out, with increases on days 0, 2, 4, and 6 of 31.2%, 44.5%, 50.3%, and 41.9% respectively, compared to the control.

Vase life

The different Ce concentrations applied to tulip plants did not have a significant effect on vase life duration (Fig. 3).

Dry biomass of the organs that make up the tulip flower stem

The dry biomass of the organs that make up the flower stem, as well as that of the flower stem as a whole, was significantly higher than the control in plants treated with 5 and 25 μM Ce (Fig. 4).

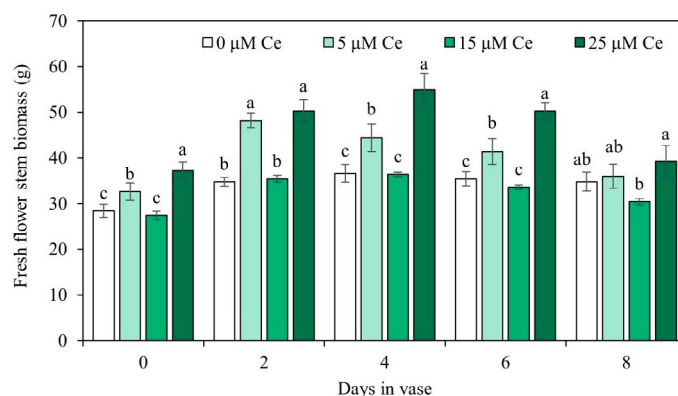


Fig. 2. Weight of fresh biomass of the flower stem of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes flower stems during vase life from plants treated with cerium (Ce) in the nutrient solution during the production cycle. Means $\pm$ SD with different letters in each evaluation indicate significant statistical differences (Tukey, $p \leq 0.05$). $n = 9$.

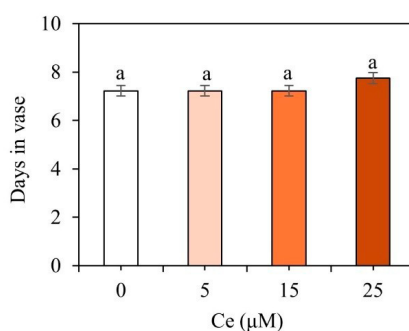


Fig. 3. Vase life of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes flower stems from plants treated with cerium (Ce) in the nutrient solution during the production cycle. Means $\pm$ SD with different letters in each bar indicate significant statistical differences (Tukey, $p \leq 0.05$). $n = 9$.

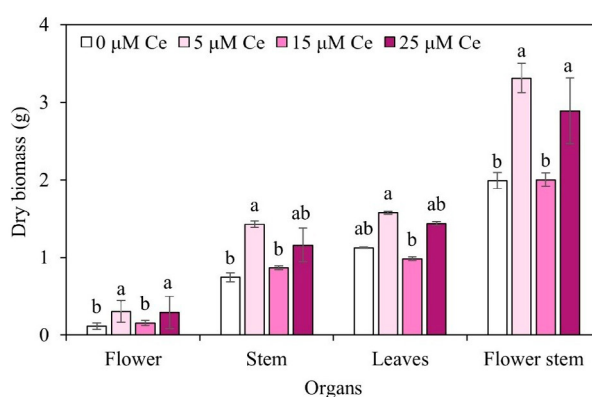


Fig. 4. Dry biomass of different organs of flower stems of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes and biomass of the flower stem at the end of vase life, from plants treated with cerium (Ce) in the nutrient solution during the production cycle. Means $\pm$ SD with different letters in each organ indicate significant statistical differences (Tukey, $p \leq 0.05$). $n = 9$.

Nutritional content in flowers, leaves, and stems

The flower stems of plants treated with 5 and 25 μM Ce exhibited a higher content of macronutrients (Fig. 5). With 5 and 25 μM , the N content in flowers increased by 99.1% and 129.7%; in leaves by 45.5% and 37.9%; and in stems by 48.3% and 25.8%, respectively, compared to the control (Fig. 5A). The P content in flowers increased with these doses by 87.2% and 100%; in leaves, by 25.3% and 41.3%; and in stems

by 6.2% and 35.8%, respectively, compared to the control (Fig. 5B). The K content in flowers was higher by 126% and 107.5%; in leaves by 13.5% and 19.2%; and in stems by 59.4% and 35.9%, compared to the control. On the contrary, the treatment with 15 μM Ce decreased the K contents in leaves by 19.7% compared to the control (Fig. 5C). The Ca content increased by 120% and 86.7% in flowers; in leaves by 36.8% and 48.8%; in stems by 46.4% and 49.2% with the doses of 5 and 25 μM Ce,

respectively, compared to the control (Fig. 5D). The Mg content in flowers increased by 104.3% and 91.3%; in leaves by 33.5% and 28.7%; and in stems by 40.6% and 36.5% (Fig. 5E). Finally, the S content in flowers

increased by 113.9% and 100%; in leaves by 24.9% and 15.7%; and in stems by 47.3% and 29.7%; while, with the 15 μM Ce dose, the S content in leaves decreased by 16.9% (Fig. 5F).

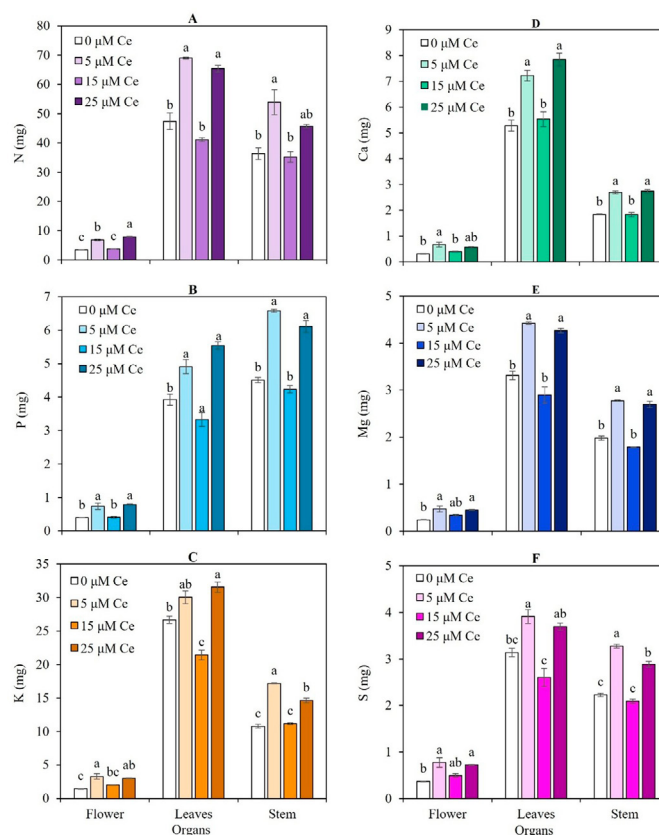


Fig. 5. Macronutrient content in different organs of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes flower stems at the end of vase life from plants treated with cerium (Ce) in the nutrient solution during the production cycle. A) Nitrogen (N) content. B) Phosphorus (P) content. C) Potassium (K) content. D) Calcium (Ca) content. E) Magnesium (Mg) content. F) Sulfur (S) content. Means $\pm$ SD with different letters in each subfigure indicate significant differences (Tukey, $p \leq 0.05$). $n = 9$.

Regarding micronutrients, plants exposed to 5 and 25 μM Ce during the productive cycle displayed significantly higher iron contents in flowers at the end of vase life, with increases of 129.3% and 134.9%, respectively, compared to the control (Fig. 6A). With these same doses of Ce, the Zn content in flowers increased by 97.9% and 88.2%; in stems the increases were 40.7% and 30.5%, respectively, while in leaves 5 and 15 μM Ce caused a reduction of 7.7% and 23% with respect to the control (Fig. 6C). The Mn content increased in all plant organs treated

with 5 and 25 μM Ce. In flowers, the increases were 164.3% and 125.1%, respectively, compared to the control. In leaves, Mn content increased by 79.2% and 69.7%, while in stems the increases were 86.1% and 72%, respectively (Fig. 6D), compared to the control. Plants treated with 5 and 25 μM Ce showed higher B contents in flowers, with increases of 87.7% and 88.2%, respectively, compared to the control (Fig. 6E). Cu content was not affected by Ce treatments (Fig. 6B).

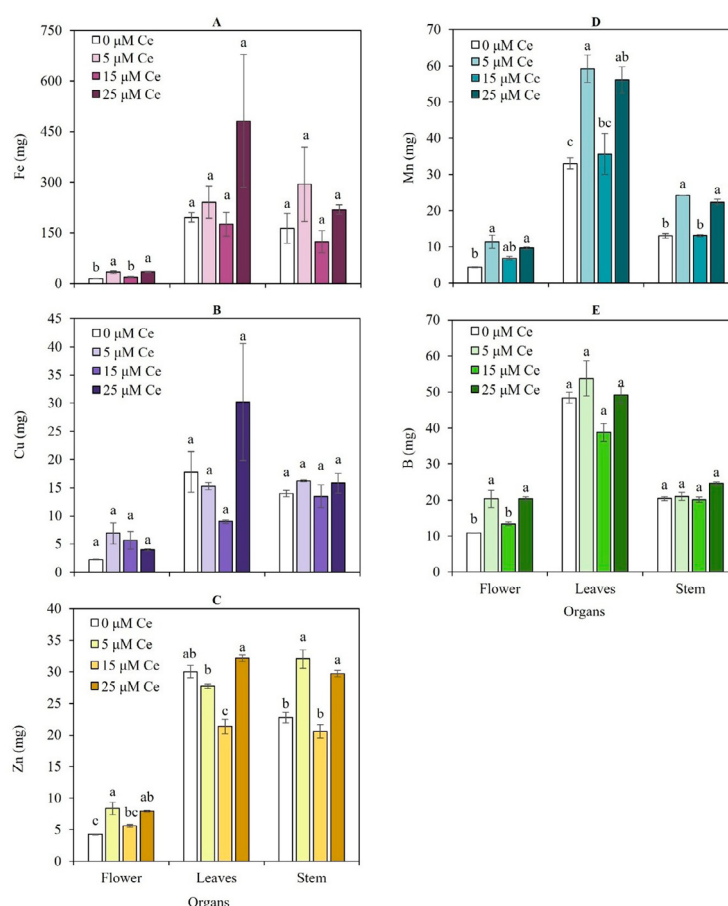


Fig. 6. Micronutrient content in different organs of tulip (*Tulipa gesneriana* L.) cv. Jan van Nes flower stems at the end of vase life from plants treated with cerium (Ce) in the nutrient solution during the production cycle. A) Iron (Fe) content. B) Copper (Cu) content. C) Zinc (Zn) content. D) Manganese (Mn) content. E) Boron (B) content. Means $\pm$ SD with different letters in each subfigure indicate significant differences (Tukey, $p \leq 0.05$). $n = 9$.

Content of total soluble sugars in leaves and flowers

The content of total soluble sugars in leaves was higher in plants treated with 25 μM Ce, exceeding the control by 138.3%; with 5 μM Ce the increases were 16.1%. Plants treated with 15 μM Ce exhibited a

lower content of total sugars, with a reduction of 39.4% with respect to the control (Fig. 7A). In flowers, the 5 and 25 μM Ce treatments increased the content of soluble sugars by 84.2% and 94.2% respectively, compared to the control (Fig. 7B).

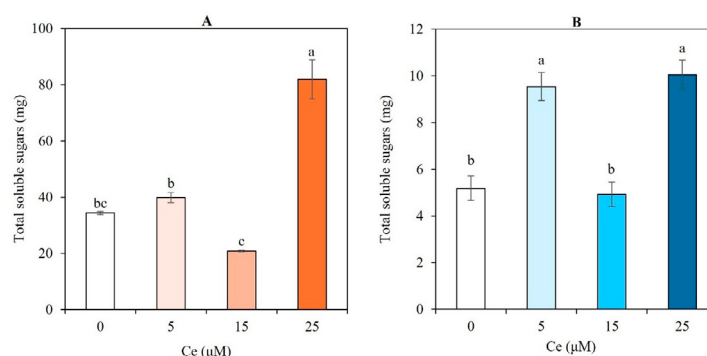


Fig. 7. Content of total soluble sugars in leaves (A) and flowers (B) of tulip (*Tulipa gesneriana* L.) plants cv. Jan van Nes at the end of vase life, from plants treated with cerium (Ce) in the nutrient solution during the production cycle. Means $\pm$ SD with different letters in each subfigure indicate significant differences (Tukey, $p \leq 0.05$).

Discussion

Stem length and diameter, flower bud size, shape, and color, leaf color, among other factors, are critical attributes when determining the quality of cut flowers (Verdonk et al., 2023). Lanthanum (La), another rare earth element with properties similar to those of Ce, has also shown benefits in cut flowers. In tulip, lanthanum prolongs vase life of cut flowers by

increasing water consumption and concentrations of sugars, proteins and chlorophylls (Gómez-Merino et al., 2020b). In this research, the supply of 25 μM Ce in the irrigation nutrient solution during the production cycle significantly increased the length of the floral stem in postharvest (Table 1). However, stem elongation in tulips is an undesirable condition as it negatively affects post-harvest quality by causing greater curvature of the

floral stems. Indeed, tulip stems can elongate between 2.5 and 15 cm after harvest, leading to arching, bending, and twisting of stems. According to Benschop and De Hertogh (1971), elongation of the stem (particularly of the last internode) should be minimal (< 5 cm) to reduce stem bending, and later studies confirmed that restricting elongation to approximately 5 cm improves vase life (Van Doorn and Perik, 1999).

The increase in flower bud diameter and length during vase life is related to the expansion and cell division of the floral petals, with a marked increase in the size of the vacuoles (Kaneeda et al., 2024). The results obtained here show that the diameter and length of the flower bud increased over time, decreasing as senescence approached. Nevertheless, plants that were exposed to concentrations of 25 μM Ce had a greater increase in flower bud length and diameter (Tables 2 and 3). Significant increases in flower bud diameter and length in tulips in response to La treatment have already been reported (Gómez-Merino et al., 2020a).

The increase in flower bud length and diameter observed here is probably due to cell elongation in petals promoted by Ce, by increasing water absorption as well as the accumulation of osmoregulatory substances such as total soluble sugars (Fig. 7B) by flower stems (Fig. 1) that increases cell turgor. Furthermore, the addition of Ce increased the K content in flowers (Fig. 5C), which is an ion that contributes to the osmotic potential (Hawkesford et al., 2023).

The increase in the weight of fresh biomass of the flower stem (Fig. 2) was positively related to water uptake (Fig. 1). The addition of 5 and 25 μM Ce significantly increased water uptake in the first days (0 to 2 d). Interestingly, only the 25 μM Ce concentration was effective in the other days of evaluation (2 to 8 d).

The flower stems that consumed more water (Fig. 1) obtained the highest values in fresh biomass weights (Fig. 2 and 3). The water absorption rate in tulips occurs rapidly during the first hours, subsequently decreases and after 5 h becomes constant (Lykas et al., 2023). It has been previously demonstrated that Ce applications result in increased growth, development and reproduction of tulip, thus stimulating the emergence of the bulb, formation of the flower bud, coloration, and advancing the flowering period (Gómez-Navor et al., 2021).

Ce may increase water uptake by stimulating total soluble sugars in the flower and thus inducing osmoregulation (Li et al., 2023). In plants exposed to salt stress, Ce improved plant growth and fruit quality by changing the antioxidant capacity and water physiology (Zhao et al., 2022). An increase in water uptake is associated with a longer vase life in tulips (Gómez-Merino et al., 2020b). However, such a trend was not observed in this research (Fig. 3). Vase life refers to the period during which a cut flower or foliage retains its appearance and quality in a vase, and represents one of the most important factors determining the marketability of cut flowers (Liu et al., 2024). Vase life depends on the genotype, pre-harvest and post-harvest conditions (Verdonk et al., 2023). In tulips, the end of useful flower life is determined by discoloration and senescence of tepals, followed by tepal abscission, yellowing of leaves, curvature of stems, turbid vase water, etc. (Verdonk et al., 2023). Our results show that the addition of Ce during the tulip production cycle did not increase vase life (Fig. 3). Importantly, the evaluated flowers presented an early abscission of tepals. It has been found that when applied at lower doses (i.e., 20 to 40 μCe), cerium may trigger positive responses in lisianthus (*Eustoma grandiflorum* cv. Pink Picotte), while application of higher doses (i.e., 80 to 200 μCe), this element results in adverse impacts (Pourzarnegar and Hashemabadi, 2020; Pourzarnegar et al., 2020). It has to be taken into consideration that in those studies, Ce was used in the vase solution; therefore, the floral stem was directly exposed to Ce, increasing the activity of antioxidant enzymes and balancing the reactive oxygen metabolism.

The average vase life of the evaluated cultivar was 7 days (Fig. 3). The vase life of tulip flowers can vary from 4–7 days, which may be associated with the genetic potential of each variety (Jahnke et al., 2022). For the Jan van Nes cultivar, an average vase life of 8 days has been reported (Gómez-Merino et al., 2020b).

Plants that received applications of 5 and 25 μM Ce during the production cycle had a higher total dry biomass weight at the end of vase life (Fig. 4). These results can be explained because Ce functions as a biostimulant that improves photosynthetic rate, efficiency of photosystem II, and electron transfer, with a concomitant greater biomass accumulation (Ahmad et al., 2024).

Optimal mineral nutrition stimulates plant growth and quality indicators, including stem length and thickness, leaf area, and fresh biomass production. It also impacts the accumulation of reserves such as carbohydrates that are used during the vase life period and promotes larger flower scape size and flower longevity (Zhang and Zhang, 2023; Paiva and Roddy, 2024). The macronutrient content in flowers, leaves, and stems increased significantly when plants were exposed to 5 and 25 μM Ce (Fig. 5). Cerium application increased the contents of N, K, Mg, and S in flowers, with both 5 and 25 μM Ce treatments showing statistically significant increases compared to the control. The N content increased by 98.6% and 129.2% at 5 and 25 μM Ce, respectively; K by 125.9% and 107.3%; Mg by 97.7% and 88.7%; and S by 110.7% and 96.9%. In the case of Ca, only the 5 μM Ce treatment led to a statistically significant increase, with a 117.2% rise in flower Ca content compared to the control. On the other hand, plants treated with 5 and 25 μM Ce had higher contents of Fe and B in flowers, Zn in flowers and stems, and Mn in all organs evaluated at the end of vase life (Fig. 6).

Contrary to the above, the dose of 15 μM Ce reduced the content of K, S, and Zn in leaves by more than 15% compared to the control (Fig. 7 and 8).

These findings show that Ce is a potential biostimulant that can improve nutrient absorption and status in tulips, due to a possible modification in the stability of the plasma membrane, which causes cellular ionic interactions to undergo modifications (Li et al., 2023). In addition, Ce can bind to membrane proteins and alter ionic fluxes (Prakash et al., 2021).

It has been shown that plants respond differentially to Ce treatment in terms of nutrient regulation in their tissues (Dridi et al., 2022). Indeed, cerium oxide has been proposed as a nanozyme for plant abiotic stress tolerance, inducing a better nutrient balance (Prakash et al., 2021). In spinach (*Spinacia oleracea* L.), Ce increased the concentrations of P, Ca, Mg, Fe, Mn, Zn and Cu in a dose dependent manner (Ahmad et al., 2024). In wheat (*Triticum aestivum* L.), applications of 10 and 25 mg Ce L⁻¹ reduced the contents of several mineral elements: K, Mg, and Zn in shoots, and Ca, Mg, and Zn in roots (Hu et al., 2002). In sunflower (*Helianthus annuus* L.), a concentration of 2.5 μM Ce increased the absorption of K in shoots and roots, Mg in roots; and finally, the concentration of Ca decreased by 18% in the shoots of plants treated with 10 μM Ce. Therefore, the application of Ce can differentially modify plant metabolism depending on various factors including concentrations applied, mode and frequency of applications, crop species treated, stage of development, among others (Dridi et al., 2022). According to a meta-analysis performed by Agathokleous et al. (2022), low Ce concentrations (i.e., < 180 μM) commonly enhance plant metabolism, whereas high concentrations (i.e., > 350 mg L⁻¹) suppress fitness-critical traits, thus demonstrating the hormetic responses triggered by Ce in plants.

The status of sugars in cut flowers can be influenced by the management and practices implemented both in production and post-harvest, while the level of soluble sugars is decisive for respiration and for processes related to senescence (Verdonk et al., 2023). Generally, the content of soluble sugars decreases during senescence due to oxidative processes that occur in plants after harvest (Verma and Singh, 2021). In our study, plants treated with 25 μM Ce during the production cycle presented the highest contents of total soluble sugars in leaves and flowers at the end of vase life; doses of 5 and 25 μM Ce significantly increased the content of soluble sugars (Fig. 7). In cut flowers, the flower acts as the main demand organ; therefore, in post-harvest, the leaves function as a source, mainly transforming starch into smaller molecules, such as soluble sugars, which are translocated to the flowers (Liu et al., 2024). In our experimental conditions, Ce may have improved the distribution or translocation of sugars from leaves to flowers. In addition, Ce may improve photosynthesis and therefore the biosynthesis of sugars (Pietrzak et al., 2024). In noble dendrobium (*Dendrobium nobile* Lindl.), low concentrations of Ce (10–20 mg L⁻¹) significantly improved the resistance and medicinal qualities of the plant such as polysaccharide, polyphenol and flavonoid, as well as the content of photosynthetic pigment, proline, soluble sugar and soluble protein (Li et al., 2023).

The data reported here prove the benefits that the use of Ce as an inorganic biostimulant can have on the quality and postharvest life of tulips. A more in-depth comprehension of the physiological, biochemical, and molecular mechanisms, as well as the anatomical adaptation of the

vascular structure and water transport improved by the application of Ce may provide insight that could improve hydration and prolong postharvest life of other tulip varieties and cultivars, as well as many other cut flower species. It will also be important to determine the types of hormetic dose-response curves that different doses of Ce applied can induce in different tulip cultivars and other cut flower species.

Conclusions

As a beneficial element triggering hormesis, Ce may have both positive effects at low concentrations and adverse effects at high doses. Under our experimental conditions, Ce treatments did not increase vase life of cut tulip. Instead, treatment with 5 and 25 μM Ce during the production cycle had a positive influence on the postharvest quality of flower stems by improving parameters such as flower bud diameter and length, increasing water uptake, and nutrient content in flowers, leaves, and stems, and increasing the total soluble sugar content. Therefore, Ce is considered a biostimulant to improve postharvest quality in tulip.

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Author Contribution

TGN: Investigation, Methodology, Writing - Original Draft. **FCGM:** Conceptualization, Writing-Review & Editing, Supervision, Validation. **YLFP:** Writing - Review & Editing. **LITT:** Conceptualization, Methodology, Data Curation, Writing - Original Draft, Writing-Review & Editing, Supervision, Resources, Validation.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Data will be made available upon request to the authors.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the use of AI and AI-assisted technologies was not applied in the writing process.

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