JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(9), 370–381
https://doi.org/10.12911/22998993/205345
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.05.07
Accepted: 2025.06.13
Published: 2025.06.23

Nitrogen use efficiency in different growth phases: A strategy to optimize melon productivity

Rika Despita[1*], Mochammad Dawam Maghfoer[2], Agus Suryanto[2], Budi Waluyo[2]

[1] Sustainable Agricultural Extension Department, Agricultural Development Polytechnic of Malang, Jl. Dr. Cipto Bedali, Lawang 65215, East Java, Indonesia
[2] Department of Agronomy, Faculty of Agriculture, Universitas Brawijaya, Jl. Veteran, Malang 65145, East Java, Indonesia
* Corresponding author's e-mail: rikadespita@polbangtanmalang.ac.id

ABSTRACT

Nitrogen use efficiency must be considered to reduce environmental pollution and production costs. Among the possible strategies is nitrogen reduction, provided it is not done during the nitrogen-critical growth phase, to avoid decrease in production. This study aims to analyze the effect of different nitrogen concentrations on three critical growth phases and assess the efficiency of nitrogen use in relation to yield. The research was conducted in a hydroponic system in the greenhouse of the Agricultural Development Polytechnic of Malang. The research method used a group randomized design. Treatments consisted of variations of 100% nitrogen concentration as control, 25%, 50%, and 75% nitrogen concentration at three growth phases: vegetative phase (V), pollination and fruit formation phase (PFF), and fruit enlargement and ripening phase (FER). Data were analyzed using ANOVA and (Turkey) test. The results showed that FER-50% treatment resulted in plant height of ± 210 cm with optimal growth balance between phases. PFF-75% showed higher total leaf area (± 77 dm^2 $plant^{-1}$) and total dry weight (± 125 g). The chlorophyll index and relative growth rate showed physiological balance as the plants entered the reproductive phase, regardless of variations in nitrogen input. The control treatment (100%) produced fruit weight that was not significantly different from other treatments except V-25%. The FER-25% treatment showed the highest nitrogen use efficiency while maintaining competitive fruit yield. Reducing nitrogen to 75% at the fruit enlargement and ripening phases maintained competitive yields while significantly improving nitrogen use efficiency. This strategy supports optimal productivity and reduces production costs and environmental impacts, supporting the evolution of agricultural practices toward more sustainable systems.

Keywords: melon, hydroponics, nitrogen concentration, growth, yield.

INTRODUCTION

Nitrogen use efficiency is a crucial issue in modern agricultural practices. The world faces increasingly complex challenges in environmental sustainability and food production. Researchers have estimated that around 70% of the nitrogen used in agriculture are wasted rather than being absorbed by plants (Anas et al., 2020). Low nitrogen use efficiency economically harms farmers and significantly contributes to pollution. Groundwater pollution and greenhouse gas emissions, especially nitrous oxide (N_2O), have a global warming potential 300 times greater than carbon dioxide. Martínez-Dalmau et al. (2021) predict a 150% increase in this pollution by 2050. The agricultural sector also accounts for 60% of the increase.

The impacts of excessive nitrogen use are becoming more extensive, including the risk of soil salinization due to salt accumulation (Machado and Serralheiro, 2017). Soil salinity can reduce land productivity in the long term. of greater concern, nitrate accumulation in drinking water has severe health implication for human and livestock (Sainju et al., 2019). The research indicates that nitrate can contribute to several cancers, such as colorectal, ovarian, thyroid, kidney, and bladder.

Temkin et al., (2019) estimated 2.300 to 12,594 cancer cases annually related to nitrate exposure, with economic losses of 250 million to 1.5 billion US dollars. They also projected an additional potential impact of US$ 1.3 to US$ 6.5 billion due to lost productivity. Improving nitrogen use efficiency through better agronomic practices and advanced technologies is crucial to reduce nitrogen's negative impacts and help ensure future production's sustainability (Govindasamy et al., 2023). Hydroponic melon cultivation with the correct nitrogen management is one of the solutions that can be applied.

Melon cultivation is growing as the demand for functional fruits increases. The increase in production is in line with the increase in the amount of fertilizer used, especially nitrogen. Increased nitrogen use in melon cultivation is not always linearly related to its efficiency. Nitrogen overuse can result in over-vegetative growth at the expense of fruit yield, reducing biomass and fruit quality (Grasso et al., 2022). Nitrogen deficiency leads to low photosynthetic efficiency, slowing melon plant growth (Zhu et al., 2024) and significantly reducing plant dry weight. Plant leaves are more sensitive to nitrogen deficiency than plant roots (Nawaz et al., 2017).

Nitrogen is absorbed by plants in the form of nitrate and ammonium. Nitrogen uptake occurs through efficient transport, even though nitrogen availability in the soil fluctuates significantly (Muratore et al, 2021). Nitrogen that has been absorbed changes to ammonia and amino acids. This mechanism involves a series of nitrate reduction reactions to ammonium and its integration into amino acid structures. Then, plants transport ammonia and amino acids to the plant organs in need (Krapp, 2015).

Nitrogen as a major component of amino acids, proteins, and nucleic acids, plays a crucial role in enzymatic activity, cell structure formation, and biosynthesis of chlorophyll and various primary and secondary metabolites. Amino acids are raw materials for protein synthesis and other important plant metabolites. The role of nitrogen in chlorophyll formation is essential for photosynthesis process. In photosynthesis, plants convert light energy into chemical energy that can be used for growth and development (Kishorekumar et al., 2020). Nitrogen also regulates growth hormones such as auxins that affect seed germination, root and stem elongation, and leaf expansion (Fu et al., 2022).

As an essential element, nitrogen often limits the plant growth due to its vital role in plant metabolism and development (Gu et al., 2018). Nitrogen affects plant height in the vegetative phase, increases leaf area by promoting leaf number and size (Nascimento et al., 2020), increases dry weight and plant biomass (Feng et al., 2023), and increases chlorophyll content which is important for photosynthesis (Wang et al., 2024). The yield of melon plants with an optimal dose of around 150 kg/ha can increase fruit yield up to 40.28 t/ha (Moreira et al., 2022). Nitrogen application through drip fertigation enhance the yield compared to conventional methods (Rolbiecki et al., 2021). Given the comprehensive role of nitrogen in plant physiology, efficient nitrogen management is crucial to optimize crop productivity and minimize the environmental impacts that can result from excessive nitrogen fertilizer use.

Three main models support the optimization of nitrogen use in melon cultivation. The Demand-Driven Nutrient Supply model focuses on nutrient application based on crop demand. Nutrients are supplied based on the specific needs of the plants (Wen et al., 2022). Critical Nutrient Concentration is a concept used to determine the minimum nutrient concentration plants need to achieve optimal growth (Chang et al., 2021). Precision Nutrition Management with nutrient delivery is based on the 4 R principle: the right level, source, application method, and time (Nasiro and Mohammednur, 2024).

Despite the significant research on the role of nitrogen in melon cultivation, research on optimal nitrogen application at different growth phases of melon remains limited. While the negative impacts of inefficient nitrogen use have been documented, including groundwater pollution, greenhouse gas emissions, risk of soil salinization, and reduced fruit quality, a comprehensive approach that integrates the optimal dose of nitrogen at different growth phases with nitrogen use efficiency is not yet available. Several approaches, such as the demand-driven nutrient supply model, critical nutrient concentration, and precision nutrition management, have been promoted, but they have not fully considered the specific needs of melon plants at each growth phase. Therefore, this study aims to analyze the effect of nitrogen application on melon plant growth at three critical phases of growth (vegetative phase, pollination and fruit formation phase, and fruit enlargement and ripening phase). In addition, it also analyses nitrogen use efficiency in melon yield, which is expected to provide important information to optimize nitrogen management in sustainable melon cultivation.

MATERIAL AND METHODS

Materials used

The experiment was carried out from February to April 2023 in a greenhouse at the Agricultural Development Polytechnic of Malang, Indonesia, 609.4 meters above sea level. The average daily temperature ranges from 22.40 °C to 25.50 °C. The average daily humidity ranges from 69.00% to 94.00%. Devina Melon variety was planted in polybags with cocopeat planting medium. Cocopeat is washed and sterilised every melon growing season. The 35 × 17.5 cm polybags were positioned with a spacing of 100 × 30 cm (Figure 1). Seeding media for melon seeds was made of cocopeat. Seeds were transplanted after 10 days of age. Water with low EC (< 0.02 mS/cm) filtered by Pureline 500 gdp RO machine was used. Watering was done using drip irrigation while at the same time fertilization was done using A B mix fertilizer with nitrogen concentration according to the treatment. Drip irrigation was set automatically, and each irrigation was 200 ml. Watering intervals increased according to the plants' age. Periodic watering was carried out to reduce nitrogen evaporation and leaching, maintaining nitrogen use efficiency. The EC of nutrient solution at 1–35 days after planting was 2 $mS\ cm^{-1}$ and at 36–63 days after planting was 2.5 $mS\ cm^{-1}$. Total watering for each plant during the vegetative phase (1–28 days after transplanting) was 19.6 liters, pollination and fruit formation phase (29–35 days after transplanting) 8.4 liters, and fruit filling and ripening phase (36–63 days after transplanting) 33 liters, so that the total watering for each plant during the production period was 61 liters. Then, the pH of the nutrients ranged from 5.8–6.4. Fruit was retained at the 10–13th internode. After the plants reached 27 internodes, the tops of the plants were removed.

Experimental design

The experimental design utilized was a randomized block design with 10 treatments and three replications. A 100% nitrogen concentration (control) was equal to 168 grams $liters^{-1}$ following previous research based on the opinion of Yam et al. (2020). Nitrogen from chemical fertilisers in the form of NO_3 and NH_4 dissolved with water EC < 0.02 mS/cm. Nitrogen concentration treatments were given at three different growth phases of melon. In the vegetative phase (V), nitrogen concentration was given at 75% (V-75%), 50% (V-50%), and 25% (V-25%) of the control. The same treatment was also applied to the pollination and fruit formation phase (PFF), which was 75% (PFF-75%), 50% (PFF-50%), 25% (PFF-25%), and the fruit enlargement and ripening phase (FER) which was 75% (FER-75%), 50% (FER-50%), and 25% (FER-25%).

Figure 1. Hydroponic melon cultivated in the greenhouse in the present study

Observation

Observations focused on four main aspects: plant growth, chlorophyll index, yield, and nitrogen use efficiency. Plant growth variables consisted of plant height, leaf area, and plant dry weight observed at three important growth phases: the vegetative phase, pollination and fruit formation phase, and fruit enlargement and ripening phase. Leaf area was measured with Digimizer application. The dry weight of the plants was observed for 48 hours after drying in an oven at 70 °C.

Relative growth rate (RGR) was observed using the following formula:

$$RGR = \frac{(InW2 - InW1)}{(T2 - T1)} \tag{1}$$

where: W – natural logarithm of plant dry weight, T – observation time.

The chlorophyll index was measured at all three growth phases using SPAD 502. Yield measurements were taken 63 days after planting by weighing the fruit using an analytical balance with two-digit accuracy. Nitrogen use efficiency was calculated using the following formula (Yue et al., 2023):

$$NUE = \frac{Y}{F} \tag{2}$$

where: Y – fruit weight, F – total fertilisers nitrogen applied.

Statistical analysis

Data were analyzed using analysis of variance (ANOVA) with DSAASTAT software. Multiple treatments were compared using the Tukey's Honestly Significant Difference (Tukey) test.

RESULTS

Plant height

Melon plants' height exhibited significant variations in response to different nitrogen application times and concentrations. Figure 2 shows that the FER-50% treatment produced the highest plant height (about 210 cm), followed by the V-75% treatment (about 200 cm), while the V-25% treatment produced the lowest plant height (about 155 cm). Plant growth at each growth phase varied between treatments. The low dose treatment (25%) in the vegetative phase showed shorter plants. The pollination and fruit formation phases were longer in the FER-50% treatment, while the fruit enlargement and ripening phases showed the highest growth in the V-75% and FER-50% treatments.

There was an interesting relationship between growth phases, with treatments with moderate to high nitrogen concentrations (50–75%) showing a better balance of growth between phases. In the V-75% and FER-50% treatments, a reasonable allocation of growth in the vegetative phase was the foundation for an optimal reproductive phase. In contrast, low nitrogen concentrations (25%) tended to suppress vegetative growth, limiting growth potential in subsequent phases. The sufficient nitrogen supply in the first stages of melon growth had a positive impact on the success of the reproductive phase, giving a profitable impact along the entire life cycle of the plant.

Leaf area

Nitrogen concentration treatments also significantly affected the leaf area of melon plants

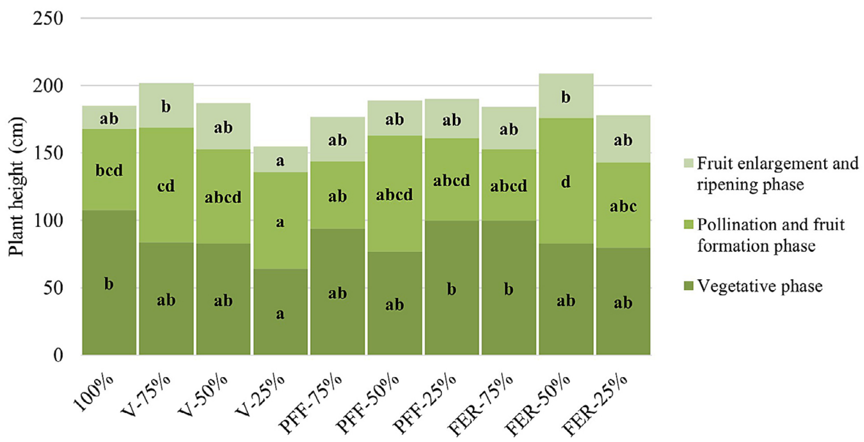

Figure 2. Height of melon plants across different nitrogen application timing and concentration treatments. Different letters in the same growth phase indicate significant differences at $p < 0.05$ according to the Tukey test

at different growth phases. Figure 3 shows the highest total leaf area in the PFF-75% treatment (about 77 dm²), followed by the V-75% treatment (about 70 dm²), while the V-25% and FER-25% treatments showed the lowest leaf area (about 38 dm² and 50 dm²). All treatments showed relatively same leaf area during the vegetative phase and the pollination and fruit formation phase. The main differences were seen at fruit enlargement and ripening, with the PFF-75% treatment displaying a larger leaf area.

The relationship of nitrogen effect between growth phases showed an interesting pattern; nitrogen concentration had more effect in the late phase than in the early phase. While all treatments showed the same leaf area growth in the vegetative phase, the allocation of resources for leaf formation in the later phase varied significantly based on nitrogen concentration. The PFF-75% nitrogen concentration treatment indicated the best ability to maintain leaf area growth. Optimal nitrogen availability was important for leaf growth initiation and maintaining efficient photosynthetic function during reproductive phase. In contrast, the low nitrogen treatment (25%), while able to support early leaf growth, failed to sustain leaf area expansion in the later phase, which could ultimately limit the capacity of the plant to produce photosynthates needed for fruit formation and filling. This relationship confirmed the critical role of nitrogen in regulating resource allocation between plant organs and between growth phases in hydroponic melon cultivation.

Dry weight

Nitrogen concentration had a significant effect on dry weight in the vegetative phase of melon plants (Figure 4). The PFF-50% formula produced the highest vegetative biomass (30 g),

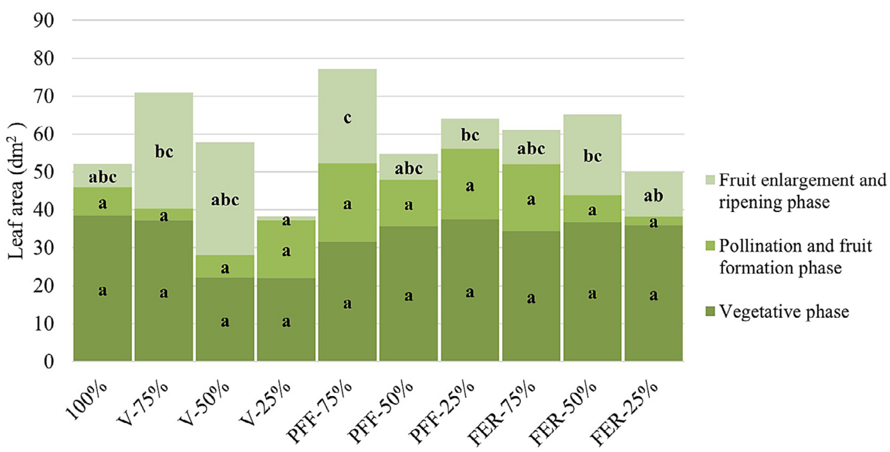

Figure 3. Leaf area of melon plants across different nitrogen application timing and concentration treatments. Different letters in the same growth phase indicate significant differences at $p < 0.05$ according to the Tukey test

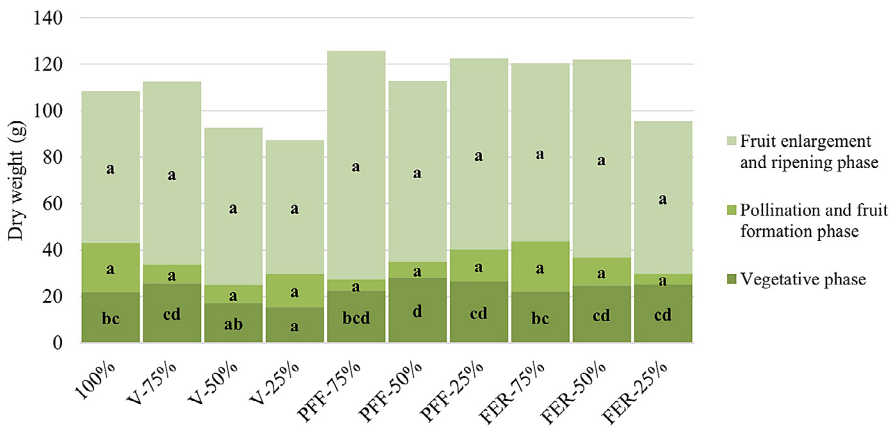

Figure 4. Dry weight of melon plants across different nitrogen application timing and concentration treatments. Different letters in the same growth phase indicate significant differences at $p < 0.05$ according to the Tukey test

followed by FER-50%, FER-25%, PFF-75%, PFF-25%, and V-75%. The PFF and FER formulas showed an advantage because the plants still consuming 100% nitrogen during the vegetative phase. The dry weight of plants in the V-25% and V-50% treatments was lower than the other treatments. Nitrogen reduction in the vegetative phase (25–50%) could have a negative impact on plants, while nitrogen reduction in PFF and FER with a nitrogen concentration of 25–50% effectively supported plant growth.

There was no significant difference between treatments in the pollination and fruit formation phase (15–30 g) and fruit enlargement and ripening phase (45–75 g). The highest total biomass was found in PFF-75% (125 g), PFF-25%, and FER-75% (120 g). Both PFF and FER treatments showed a more balanced biomass distribution, with 50–60% of the biomass allocated to the reproductive phase to produce fruit, unlike the vegetative phase treatments which more dominant in producing leaves and stems. Nitrogen reduction with PFF and FER formulas (25–75%) maintained total productivity and increased photosynthate allocation to reproductive organs that contributed directly to the yield.

The distribution of the effect of nitrogen concentration on biomass accumulation in various organs of melon plants can be seen in Figure 5. Total biomass showed a relatively balanced pattern in all treatments with an increasing trend in the V-75%, PFF-75%, PFF-50%, PFF-25%, and FER-75% FER-50% treatments. The distribution of fruit biomass illustrated an almost parallel pattern with the total biomass, meaning that most plant biomass was allocated for fruit production. Meanwhile, leaf biomass indicated a more limited, but more even distribution pattern across all treatments. Surprisingly, the distribution of stem biomass was concentrated at the center of the graph with low values, signifying minimal biomass allocation to this structural organ compared to other organs.

Nitrogen effect relationships among plant organs in the various treatments showed different resource allocation strategies in response to nitrogen availability. In the treatments with V-75% and PFF-75% nitrogen concentrations, plants could optimally allocate biomass to all organs, emphasizing high fruit production without compromising vegetative growth. This signified an efficient balance between source and sink functions. Conversely, in treatments with low nitrogen concentrations, such as V-25%, the plants showed a conservative strategy with lower biomass allocation to all organs while maintaining similar relative proportions between organs. Of particular interest was the FER-50% treatment, which demonstrated high efficiency in converting biomass to fruit, indicating that this formulation might optimize the translocation of assimilates to reproductive organs. This distribution pattern also revealed that

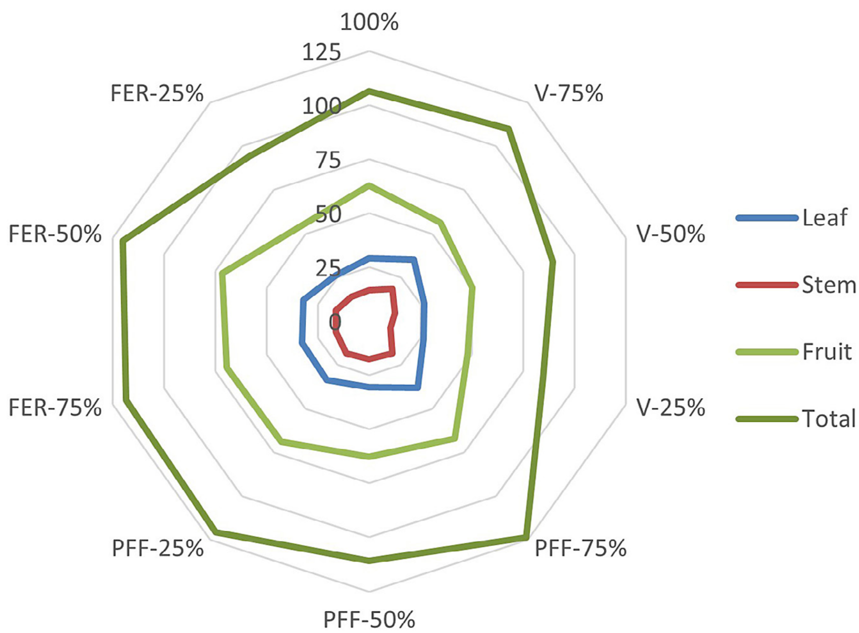

Figure 5. Dry weight of melon plant organs across different nitrogen application timing and concentration treatments

stem remained the lowest priority in biomass allocation at all levels of nitrogen availability. This highlights a strategy of minimizing investment in structural organs to maximize resource allocation towards organs directly contributing to plant productivity and survival. These findings support the understanding of the physiological plasticity of melon plants in response to nutrient variation in hydroponic systems.

Relative growth rate

The relative growth rate of melon plants showed significant differences at 28–35 days after planting (Figure 6). The control treatment did not differ from the V-25% and PEF-75% treatments (ranging from 95–100 mg day^{-1}). The treatments of V-75%, 50%, PFF-75%, PFF-25%, and FER-50% demonstrated moderate growth rates (ranging from 50–60 mg day^{-1}). At the same time, other treatments exhibited lower growth rates. Unlike the early period, 35–63 days after transplanting, all treatments displayed relatively same growth rates (ranging from 30–45 mg day^{-1}) and were not significantly different in all treatments.

The relationship between the effect of nitrogen on the growth rate of melon plants revealed contrasting patterns between growth periods. In the pollination and fruit formation (28–35 days), nitrogen concentration significantly affected the growth rate. The V-25% treatment was given 100% nitrogen in this phase, while the previous phase received only 25% nitrogen. In the active vegetative phase, adequate nitrogen availability was a critical factor that supported rapid cell division and expansion. In the later period (36–63 days), the differential effect of nitrogen was reduced, indicating a metabolic transition from the dominant vegetative growth to the reproductive phase. The plant focused on the development and filling of reproductive organs, thus leading to uniformity in relative growth rates across all treatments. This phenomenon showed the adaptive strategy of plants in the face of nitrogen limitation. Nitrogen-deprived plants in the vegetative phase with slow growth were then adapted to physiological mechanisms to achieve growth rates comparable to the high nitrogen concentration treatments. This finding strengthens the understanding of the flexibility of melon plants in regulating resource allocation and growth patterns in response to the dynamics of nutrient availability in hydroponic systems.

Chlorophyll index

The chlorophyll index in melon plants presented different responses due to nitrogen concentration treatment at various growth phases (Figure 7). The chlorophyll index in all treatments showed relatively similar values, with an increasing trend in the V-25% treatment. In the vegetative phase, in the control treatment (100%), PFF-25%, showed a higher chlorophyll index, while V-50% and V-25% treatments showed a lower chlorophyll index. However, during the pollination and fruit formation phase, as well as fruit enlargement and ripening phase, all treatments

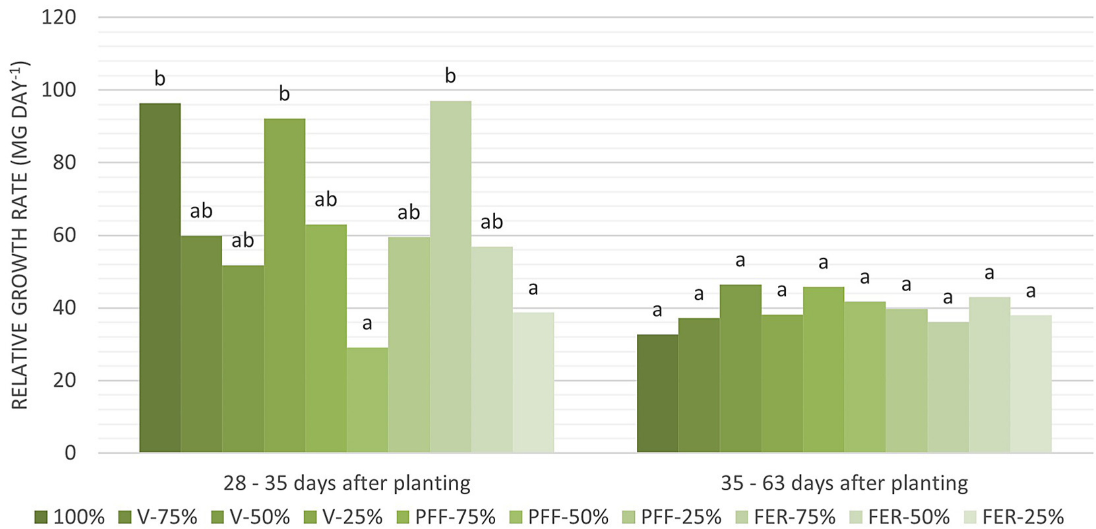

Figure 6. Growth rate of melon plants across different nitrogen application timing and concentration treatments. Different letters in the same growth phase indicate significant differences at $p < 0.05$ according to the Tukey test

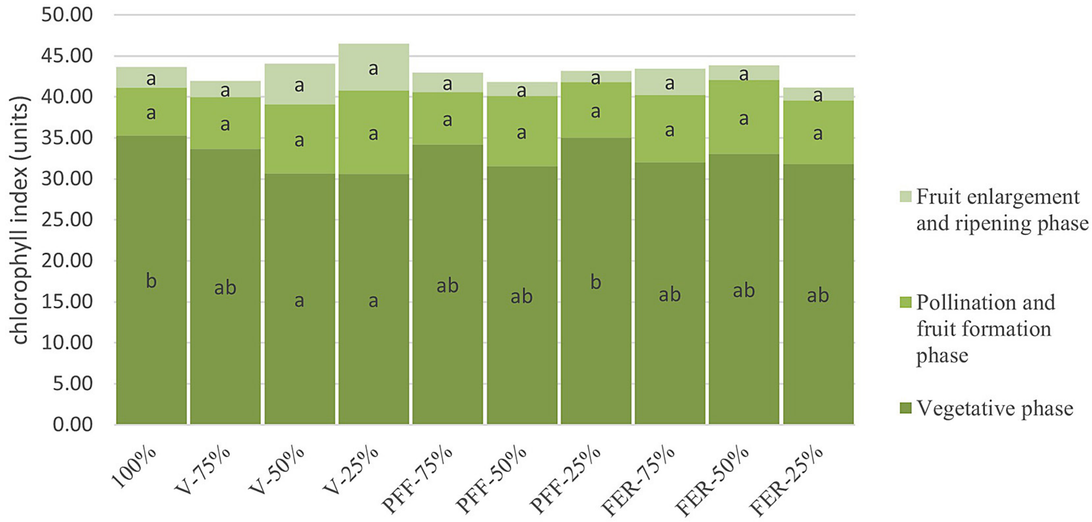

Figure 7. Chlorophyll index across different nitrogen application timing and concentration treatments. Different letters in the same growth phase indicate significant differences at $p < 0.05$ according to the Tukey test

displayed chlorophyll levels that were not significantly different.

In the physiological adaptation of melon plants, the chlorophyll index between growth phases exhibited an interesting relationship pattern. In the vegetative phase, plants with optimal nitrogen treatment (100%) and PFF-25% treatment showed high efficiency in nitrogen utilization for photosynthetic pigment synthesis. However, this advantage did not continue in the following phases, as all treatments produced the same chlorophyll index. Interestingly, the V-25% treatment, which showed a low chlorophyll index in the vegetative phase, increased its chlorophyll index in the next phase to the same level as the other treatments. Plants have strong adaptability to nitrogen limitation. Additionally, the consistency of a relatively high chlorophyll index across all growth phases indicates that melon plants prioritize the maintenance of an efficient photosynthetic apparatus to support the production of assimilates required during fruit development, even under conditions of variable nitrogen availability. This pattern confirms the strategic role of chlorophyll in maintaining the balance of plant metabolism during the transition from the vegetative to the reproductive phase in hydroponic melon cultivation.

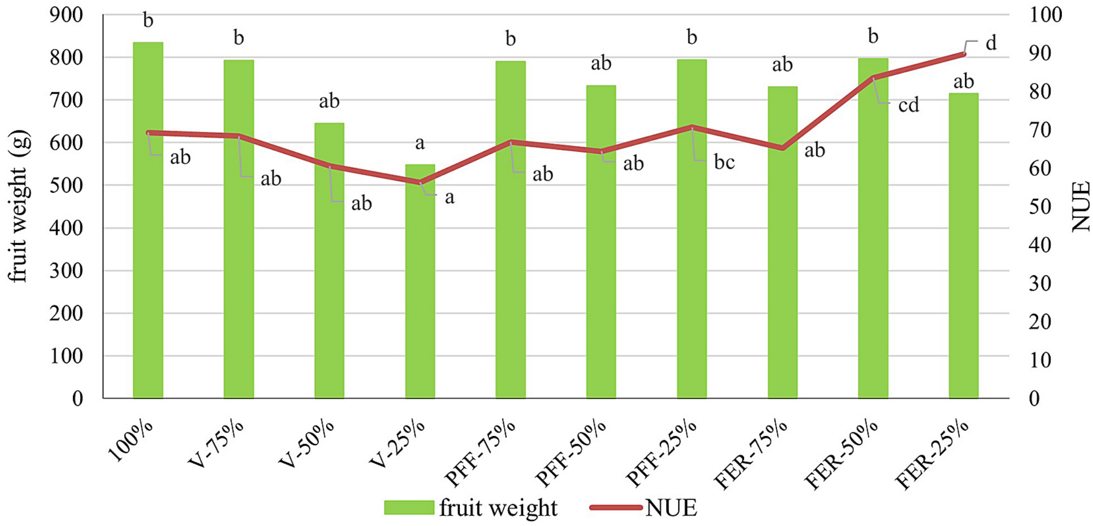

Figure 8. Yield and nitrogen use efficiency across different nitrogen application timing and concentration treatments. Different letters in the same growth phase indicate significant differences at $p < 0.05$ according to the Tukey test

Yield and nitrogen use efficiency

Nitrogen concentration had a significant effect on melon yield (Figure 8). The control treatment (100%) gave a yield of 830 g which was not different from V-75% (780 g), PFF-75% (790 g), FER-25% (794 g), and FER-50% (796 g), PFF-50% (733 g), FER-75% (730 g), FER-25% (714 g) and V-50% (644 g). Meanwhile, the V-25% treatment produced the lowest fruit weight of 547 g, showing significant differences from the other treatments. Nitrogen use efficiency (NUE) values differed significantly between treatments. The trend of NUE value did not align with the trend of differences in melon yield. The FER-25% treatment presented the highest NUE, approximately 90%, followed by the FER-50% treatment (83%). Meanwhile, the control (100%), V-75%, PFF-75%, and PFF-25% treatments that produced the highest fruit weight showed lower NUE ranging from 60-71%. Moreover, higher nitrogen use did not always result in optimal nitrogen use efficiency.

The relationship between yield and NUE in each treatment was rather interesting. Treatments with high nitrogen concentrations, such as the control (100%) and V-75%, tended to give high yields, but relatively lower NUE, resulting in less efficient nitrogen use. In contrast, the FER-25% treatment showed a better balance between yield and NUE. The plants could provide high yields with optimal nitrogen use efficiency at lower nitrogen concentrations. FER-25% might be a more sustainable option from an agronomic and environmental perspective, as it could minimize nitrogen inputs while maintaining relatively high yields. The study showed that a 25% nitrogen concentration at the enlargement and fruit ripening phases resulted in optimal plant growth, underlining the importance of efficient nitrogen management to improve productivity and nitrogen use efficiency in melon cultivation.

DISCUSSION

Nitrogen management is vital for the different growth phases of melon plants in hydroponic systems. Results showed that nitrogen effectivities varied significantly depending on the plant growth phase, with specific nitrogen treatments at each phase resulting in different growth and yield responses. The FER-50% treatment produced the tallest plants (± 210 cm), while the V-75% and PFF-75% treatments showed superiority in other growth parameters. These findings address the research objectives of analyzing the effect of nitrogen on melon plant growth parameters at various critical phases and investigating nitrogen use efficiency.

The effect of nitrogen on melon plant height is in line with the studies of Nascimento et al. (2020) and Zhu et al. (2024), which confirmed that nitrogen plays an important role in vegetative growth. However, the results of this study provide new insights by identifying the specific phase at which nitrogen application is most effective. The FER-50% treatment showed that moderate nitrogen concentrations at the fruit enlargement and ripening phases were more favorable than high concentrations, contradicting the findings of Cai et al. (2023) who recommended increasing nitrogen doses for optimal growth. These findings highlight the importance of phase-specific nitrogen regulation rather than just focusing on the total dose.

The leaf area distribution in this study was worth noting, with PFF-75% producing the highest total leaf area (±77 dm^2), supporting the statement of Nascimento et al. (2020) that nitrogen promotes leaf number and size. Nitrogen reduction at the pollination and fruit formation phases and fruit enlargement and ripening phases were still able to produce better leaf area. High nitrogen application in the vegetative phase supports strategic nitrogen allocation in the reproductive phase, which can maximize photosynthetic efficiency when the plant needs it most for fruit filling. Plants accumulate sufficient nitrogen reserves during vegetative growth, so that when entering the reproductive phase, nitrogen reallocation can occur optimally to support efficient photosynthesis processes, thereby increasing fruit filling productivity and overall yield.

Dry weight variables revealed a complex biomass allocation. The PFF-75% treatment resulted in higher total dry weight (± 125 g), but the biomass distribution between phases showed a different pattern from the other parameters. The vegetative phase shows significant variation between treatments, but the reproductive phase shows no significant differences. These results complement the understanding (Feng et al., 2023) on the effect of nitrogen on biomass allocation that melon plants have an internal mechanism to allocate resources more evenly during the reproductive phase regardless of variations in nitrogen inputs.

The results of the analysis of biomass accumulation in different plant organs reinforce the finding

(Grasso et al., 2022) that a proper nitrogen balance is essential for optimal biomass allocation. The biomass distribution pattern in Figure 4 indicates different resource allocation strategies in response to nitrogen availability. The FER-50% treatment showed high efficiency in converting biomass to fruit. Nitrogen concentration at the fruit filling and enlargement phases has a major influence on final productivity, a finding that has not been comprehensively discussed in previous literature.

The relative growth rate of melon plants is strongly influenced by nitrogen (Wang et al., 2024). In the period 28–35 days after planting, high nitrogen concentrations (75–100%) resulted in superior growth, supporting the findings of Chen et al. (2022) on the positive relationship between nitrogen concentration and RGR. Under suboptimal nitrogen supply conditions, such as in the V-25% treatment, the plants showed higher nitrogen utilization efficiency, contributing to increased RGR (Negrini et al., 2020). However, in the period 36–63 days after planting, the relative growth rate of plants was the same, indicating a metabolic transition from vegetative growth to the reproductive phase. This phenomenon has not been discussed in depth in the literature, but it provides new insights into the flexibility of melon plants in regulating growth in response to nutrient dynamics.

The results of the chlorophyll index analysis showed an interesting pattern of homeostasis. Despite variations in the vegetative phase, chlorophyll concentrations converged at the same rate in subsequent phases, implying a regulatory mechanism that maintains an optimal photosynthetic apparatus regardless of variations in nitrogen inputs. These findings extend the knowledge from Qu et al. (2022) and Zhu et al. (2024) regarding the influence of nitrogen on chlorophyll by showing how melon plants prioritize the maintenance of photosynthetic capacity during the transition from vegetative to reproductive phases.

Yield and nitrogen utilization efficiency (NUE) displayed an important inverse relationship. The control treatment (100%) produced the highest fruit weight (± 830 g), but the FER-25% treatment showed the highest NUE (± 90%). This finding supports the studies of Yue et al. (2023) and Xue et al. (2017) that nitrogen use efficiency can be improved by reducing nitrogen dosage while maintaining relatively high yields. These results also enrich the studies of Cai et al. (2023), Moreira et al. (2022), and Rolbiecki et al. (2021) by providing specific data on the optimal balance between productivity and nutrient efficiency. The theoretical implication of this study is the development of understanding concerning the economics of nitrogen in melon crops. The results showed the importance of considering nitrogen distribution according to the crop's phase-specific needs. The findings assist the evolution of the Demand-Driven Nutrient Supply approach (Wen et al., 2022) into a more comprehensive model that integrates the dynamics of plant nutrient requirements.

Practically, the results demonstrate that melon farmers can optimize nitrogen use by applying phase-specific strategies. Nitrogen reduction by 75% in the enlargement and fruit ripening phases (FER-25%) could maintain competitive yields while significantly improving NUE. These implications are highly relevant to the challenges of sustainable agriculture, in line with the findings of Sainju et al. (2019) and Martínez-Dalmau et al. (2021) on the negative environmental impacts of excessive nitrogen use. The results support the development of regulations and incentives that promote precision nitrogen management practices. Reduction of nitrogen use by 75% at specific phases could reduce environmental pollution and the carbon footprint of melon production, contributing to the mitigation of agriculture's impact on climate change, as discussed by Dimkpa et al. (2020).

An unpredictable finding of this study was that chlorophyll index and dry weight in the reproductive phase were not significantly different across all treatments, contrasting with the vegetative phase. This phenomenon suggests a homeostasis mechanism that is not yet fully understood. Melon plants can adjust their physiology to maintain essential functions regardless of variations in nitrogen inputs. This may reflect prioritization to confirm reproductive success even under suboptimal conditions.

Farmers can apply the results of this study. Hydroponic melon farmers can directly adopt the results of this study to reduce production costs and environmental pollution. For farmers using soil cultivation, it can be used as a reference for nitrogen reduction, but the appropriate nitrogen concentration according to soil fertility must be reviewed.

To summarize, this study confirmed that a 'one-size-fits-all' approach is not optimal for nitrogen management in melon cultivation. Instead, precision strategies adapted to the crop's phase-specific needs can simultaneously improve productivity, nutrient use efficiency, and environmental sustainability. These findings provide a scientific foundation for the evolution of farming practices from conventional nitrogen management towards more sophisticated and sustainable approaches that maximize benefits and minimize economic and environmental costs.

CONCLUSIONS

The results of this study suggest that optimal nitrogen management in melon requires a growth-phase-based approach rather than focusing solely on total dosage. Nitrogen reduction at the right growth phase did not reduce melon yield. The development of a precision nitrogen management model can be done by considering the nitrogen needs of plants according to their growth phase. Melon plants show remarkable adaptability to variable nitrogen availability. Physiological homeostasis mechanisms play an important role in maintaining the balance of plant metabolism, which is reflected in the stable chlorophyll index and relative growth rate in the reproductive phase. This study also revealed the existence of a sophisticated internal regulatory system in melon plants. This system consistently prioritizes reproductive function and fruit set despite facing suboptimal nitrogen supply conditions. Reduction of nitrogen input by 75% in the enlargement and fruit ripening phases was possible without significantly compromising yield. Nitrogen reduction at the appropriate growth phase increases efficiency, reducing production costs and minimizing environmental impacts such as groundwater pollution and greenhouse gas emissions. Nitrogen use efficiency is highly relevant to the sustainability challenges of modern agriculture.

REFERENCES

1. Anas, M., Liao, F., Verma, K., Sarwar, M., Mahmood, A., Chen, Z., Li, Q., Zeng, X.-P., Liu, Y., Li, Y. (2020). Fate of nitrogen in agriculture and environment: agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. *Biological Research*, *53*. https://doi.org/10.1186/s40659-020-00312-4
2. Cai, Z., Bai, J., Li, R., He, D., Du, R., Li, D., Hong, T., Zhang, Z. (2023). Water and nitrogen management scheme of melon based on yield–quality–efficiency matching perspective under CO_2 enrichment. *Agricultural Water Management*, *285*, 108379. https://doi.org/10.1016/j.agwat. 2023.108379
3. Chang, L., Li, D., Hameed, M. K., Yin, Y., Huang, D., Niu, Q. (2021). Using a hybrid neural network model DCNN–LSTM for image-based nitrogen nutrition diagnosis in muskmelon. *Horticulturae*. https://doi.org/10.3390/horticulturae7110489
4. Chen, Y., Chu, C., He, F., Fang, S. (2022). A mechanistic model for nitrogen-limited plant growth. *Annals of Botany*.583–591. https://doi.org/10.1093/aob/mcac018
5. Dimkpa, C., Fugice, J., Singh, U., Lewis, T. (2020). Development of fertilizers for enhanced nitrogen use efficiency - Trends and perspectives. *The Science of the Total Environment*, *731*, 139113. https://doi.org/10.1016/j.scitotenv.2020.139113
6. Feng, H., Guo, J., Peng, C., Kneeshaw, D., Roberge, G., Pan, C., Xuehong, Zhou, D., Wang, W. (2023). Nitrogen addition promotes terrestrial plants to allocate more biomass to aboveground organs: A global meta-analysis. *Global Change Biology*, *29*, 3970–3989. https://doi.org/10.1111/gcb.16731
7. Fu, Y., Yang, X., Zhang, Z., Yuan, S. (2022). Synergistic effects of nitrogen metabolites on auxin regulating plant growth and development. *Frontiers in Plant Science*, *December*, 1–7. https://doi.org/10.3389/fpls.2022.1098787
8. Govindasamy, P., Muthusamy, S., Bagavathiannan, M., Mowrer, J., Jagannadham, P., Maity, A., Halli, H., K., S., Vadivel, R., K., D., Raj, R., Pooniya, V., Babu, S., Rathore, S., L., M., Tiwari, G. (2023). Nitrogen use efficiency—a key to enhance crop productivity under a changing climate. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1121073
9. Grasso, R., Peña-Fleitas, M., De Souza, R., Rodríguez, A., Thompson, R., Gallardo, M., Padilla, F. (2022). Nitrogen effect on fruit quality and yield of muskmelon and sweet pepper cultivars. *Agronomy*. https://doi.org/10.3390/agronomy12092230
10. Gu, J., Li, Z., Mao, Y., Struik, P. C., Zhang, H., Liu, L., Wang, Z., Yang, J. (2018). Roles of nitrogen and cytokinin signals in root and shoot communications in maximizing of plant productivity and their agronomic applications. *Plant Science*, *274*, 320–331. https://doi.org/10.1016/j.plantsci. 2018.06.010
11. Kishorekumar, R., Bulle, M., Wany, A., Gupta, K. J. (2020). An overview of important enzymes involved in nitrogen assimilation of plants. *Methods in Molecular Biology (Clifton, N.J.)*, *2057*, 1–13. https://doi.org/10.1007/978-1-4939-9790-9_1
12. Krapp, A. (2015). Plant nitrogen assimilation and its regulation: a complex puzzle with missing pieces. *Current Opinion in Plant Biology*, *25*, 115–122. https://doi.org/10.1016/j.pbi.2015.05.010
13. Machado, R. M. A., Serralheiro, R. P. (2017). Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil

salinization. *Horticulturae*, *3*(2), 30. https://doi.org/10.3390/horticulturae3020030

14. Martínez-Dalmau, J., Berbel, J., Ordonez-Fernandez, R. (2021). Nitrogen fertilization. A review of the risks associated with the inefficiency of its use and policy responses. *Sustainability*, *13*, 5625. https://doi.org/10.3390/SU13105625
15. Moreira, L., Da Silva, L. D., Nascimento, B. M. Do, Da Silva, A. J. B., Teixeira, A., De Oliveira, M. R. R. (2022). Agronomic performance and fruit quality of yellow melon fertilized with doses of nitrogen and potassium. *Revista Caatinga*. https://doi.org/10.1590/1983-21252022v35n208rc
16. Muratore, C., Espen, L., Prinsi, B. (2021). Nitrogen uptake in plants : The plasma membrane root transport systems from a physiological and proteomic perspective. *Plants*. https://doi.org/ 10.3390/plants10040681
17. Nascimento, C., Nascimento, C., Filho, A. C. (2020). N:K ratio for phenological growth stages of net melon cultivated in nft hydroponic system1. *Revista Caatinga*. https://doi.org/10.1590/1983-21252020v33n112rc
18. Nasiro, K., Mohammednur, T. (2024). Precision nutrient management amid climate change challenges : a review. *Science Frontiers*, *5*(3), 110–122. https://doi.org/10.11648/j.sf. 20240503.12
19. Nawaz, M., Wang, L., Jiao, Y., Chen, C., Zhao, L., Mei, M., Yu, Y., Bie, Z., Huang, Y. (2017). Pumpkin rootstock improves nitrogen use efficiency of watermelon scion by enhancing nutrient uptake, cytokinin content, and expression of nitrate reductase genes. *Plant Growth Regulation*, *82*, 233–246. https://doi.org/10.1007/s10725-017-0254-7
20. Negrini, A. C. alves, Evans, J. R., Kaiser, B. N., Millar, A. H., Kariyawasam, B. C., Atkin, O. K. (2020). Effect of N supply on the carbon economy of barley when accounting for plant size. *Functional Plant Biology*, *47*(4), 368–381. https://doi.org/10.1071/FP19025
21. Qu, F., Peng, T., Jia, Y., Yang, M., Meng, X., Mao, S., Zhou, D., Hu, X. (2022). Adjusting leaf nitrogen allocation could promote photosynthetic capacity, and nitrogen accumulation in *Cucumis sativus* L. *Environmental and Experimental Botany*, *198*, 104855. https://doi.org/10.1016/ j.envexpbot.2022.104855
22. Rolbiecki, R., Rolbiecki, S., Figas, A., Jagosz, B., Wichrowska, D., Ptach, W., Prus, P., Sadan, H., Ferenc, P., Stachowski, P., Liberacki, D. (2021). Effect of drip fertigation with nitrogen on yield and nutritive value of melon cultivated on a very light soil. *Agronomy*, *11*, 934. https://doi.org/10.3390/agronomy11050934
23. Sainju, U., Ghimire, R., Pradhan, G. (2019). Nitrogen fertilization I: Impact on crop, soil, and environment. *Nitrogen Fixation*. https://doi.org/10.5772/intechopen.86028
24. Temkin, A., Evans, S., Manidis, T., Campbell, C., Naidenko, O. V. (2019). Exposure-based assessment and economic valuation of adverse birth outcomes and cancer risk due to nitrate in United States drinking water. *Environmental Research*, *176*, 108442. https://doi.org/ 10.1016/j.envres.2019.04.009
25. Wang, Q., Li, S., Li, J., Huang, D. (2024). The utilization and roles of nitrogen in plants. *Forests*. https://doi.org/10.3390/f15071191
26. Wen, M., Yang, S.-C., Huo, L., He, P., Xu, X., Wang, C., Zhang, Y., Zhou, W. (2022). Estimating nutrient uptake requirements for melon based on the QUEFTS model. *Agronomy*. https://doi.org/10.3390/agronomy12010207
27. Xue, L., Zhong-Ming, Du, S. (2017). Effects of grafting and nitrogen fertilization on melon yield and nitrogen uptake and utilization. *Ying Yong Sheng Tai Xue Bao = The Journal of Applied Ecology*, *28 6*, 1909–1916. https://doi.org/10.13287/j.1001-9332.201706.004
28. Yam, R., Fan, Y.-T., Lin, J., Fan, C., Lo, H. (2020). Quality improvement of netted melon (cucumis melo L. var. reticulatus) through precise nitrogen and potassium management in a hydroponic system. *Agronomy*. https://doi.org/10.3390/agronomy10060816
29. Yue, W., Chen, S., Gao, L., Li, N., Liu, L. (2023). Effects of water and nitrogen coupling on yield, quality, water and nitrogen use efficiencies of greenhouse muskmelon. *Water*. https://doi.org/ 10.3390/w15142603
30. Zhu, Y., Sun, Z., Wu, H., Cui, C., Meng, S., Xu, C. (2024). Transcriptomic analysis of the molecular mechanism potential of grafting – enhancing the ability of oriental melon to tolerate low-nitrogen stress. *International Journal of Molecular Sciences*, *25*. https://doi.org/10.3390/ijms 25158227