

Research Paper

Effect of nitrogen forms on vegetative growth and flower development at hydroponically grown geraniums (*Pelargonium zonale* × *Pelargonium peltatum*)

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ABSTRACT

Nitrogen is an essential macronutrient that greatly influences plant metabolism, growth and development. In plants, nitrogen is taken up in the form of nitrate (NO_3^-) or ammonium (NH_4^+), which affect plant physiology, root and shoot growth and the transition to generative phase differently. In this study we investigated the effect of nitrate and ammonium nitrogen forms on growth and development of hydroponically grown geranium plants. Rooted cuttings were cultivated in a floating hydroponic system with four treatments, differing in the nitrate-to-ammonium ratio in the nutrient solution. Treatment with an equal ratio of nitrate and ammonium resulted in greatest increase in shoot and root biomass, together with higher concentrations of chlorophyll a, and ammonium nitrogen in leaves. Treatment with 80:20 ratio (NO_3^- : NH_4^+) also had a positive effect on biomass production. Higher nitrate ratios (90%, 100%) promoted higher flowering intensity compared to the 50% nitrate treatment. These findings suggest that a proper ratio of nitrate and ammonium can positively influence growth by increasing shoot and root biomass and enhancing leaf production. The quality of hydroponically grown geraniums can be improved through the optimization of nitrogen form ratios in the nutrient solution.

1. Introduction

Modern requirements for the production of ornamental plants are highly demanding. To achieve market-ready plants of high quality (well-developed root system, a compact shoot structure featuring numerous lateral branches, at least one blooming flower), it is important that each step of production is executed with precision and specified for each ornamental plant species. Proactive nutrient management is of great importance, since balanced and adequately supplemented nutrients enable plants to achieve maximum growth potential and production standards (Beytes et al., 2021; Leskovar, 2020).

Nitrogen is one of the most significant nutrients that influence plant development, as it plays a key role in forming cells, tissues and organs, as well as in the biosynthesis of proteins, nucleic acids, chlorophyll, phospholipids, vitamins, hormones and secondary metabolites (Marschner, 2012). Plants acquire nitrogen mainly in inorganic forms such as nitrate (NO_3^-) and ammonium (NH_4^+) and in lower quantities as organic forms (amino acids) (Miller et al., 2007). Both inorganic forms differ in uptake and assimilation, with ammonium being associated with a lower energetic cost, as it does not require reduction before

incorporation into molecules (Kong et al., 2022). In addition to nutritional effect, nitrate and ammonium can also act as signaling molecules, resulting in different root architecture (Hachiya and Sakakibara, 2016; Lima et al., 2010; Liu and von Wirén, 2017) and initiation of flowering (Olas et al., 2019).

Ammonium as a sole nitrogen source can, if not efficiently incorporated into amino acids, cause ammonium toxicity, which is shown as stunted growth and leaf chlorosis, as well as inhibited root growth (Britto and Kronzucker, 2002). Generally, the combination of nitrate and ammonium in different ratios stimulates growth more than a sole supply of one form. Assimilation of ammonium into amino acids via the glutamine synthetase/glutamine oxoglutarate aminotransferase (GS/GOGAT) cycle requires carbon skeletons (2-oxoglutarate), which are derived from the tricarboxylic acid (TCA) cycle (Hodges, 2002; Rivero-Marcos et al., 2026). Addition of nitrate increases the activity of enzymes involved in carbon metabolism and the concentration of TCA cycle intermediates, consequently producing more carbon skeletons. This improves the efficiency of ammonium assimilation (Du et al., 2021; Li et al., 2024).

The form of nitrogen that is available and taken up by plant depends

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on plant species, soil type, soil water content and pH. Generally, plants that grow in soil with low pH, low redox potential and low nitrification prefer ammonium (Miller & Cramer, 2004). In hydroponic conditions, of most importance are concentration, ionic form of nutrients and their ratio, as well as pH (Rajaseger, 2023). Co-provision of nitrate and ammonium can be used as a pH management strategy in hydroponic conditions, as net cation/anion uptake by roots influences the solution pH. In geranium (*Pelargonium × hortorum*), nitrate-dominant nutrition can increase solution pH, while higher ammonium proportions promote acidification. A nutrient solution containing 10% of ammonium has been suggested to result in stable pH levels (Dickson et al., 2016). However, optimal nitrate-to-ammonium ratios for optimizing vegetative growth and flowering performance in geranium remain unclear.

The aim of the study was to study the response of geranium plants to different nitrate-to-ammonium ratios in nutrient solutions. We aimed to assess the importance of nitrogen form used for fertilization for plant growth and development. Our focus was on differences in root development regarding the nitrogen form which has been chosen. Therefore, the growth and morphological characteristics of the plants (shoot growth, number of leaves, root and shoot weight, quality of flowering), as well as measurement of leaf pigments were included in the study. These findings will provide insights into hydroponic growing of geraniums and precise nitrogen nutrient management during the phase of production.

2. Materials and methods

2.1. Experimental design

In spring 2025, from March 18 to May 16, a hydroponic experiment was conducted at the Biotechnical Faculty in Ljubljana (Slovenia; 46° 3' 4" N; 14° 30' 18" E) in a shaded greenhouse without climate control. One month old rooted geranium cuttings, *Pelargonium interspecific* (*Pelargonium zonale* × *Pelargonium peltatum*) 'MojoTM', colour Cranberry splash were acquired from Picount d. o. o (Radovljica, Slovenia). The cuttings were uniform in size and development, with an average of 5.25 ± 0.19 leaves (mean $\pm$ standard error) and shoot length 3.645 ± 0.198 cm. Air temperature and light intensity were continually monitored using digital sensors (SHT21 for temperature; LP PAR 03 for Photosynthetic Photon Flux Density (PPFD)). Average weekly temperatures were between 15.2°C and 18.4°C, PPFD was between 145 and 389 $\mu\text{mol m}^{-2} \text{s}^{-1}$, and daily light integral (DLI) was 6.5–18.9 $\text{mol m}^{-2} \text{d}^{-1}$.

A floating hydroponic system was chosen to exclude the effect of the substrate and allow direct observation of root development. Rooted cuttings were grown in a floating hydroponic system using four plastic containers, each fitted with a polystyrene board containing 24 holes for perforated cups holding the geranium cuttings. Each container had a pump for oxygenation. Plant roots were fully submerged in the nutrient solution.

Four treatments differed in the nitrate-to-ammonium ratio (NO_3^- : NH_4^+) in the nutrient solution: i) 100:0 (N100), ii) 90:10 (N90), iii) 80:20 (N80), iv) 50:50 (N50). The nutrient solution was modified Hoagland's solution (Table 1). Electrical conductivity and pH of the nutrient solution were measured weekly and maintained within range of pH 5.5–6.5 using H_2SO_4 and EC 2.1–2.9 mS/cm. Nutrient solution was changed

after one month of the experiment. Each treatment included 24 plants.

2.2. Assessment of growth dynamics and geranium sampling for chlorophyll, nitrate and ammonium extraction, biomass quantification

Number of leaves and plant height (length of the main shoot) of geraniums were measured every two weeks. For pigment, nitrate and ammonium contents, three plants (three repetitions) per treatment were harvested in weeks 3, 6, and 8. At the end of the experiment, flowering was assessed by recording the total number of flowers and the number of flowering (open) flowers per plant. At the end of experiment all geraniums were harvested, weighed, and dried for dry biomass determination.

2.2.1. Pigment extraction and spectrophotometric assay

The pigment content was determined based on Wellburn (1994). For pigment analysis, three leaf discs per plant (0.4 mm diameter) from harvested plants were taken, flash frozen in liquid nitrogen and stored at -80°C until analysis. Extraction was carried out based on Zamljen et al. (2025).

2.2.2. Nitrate and ammonium extraction and analysis

For nitrate and ammonium analysis, harvested plants were measured for fresh weight, dried at 40°C for 5 days and then grinded with mortar and pestle into a fine powder, which was used for extraction. 1.5–2 g dried mass was extracted with 200 ml of distilled water for two hours on a shaker. Supernatant was then filtered through 0.20 μm cellulose filter (Chromafil A-20/25; Macherey-Nagel, Dueren, Germany), and analysed on Thermo scientific Gallery.

2.3. Statistical analysis

Analyses were performed in R (version 4.3.1). Plant growth dynamics (plant height and number of leaves) were analyzed using linear mixed-effects models (LMMs) with treatment, sampling week and their interaction as fixed effects, and plant identity as a random factor. Final dry shoot and root weight were analyzed using one-way ANOVA and Tukey HSD test. Flowering intensity was expressed as number of flowering (open) buds divided by the total number of buds per plant. Based on this proportion, plants were classified into three ordinal categories: low (≤ 0.33), medium (0.34–0.66), high (≥ 0.67). The effect of treatment on flowering intensity was analyzed using an ordinal logistic regression model. The proportional odds assumption was assessed using Brant test. Pigment contents, as well as nitrate and ammonium contents, were analyzed using two-way ANOVA with treatment, sampling week and their interaction as fixed effects. When the treatment $\times$ week interaction was not significant, treatment main effects averaged across sampling weeks were compared. Model assumptions were evaluated based on residual diagnostics.

3. Results

3.1. Plant growth dynamics

Shoot height and number of leaves increased over time in all

Table 1
Ion concentrations supplied (mg l^{-1}) in nutrient solutions used in the experiment^a.

Treatment	Solution $\text{NO}_3^-:\text{NH}_4^+$ ratio	N- NO_3^- (mg l^{-1})	N- NH_4^+	PO_4^{2-}	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Cl^-
N100	100:0	204	0	26	250	180	48	63.3	0
N90	90:10	189	21	31	234	170	48	87.3	0
N80	80:20	168	42	31	234	170	48	127.2	17.9
N50	50:50	105	105	31	234	170	48	255.2	53.8

^a Micronutrients were supplied in all nutrient solutions at (in $\mu\text{g l}^{-1}$): 330 B, 327 Zn, 550 Mn, 48 Cu, 48 Mo, 500 Fe

treatments ($p < 0.001$) (Fig. 1). Plants grown in N100 treatment were significantly shorter (2.61 ± 0.16 cm) than in other treatments in week 2. From week 4 onwards, plants supplied with 50% ammonium (N50) had significantly greater height than N90. At week 6, both N50 and N80 showed significantly greater height than N100 and N90. At week 8, N50 produced the tallest plants (10.22 ± 0.67 cm), which were 2.63 cm (34.7%) higher than N90 (7.59 ± 0.45 cm) (Fig. 1A).

A similar pattern was observed for leaf number (Fig. 1B). Leaf number increased over time, in week 2, leaf number did not differ among treatments. From week 6 onwards, the treatment with 50% of ammonium (N50) developed significantly more leaves than the treatment with 10% or 0% of ammonium. By week 8, plants in N50 treatment developed 47.5% more leaves (21.53 ± 1.05 leaves) compared to N90 treatment (14.60 ± 0.79 leaves), plants in N80 (19.51 ± 1.07 leaves) also developed 33.6% more leaves compared to plants in N90.

3.2. Biomass

Dry shoot and root mass increased with increasing ammonium proportion in the nutrient solution. The highest dry shoot weight (6.20 ± 0.67 g) and dry root weight (0.63 ± 0.06 g) were observed in the N50 treatment. Dry shoot weight of N50 differed significantly from those of N90 (3.04 ± 0.32 g) and N100 (3.85 ± 0.35 g). Dry root weight significantly differed between N50 and N90, with N50 showing 0.21 g greater root weight than N90 (0.42 ± 0.05 g), representing a 49.7 % increase (Fig. 2).

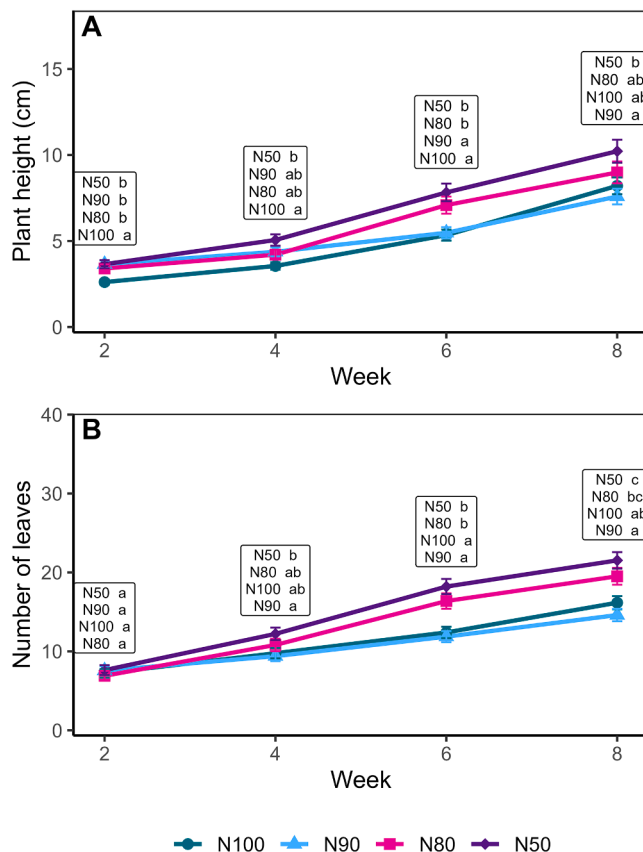


Fig. 1. Growth parameters of *Pelargonium interspecific*, grown under different nitrate-to-ammonium ratios in nutrient solutions (N100 = 100% N-NO₃⁻; N90 = 90% N-NO₃⁻ + 10% N-NH₄⁺; N80 = 80% N-NO₃⁻ + 20% N-NH₄⁺; N50 = 50% N-NO₃⁻ + 50% N-NH₄⁺). Data are estimated marginal means $\pm$ standard error (n = number of plants per treatment at each sampling week; 13–18 plants depending on survival). Data with different lower-case letters (a–c) are significantly different at each time point (LMM, Tukey-adjusted comparisons, $p < 0.05$).

3.3. Flower development

Nitrogen treatment significantly affected flowering intensity. The distribution of flowering categories differed among treatments, with N90 and N100 showing a higher proportion of plants in the medium and high flowering categories, N80 and N50 showed a higher proportion of plants in the low category (Fig. 3). Ordinal logistic regression showed that plants grown under N50 ($\beta = -1.69$, $p = 0.017$) and N80 ($\beta = -1.44$, $p = 0.037$) had a significantly lower probability of belonging to higher flowering categories compared with N100. No significant difference was observed between N90 and N100 ($p = 0.52$). Compared to N100, N50 had 81.5% lower odds of belonging to a higher flowering category, plants grown under N80 had 76.3% lower odds.

3.4. Leaf pigments and nitrogen status

Chlorophyll and carotenoid contents varied over time (Fig. 4). Averaged across sampling weeks, treatment N50 had the highest chlorophyll a and b contents (Table 2). In contrast, carotenoids showed a significant treatment $\times$ week interaction; carotenoid contents differed only in week 3, with N100 having greater content than N90.

The level of ammonium nitrogen (NH₄-N, mg g⁻¹ DW) in plant leaves increased significantly over time ($p < 0.001$). The highest content, averaged across sampling weeks, was in plants, grown under N50, which was significantly greater than N90 and N100 (Fig. 5A). Nitrate nitrogen (NO₃-N, mg g⁻¹ DW) was affected only by sampling week ($p = 0.0034$) and did not differ among treatments.

4. Discussion

Geraniums (*Pelargonium interspecific*) were grown in hydroponic conditions, under four different nitrate-to-ammonium ratios in nutrient solutions. The hydroponic type of experiment was chosen for better determination of how each ratio impacts plant development without the effects of other factors, such as nitrification, which should be observed in soil or substrates. We investigated how different ratios of two inorganic nutrient forms affected plant growth, flowering, pigment content, and nitrate and ammonium nitrogen in plants. Higher ammonium ratios (50%, 20%) promoted vegetative growth, reflected in increased shoot biomass, leaf number and leaf chlorophyll a content, as well as higher leaf ammonium nitrogen content. In contrast, nitrate-dominant nutrition enhanced the quality of flowering. Plants, grown with a higher percentage of ammonium did not show any visible symptoms of ammonium toxicity (leaf chlorosis, stunted growth), which suggests that nitrogen form ratios and concentrations were within a tolerable range for this species under hydroponic conditions. Similarly, geraniums grown under NO₃⁻: NH₄⁺ ratios up to 50:50 showed normal growth and biomass accumulation without reported symptoms of ammonium toxicity (Dickson et al., 2016). Besides plant species preferences for nitrogen forms, toxicity is highly connected with other nutrients supplied in a nutrient solution. Previous studies have shown that ammonium toxicity can be alleviated with addition of nitrate, potassium ions (K⁺) and with controlled pH (Britto and Kronzucker, 2002; Fang et al., 2021; Li et al., 2024; Zhu et al., 2021). In our experiment pH was controlled in the range of 5.5–6.5, which may have contributed to mitigating ammonium toxicity.

Vegetative growth and biomass

The strongest response to nitrogen form was observed in vegetative growth and biomass accumulation. The highest dry shoot weight was recorded in treatment with equal proportions of ammonium and nitrate (105 ppm). Plants supplied with 20 % and 50 % NH₄⁺ (N80, N50) also developed the greatest number of leaves. This could be due to ammonium assimilation being energetically less demanding than nitrate reduction and therefore supporting faster early growth when toxicity is avoided through pH management and sufficient carbon supply, as it is needed for efficient ammonium assimilation (Bittsánszky et al., 2015;

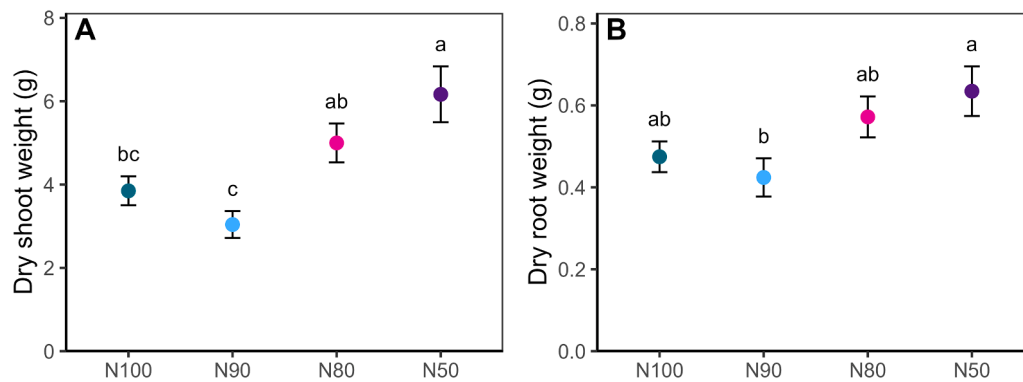


Fig. 2. Dry shoot (A) and root weight (B) of *Pelargonium interspecific*, grown under different nitrate-to-ammonium ratios in nutrient solutions (N100 = 100% N-NO₃⁻; N90 = 90% N-NO₃⁻ + 10% N-NH₄⁺; N80 = 80% N-NO₃⁻ + 20% N-NH₄⁺; N50 = 50% N-NO₃⁻ + 50% N-NH₄⁺). Data are estimated means ± standard error (N100 n = 18, N90 n = 18, N80 n = 10, N50 n = 13). Data with different lower-case letters (a-c) are significantly different (HSD test, $p < 0.05$).

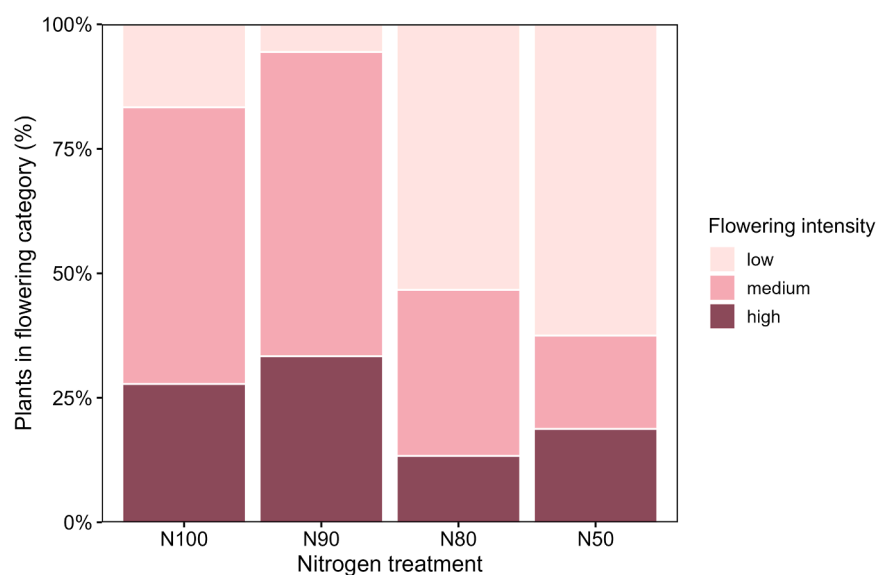


Fig. 3. Distribution of flowering intensity categories (low (≤ 0.33), medium (0.34–0.66), high (≥ 0.67), under different nitrate-to-ammonium ratios in nutrient solutions (N100 = 100% N-NO₃⁻; N90 = 90% N-NO₃⁻ + 10% N-NH₄⁺; N80 = 80% N-NO₃⁻ + 20% N-NH₄⁺; N50 = 50% N-NO₃⁻ + 50% N-NH₄⁺). Bars represent the percentage of plants assigned to each flowering category (N100 n = 18, N90 n = 18, N80 n = 15, N50 n = 16).

Britto and Kronzucker, 2002; Horchani et al., 2010). A balanced supply of NO₃⁻ and NH₄⁺ may enhance growth by a synergetic effect of both nitrogen forms, with nitrate functioning also as a signal, modulating nitrogen uptake (Britto and Kronzucker, 2002; Du et al., 2021; Yan et al., 2023), which could explain better vegetative growth in mixed treatments (50 % and 80 % of nitrate). As reported by Khalaj et al. (2017), gerbera plants (*Gerbera jamesonii* L.), grown under hydroponic conditions with 20 % of ammonium also had an increased number of leaves, fresh and dry weight of shoots and roots. Contrary to our results, treatment with 40 % of ammonium in nutrient solution showed slower growth. The efficiency of mixed nitrogen form nutrition is highly dependent on plant species, as greater effects in growth are achieved with plant species, known for their preference for ammonium, such as azaleas. Two cultivars of azaleas responded best to higher ammonium ratios, which resulted in better vegetative growth, nutrient uptake and distribution in plants (Clark et al., 2003). The effect of different plant species adaptation to nitrogen form can be proposed from a study on rose scented geranium (*Pelargonium graveolens*), which demonstrated that moderate nitrate concentrations (10–12 meq L⁻¹; 140–168 ppm N-NO₃⁻) best affected growth and biomass, while ammonium had limited effects on growth (Sedibe, 2020).

These findings suggest that ammonium can promote vegetative

growth if supplied in optimal concentrations under controlled pH conditions, and with addition of nitrate, growth can be improved. In our study, growth parameters between treatments with 20% and 50% of ammonium nitrogen did not differ significantly, suggesting that increasing the ammonium ratio beyond 20% does not necessarily provide significant vegetative growth benefits, which is consistent with the results reported by Khalaj et al. (2017).

Complementary and potentially synergistic effects of ammonium and nitrate may explain differences in root growth. In our experiment, treatments with a higher percentage of ammonium had greater root weight, which could be attributed to ammonium transporters (AMT1;3) that can induce growth of the lateral roots (Lima et al., 2010), while nitrate can affect their elongation (Remans et al., 2006). Combined effect of both forms may therefore result in greater root biomass overall. However, detailed analysis of root system architecture would be required to confirm the underlying mechanisms. A more developed root system can absorb more macro- and micronutrients, indicating optimal nutrient supply and therefore cause plants to invest more assimilates to support the growth of shoots (Wang et al., 2016), which can be proposed in our experiment, as plants with greater root weight also had greater shoot weight.

Effect on flowering

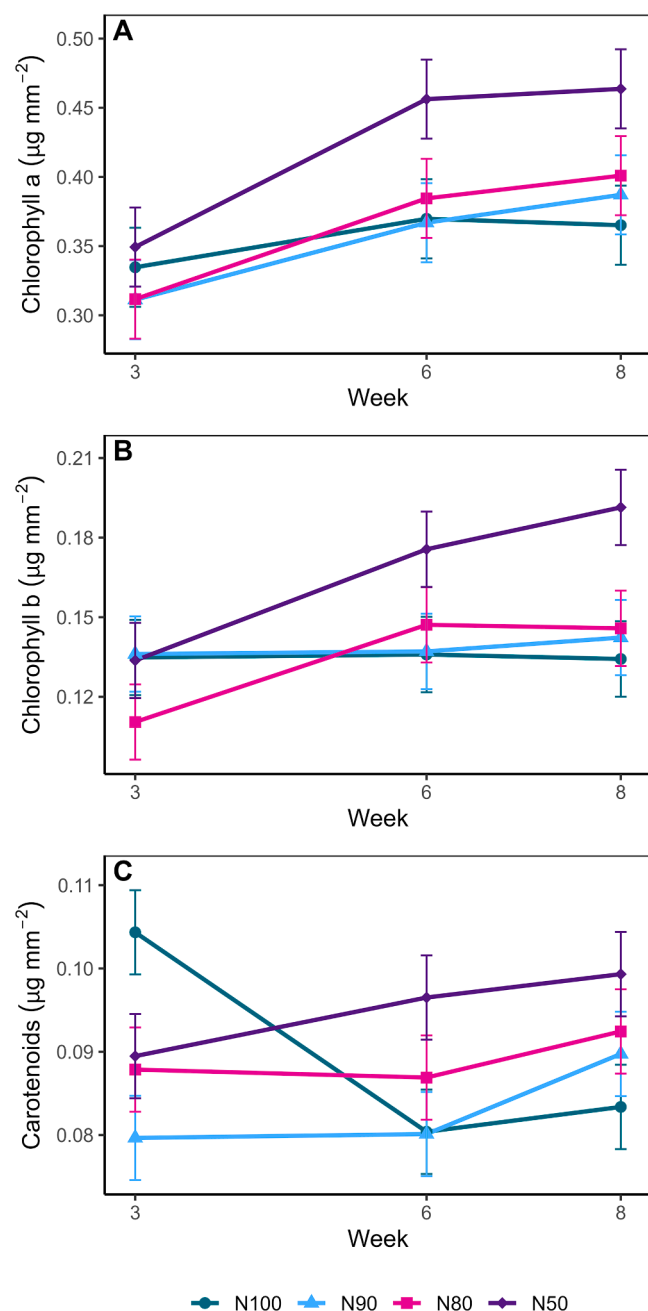


Fig. 4. Pigment contents: chlorophyll a (A), chlorophyll b (B), carotenoids (C) over sampling weeks in the leaves of *Pelargonium interspecific*, grown under different nitrate-to-ammonium ratios in nutrient solutions (N100 = 100% N-NO₃⁻; N90 = 90% N-NO₃⁻ + 10% N-NH₄⁺; N80 = 80% N-NO₃⁻ + 20% N-NH₄⁺; N50 = 50% N-NO₃⁻ + 50% N-NH₄⁺). Data are estimated marginal means ± standard error (n = 3 biological replicates per treatment per sampling week).

Our results showed a different flowering intensity among treatments, as higher ammonium ratios in nutrient solutions had lower odds of belonging to a higher flowering intensity compared to nitrate rich treatment, suggesting that nitrate-to-ammonium ratios in nutrient solutions could affect the quality of flowering. Increased ammonium percentage in the nutrient solution was associated with reduced flowering intensity. This effect may be related to delayed flower development in ammonium rich treatment, which grew stronger vegetatively. Similarly, nitrate dominant nutrition (75%) improved flowering of *Phalaenopsis* (Wang, 2008) and ammonium-rich treatment (40%) showed a decrease in developed inflorescences compared to nitrate rich treatments (80%,

Table 2

Chlorophyll a (µg mm⁻²), chlorophyll b (µg mm⁻²), ammonium nitrogen (mg g⁻¹ DW) and nitrate nitrogen contents (mg g⁻¹ DW) in the leaves of *Pelargonium interspecific*, grown under different nitrate-to-ammonium ratios in nutrient solutions (N100 = 100% N-NO₃⁻; N90 = 90% N-NO₃⁻ + 10% N-NH₄⁺; N80 = 80% N-NO₃⁻ + 20% N-NH₄⁺; N50 = 50% N-NO₃⁻ + 50% N-NH₄⁺).

	N100	N90	N80	N50
Chlorophyll a	0.357 ± 0.017 a	0.355 ± 0.017 a	0.366 ± 0.017 ab	0.423 ± 0.017 b
Chlorophyll b	0.135 ± 0.008 ab	0.139 ± 0.008 ab	0.134 ± 0.008 a	0.167 ± 0.008 b
Ammonium nitrogen	0.226 ± 0.014 a	0.237 ± 0.015 a	0.260 ± 0.017 ab	0.327 ± 0.021 b
Nitrate nitrogen	1.800 ± 0.256 a	1.540 ± 0.256 a	2.020 ± 0.256 a	2.180 ± 0.256 a

Data are estimated marginal means ± standard error (n = 3 biological replicates per treatment per sampling week). Different letters within a row indicate significant differences among treatments (two-way ANOVA, Tukey HSD, p < 0.05). The main effect of treatment was significant for chlorophyll a (p = 0.022), chlorophyll b (p = 0.028), ammonium nitrogen (p = 0.0019).

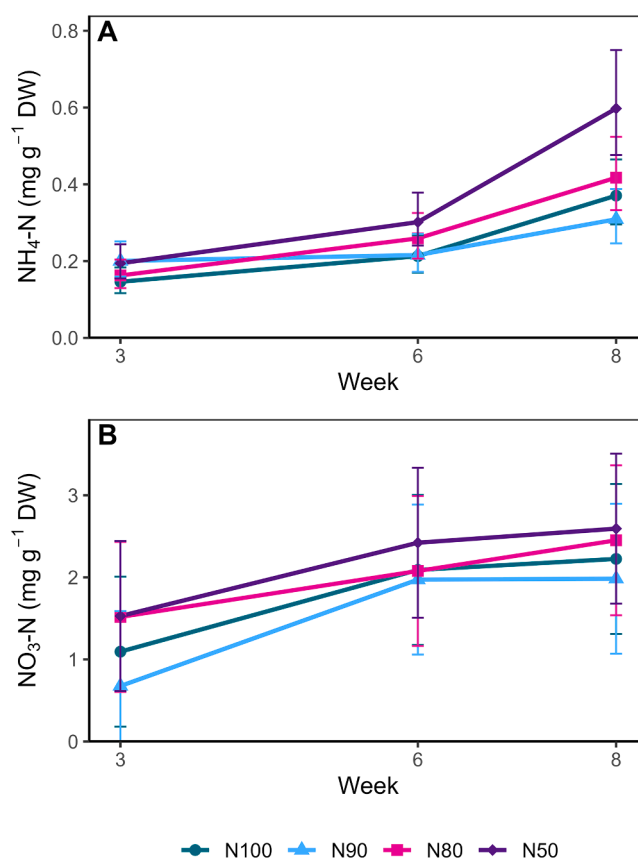


Fig. 5. Ammonium nitrogen (A) and nitrate nitrogen (B) over sampling weeks in the leaves of *Pelargonium interspecific*, grown under different nitrate-to-ammonium ratios in nutrient solutions (N100 = 100% N-NO₃⁻; N90 = 90% N-NO₃⁻ + 10% N-NH₄⁺; N80 = 80% N-NO₃⁻ + 20% N-NH₄⁺; N50 = 50% N-NO₃⁻ + 50% N-NH₄⁺). Data are estimated marginal means ± standard error (n = 3 biological replicates per treatment per sampling week).

100%) in strawberry cultivar *Fragaria* × *ananassa* Albion (Shi et al., 2021). There are several mechanisms proposed by Kant et al. (2011) and Olas et al. (2019), that explain how nitrate can induce flowering by modulating gene expression and how limiting or excessive nitrogen can delay the start of flowering (Lin & Tsay, 2017). However, the transition to flowering and the quality of flowering are dependent on many factors besides nitrogen and other nutrients supply, as photoperiod,

temperature, light intensity, stress and hormone levels also affect flowering (Kobayashi and Weigel, 2007). In our study, these mechanisms were not studied, and we cannot therefore assess the cause of different quality of flowering. Our results indicate that higher nitrate levels promote flowering, reflected in more plants belonging to a higher flowering intensity category, which is an important trait for the market value of geraniums.

Effect on pigments and nitrogen contents

Increased chlorophyll a content observed in plants, grown under treatment with 50% ammonium compared with 10% and 0%, may reflect improved nitrogen status. This is supported by the same difference in ammonium nitrogen content. In general, it is reported that there is a positive relationship between chlorophyll and N-content (Abasi et al., 2016; Gholizadeh et al., 2017). Kang & van Iersel (2004) and Mak & Yeh (2001) also observed increased chlorophyll contents in plants with increasing nitrogen content in plants. In our study, plants with higher chlorophyll a and ammonium nitrogen contents also had greater biomass, which could indicate efficient nitrogen assimilation and allocation.

5. Conclusions

From a production perspective, a 50:50 or 80:20 $\text{NO}_3^-:\text{NH}_4^+$ ratio appears promising for producing compact, high-quality geranium. However, hydroponic systems differ from the substrate-based cultivation, which is more common in ornamental plant production. In substrate, nitrogen availability is influenced not only by the supplied fertilizer but also by microbial processes such as nitrification, which depend on substrate properties including organic matter content and microbial activity (Norton and Ouyang, 2019). Further experiments are needed to achieve the desired effect of nitrogen forms when plants are grown in substrate.

As our results suggest, increasing ammonium supply up to 50% enhances vegetative growth of hydroponically grown geranium without visible toxicity symptoms, nitrate-based nutrition promotes flowering quality. Strategic adjustment of nitrogen forms during different production phases, with greater ammonium proportion at the beginning of production for increasing vegetative growth and greater nitrate proportion nearing the end of production for improved flowering, may represent an effective tool for optimizing geranium production performance.

CRediT authorship contribution statement

Lucija Benedik: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Tilen Zamljen:** Writing – review & editing, Methodology. **Gregor Osterc:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing 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.

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Data availability

Data will be made available on request.

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