Root Architectural Responses Mediate Productivity under Balanced Nitrogen and Magnesium Nutrition in Greenhouse-Grown Asparagus

Dinh Thi Ngoc Nguyen
ngocdinhhau1@gmail.com

Vietnam National University of Agriculture
Nguyen Hong Hanh
Roel Rodriguez Suralta
Khuynh The Bui

Research Article

Keywords: Asparagus officinalis, ecological nutrient management, magnesium, nitrogen use efficiency, nitrate accumulation, root architecture, sustainable greenhouse production

Posted Date: August 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10560649/v1

Abstract

Purpose

This study evaluated the interactive effects of nitrogen (N) and magnesium (Mg) fertilization on growth, yield, spear quality, nitrate accumulation, and root system architecture of greenhouse-grown asparagus (*Asparagus officinalis* L.) under Northern Vietnam conditions.

Methods

A factorial experiment was conducted using three nitrogen rates (3, 4.5, and 6 g N pot^{-1}) and three magnesium rates (0, 1, and 2 g MgO pot^{-1}) arranged in a completely randomized design with three replications. Plant growth, chlorophyll content, spear yield, quality traits, root morphology, and root anatomy were evaluated. Pearson correlation and principal component analysis (PCA) were performed to identify relationships among productivity-related traits.

Results

Moderate nitrogen supply (4.5 g pot^{-1}) combined with 1 g MgO pot^{-1} significantly improved yield, spear quality, chlorophyll content, and root development. Excessive nitrogen (6 g pot^{-1}) increased nitrate accumulation without proportional yield improvement and reduced root growth. Correlation and PCA results showed that productivity during the first harvest was primarily associated with aboveground traits, whereas root system architecture became increasingly important during the second harvest. Root length, diameter, and volume were strongly associated with harvested yield.

Conclusions

These findings demonstrate that balanced N–Mg nutrition promotes asparagus productivity by coordinating root structural development with physiological performance rather than simply increasing nutrient supply. The transition from shoot-dependent to root-mediated productivity provides new insight into nutrient-response mechanisms in perennial asparagus and highlights root system development as a key target for improving nutrient-use efficiency and sustainable greenhouse production.

Introduction

Asparagus (*Asparagus officinalis* L.) is a high-value perennial vegetable crop widely cultivated for its nutritional quality and economic returns. In recent years, asparagus production has expanded rapidly in tropical and subtropical regions, including Vietnam, where greenhouse and protected cultivation systems have been increasingly adopted to stabilize yield and improve market quality. However, intensive asparagus cultivation is often associated with high fertilizer inputs, particularly nitrogen (N), which may increase productivity in the short term but frequently results in low nutrient-use efficiency, nitrate accumulation, and environmental risks associated with nutrient losses (Wang et al., 2022). In protected cultivation systems, where nutrient inputs are highly concentrated and soil buffering capacity is limited, improving fertilization efficiency has become a major challenge for sustainable crop production and environmental management (Savvas & Gruda, 2018).

Nitrogen (N) is a key macronutrient governing plant growth, playing essential roles in chlorophyll synthesis, protein formation, and vegetative development (Zhang et al., 2015). Previous studies have demonstrated that increasing N supply enhances spear emergence, biomass accumulation, and overall yield in asparagus (Hikasa, 2000; Nicola, 2000). However, the response to N is strongly rate-dependent. Optimal yields have been reported at approximately 200–250 kg N ha^{-1} (Hikasa, 2000; Xikang et al., 2005), whereas excessive application, particularly above 400 kg N ha^{-1}, can suppress root development, reduce yield, and increase nitrate accumulation in spears, posing both agronomic and environmental risks (Hu et al., 1992; Ji et al., 2006). In Vietnam, current fertilization practices often exceed recommended levels (350–500 kg N ha^{-1}), raising concerns about nutrient use efficiency and sustainability. Beyond nitrogen management, magnesium (Mg) has emerged as an important but frequently overlooked nutrient in intensive horticultural systems. Magnesium is the central atom of the chlorophyll molecule and serves as an activator of numerous enzymes involved in photosynthesis, carbohydrate metabolism, and assimilate transport (Cakmak & Yazici, 2010; Hermans et al., 2013). In perennial crops such as asparagus, Mg availability may be particularly important because spear production depends not only on current photosynthesis but also on the remobilization of carbohydrate reserves stored in underground root systems and crowns. Recent studies have suggested that adequate Mg supply can improve nitrogen assimilation efficiency, enhance carbon allocation, and mitigate the negative physiological consequences of excessive nitrogen supply (Guo et al., 2016; Tränkner et al., 2018). Despite this recognized physiological role, the interaction between N and Mg remains insufficiently understood in asparagus production systems, particularly under greenhouse conditions.

Increasing evidence suggests that sustainable nutrient management should move beyond single-factor fertilization approaches toward integrated strategies that improve nutrient-use efficiency while minimizing environmental risks. In perennial crops, root system architecture plays a pivotal role in regulating nutrient acquisition, water uptake, and long-term productivity (Lynch, 2019; Rogers & Benfey, 2015). Root traits such as root length, diameter, surface area, and volume are increasingly recognized as functional indicators of plant adaptation to nutrient availability and resource-use efficiency (Lynch, 2019). However, little information is available regarding how balanced N and Mg inputs influence root system development and whether root traits mediate yield responses in greenhouse asparagus cultivation. This knowledge gap remains particularly important in emerging asparagus production regions, where fertilization practices are often based on empirical experience rather than physiological evidence.

Recent advances in root phenotyping technologies have created new opportunities to investigate plant responses to fertilization with greater precision. Tools such as RhizoVision Explorer enable quantitative assessment of root morphology and architecture, providing mechanistic insights into how nutrient management affects belowground processes linked to crop productivity (Seethepalli et al., 2021). Integrating root phenotyping with physiological, yield, and quality assessments may therefore improve understanding of nutrient-response mechanisms and support the development of ecologically efficient fertilization strategies.

Therefore, this study aimed to evaluate the interactive effects of nitrogen and magnesium inputs on plant growth, spear yield, quality traits, nitrate accumulation, and root system architecture of greenhouse-grown asparagus under Northern Vietnam conditions. Unlike conventional fertilizer studies focusing solely on yield response, this study integrates root phenotyping and multivariate analysis to elucidate the mechanisms linking nutrient supply, root development, and productivity. The findings are expected to provide a scientific basis for balanced nutrient management strategies that enhance production efficiency while reducing nitrate-related environmental risks in protected asparagus cultivation.

Materials and methods

Experimental site and Plant Materials

The experiment was conducted in a greenhouse at the Faculty of Agronomy, Vietnam National University of Agriculture (VNUA), located in Hanoi, Vietnam from May to September 2021. The average daytime temperature in the greenhouse ranged from 28–35°C, with relative humidity between 65–85% measured using ElitechLog V6.4.3 self-recording therm-hygrometer.

The asparagus “Atlas” cultivar was planted on the 19th May 2021 using 2.5 - month - old pre-grown seedlings in pots in the greenhouse of the Faculty of Agronomy, Vietnam National University of Agriculture - VNUA, Trau Quy town, Gia Lam district, Hanoi city, Vietnam (21°00'00" N, 105°56'00" E). The first harvest was conducted from March 1 to 31, 2022, corresponding to 10 months after planting (MAP) while the second harvest was done on July 1 to 31, 2022, (14 MAP) or 4 months after the first harvest.

Experimental Design and Fertilizer Treatments

A factorial experiment was arranged in a completely randomized design (CRD) with three replications, totaling 27 pots (3 N × 3 MgO × 3 reps). The experiment included 2 factors: 3 nitrogen levels: 3g N pot^{-1} (N_3), 4.5g N pot^{-1}($N_{4.5}$) and 6g N pot^{-1} (N_6) and 3 Magnesium levels: no MgO applied (M_0) 1g MgO pot^{-1}(M_1) and 2g MgO pot^{-1} (M_2). Each pot (19 × 13 × 14 cm) containing 10 kg of alluvial soil. The sources of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) were urea (46% N), super phosphate (16% P_2O_5), and potassium chloride (60% K_2O), respectively. Compost fertilizer (relative humidity 30%, nitrogen 1.0%, organic matter 25%) was applied at a rate of 30 g pot^{-1} one day before transplanting.

Measurements

The pH, EC in the soil solution for growing asparagus was measured monthly by collecting the solution flowing from the bottom of the pot (100ml/pot) using Mettler Toledo (Japan). The growth dynamics of height, diameter and number of mother stem/cluster were measured once a month, using the mother stem with maximum height and diameter/cluster. *The* Chlorophyll a, b and a + b content in phylloclades at 9 MAP were measured according to the method of Wintermans and De Mots (1965) (Nguyen Hong Hanh et al., 2024). Carbohydrate content (CHO) in roots at 9 MAP through measuring Brix roots by Wilson et al., (2005) method according to the formular: CHO = 21.1 x Brix% + 42.9 (mg g^{-1}).

The *yield, yield components* and quality characteristics measurements were done at 10 months after planting, when the main plants turned yellow. The entire stem of the mother plant was cut and the emerging spears were cut when they reached approximately 27cm in length. The number of spears in a plant was counted and weighed to record the harvested yield during the harvesting time at 30 days after planting. A second harvest was conducted four months after the first harvest following standard asparagus harvesting procedures described for perennial spear production systems (Hikasa, 2000; Nicola, 2000). *For spear quality characteristics*, the spears were classified based on their thickness as follows: Grade 1: diameters of spear bases ≥ 12.0 mm; Grade 2: 10.0-11.9 mm; Grade 3: 7.0 -9.9 mm; and Grade 4: 4.0 -6.9 mm. Brix content of spear (%) measured using a Milwaukee 882 meter; NO_3^- accumulation was analyzed according to Vietnamese standard (10 TCN 457–2001).

Root characteristics: For the total root length, root diameter, root volume, root surface area, at harvest, the intact root systems were scanned with a flatbed scanner (GT-X980, EPSON, Tokyo, Japan). The scanned images were then subjected to RhizoVison Explorer software to measure the following traits: total root length (TRL); average root diameter (ARD), total root surface area (RSA), and total root volume (Vol), following the methods of Seethepalli et al. (2021). Fresh and dry weight of root after dried to a constant weight.

Root anatomical analysis: At the second harvest (14 months after planting), five representative storage roots were collected from each experimental replicate for anatomical analysis. To minimize developmental variation, roots selected within each replicate were of similar age, diameter, and developmental stage, and were collected from comparable positions on the crown. Root segments approximately 2 cm in length were excised from the middle portion of each storage root, avoiding both the root apex and the basal attachment region to ensure anatomical consistency among samples. Immediately after sampling, the root segments were fixed in FAA solution consisting of 90% (v/v) 50% ethanol, 5% formaldehyde, and 5% glacial acetic acid for 48 h at room temperature. After fixation, the samples were transferred to 70% ethanol and stored at 4°C until anatomical observations. Transverse sections were prepared manually using the hand-section technique with a sharp double-edged razor blade. Thin cross-sections were obtained from the middle portion of each root segment and stained with 1% safranin O for approximately 5 min, followed by rinsing with distilled water and mounting on glass slides using glycerol for microscopic observation. Root cross-sections were examined under an Olympus BX53 light microscope (Olympus Corporation, Tokyo, Japan) equipped with a digital imaging system. Digital micrographs were captured under identical magnification for all samples. Anatomical measurements were performed using cellSens Standard software (Olympus Corporation, Tokyo, Japan). The following anatomical parameters were quantified: pericycle area (μm^2), pericycle perimeter (μm), and pericycle diameter (μm). For each replicate, measurements were obtained from five representative roots, and the mean value was used for subsequent statistical analysis.

Data analysis

Analysis of variance (ANOVA) of agronomical characteristics was performed using Minitab 16, the significance of mean values was analyzed using Tukey's test at 5% level of significance. In addition, Pearson correlation analysis was performed to assess the strength and direction of relationships among growth, yield, quality, and root traits, with significance evaluated at $P < 0.05$ and $P < 0.01$. Principal component analysis (PCA) was conducted using a correlation matrix to reduce data dimensionality and identify key variables driving variation among treatments. Principal components with eigenvalues greater than 1 were retained, and score plots and biplots were used to interpret the multivariate structure and relationships among variables.

Results

Soil pH and EC

The pH and the electrical conductivity of the solution were relatively stable throughout the experiment (Figs. 1A and 1B).

Plant growth parameters

Asparagus height increased over time, with the maximum height (192 cm) occurred at 10 months after planting (MAP) in asparagus applied with 3 g of N and 1 g of MgO (N_3M_1) (Fig. 2A). The stem diameter also increased gradually over time, there was no significant difference among treatment combinations (Fig. 2B).

The number of mother stems per plant increased gradually over time, in which the asparagus applied with 4.5 g N and no MgO ($N_{4.5}M_0$) produced the highest number of stems per plant at 16.3 while those applied with 3 g N with no MgO (N_3M_0) had the lowest number of stems per plant at 9.3 stems per plant (Fig. 3).

Chlorophyll Content

There was no significant interaction between N and MgO treatments on Chl. a and Chl b contents (Table 1). The Chl.a was significantly affected by both N and MgO rates while Chl. b was not significantly affected by either N and MgO rates. On the other hand, there was a significant interaction between N and MgO rates on Chl. a + b. Increasing N levels led to a corresponding increase in chlorophyll a (Chl.a) content, which was significantly higher in 6g than either in 4.5 and 3 g N per pot, regardless of MgO levels. On the other hand, N levels, the application of 1MgO of MgO significantly increased the Chl a level. The combined chlorophyll a + b content increased was significantly increased by MgO level at 1g per pot, relative to the control in both 3 and 6g N per pot (Table 1).

Spear Yield and Yield Components

There was no significant interaction between N and MgO levels on the number and weight of spear and the harvested yield regardless of harvesting time (Table 2). At 10MAP, the number of spear per plant was significantly affected by MgO rates only. Highest number of spears was observed at 1g MgO per pot, regardless of N levels. On the other hand, the spear weight was significantly affected by N rates only with heaviest spear weight observed at 6MgO N per pot, regardless of MgO rates. Finally, the harvested yield at 10 MAP was affected by N rates only, where the harvested yield was highest at 4.5 g N per pot, regardless of MgO rates. At second harvest (14 MAP), the number of spears per plant was significantly affected by both N and MgO rates. Across N, highest number of spears per plant was observed in 1g MgO per pot whole across MgO, the highest number of spears per plant was observed 4.5g N per pot. The spear weight was significantly affected by MgO rates only with heaviest spear weight was observed in 1g MgO per pot. Furthermore, the harvested yield at 14 MAP was significantly affected by both N and MgO rates (Table 3). At the first harvest, harvested yield was significantly affected by both N and MgO rates. Across nitrogen treatments, the highest mean yield was observed at 2 g MgO pot^{-1}, although no significant difference was detected compared with 1 g MgO pot^{-1}. Meanwhile, across MgO treatments, the highest harvested yield was achieved at 4.5 g N pot^{-1}.

Asparagus Quality Traits

As for the quality of harvested asparagus at 10 MAP, there was a significant interaction between N and MgO rates on spear brix and NO_3^- but not dry matter (Table 3). The percent dry matter was significantly affected by MgO rates only, with highest value observed at 2g MgO per pot, across N rates. For spear brix, the highest value (7.3) was observed in $N_{4.5}M_2$ treatments. Furthermore, the highest NO_3^- values was observed at in treatments applied with 6g N and 3 g MgO per pot (N_6M_2) (Table 4).

At 14 MAP, there was no significant interaction between N and MgO rates on percent dry matter, spear brix and NO_3^- (Table 4). The percent dry matter was significantly affected by N rates only. Across MgO rates, the percent dry matter was highest in 4.5 g N per pot. Spear brix was not significantly affected by either N or MgO rates at 14 MAP. On the other hand, the NO_3^- was significantly affected by N rates only, peaking at 3 g N per pot, regardless of MgO rates.

Root system development and anatomical responses

Nitrogen and magnesium fertilization significantly influenced root system architecture of asparagus, with clear differences observed among treatment combinations (Table 5). A significant interaction between N and MgO was detected for total root length (TRL), root diameter (AD), root surface area (SA), and root volume (TV) ($P < 0.01$), indicating that root responses depended on the combined nutrient supply rather than individual nutrient effects alone.

Across nitrogen levels, the moderate N treatment (4.5 g pot^{-1}) produced the most developed root system, exhibiting significantly greater TRL (99,678.7 mm), root diameter (3.12 mm), and root volume (854,659 mm^3) compared with lower or excessive N inputs. Magnesium supplementation also markedly enhanced root development, with 1 g MgO pot^{-1} (M1) resulting in the highest TRL (89,524.7 mm), surface area (754,089 mm^2), and root volume (838,276 mm^3) across nitrogen treatments.

Among all treatment combinations, N4.5M1 produced the most extensive root system, characterized by the greatest total root length (123,578 mm), root diameter (3.28 mm), and root volume (1,122,779 mm^3), whereas N3M1 recorded the highest root surface area (932,827 mm^2). In contrast, treatments without MgO supplementation (M0) generally exhibited smaller and less developed root systems regardless of nitrogen level. Excessive nitrogen input (N6), despite increasing root diameter relative to N3, did not result in proportional increases in root length or root volume, particularly under low Mg availability.

Root anatomical traits also responded to nutrient treatments (Table 6; Fig. 4). Significant N × Mg interactions were observed for pericycle area and pericycle diameter ($P < 0.01$), whereas pericycle perimeter was not significantly affected. Larger pericycle areas and diameters were generally observed under moderate-to-high nutrient inputs, particularly in N3M2, N4.5M1, and N6M1 treatments, suggesting structural modifications of root tissues in response to nutrient availability.

Regression analysis further demonstrated positive relationships between root system development and asparagus productivity (Fig. 5). Total harvested yield increased significantly with increasing root length ($r = 0.41$, $P < 0.01$) and root diameter ($r = 0.55$, $P < 0.01$), indicating that plants with larger and thicker root systems tended to achieve higher productivity under greenhouse conditions.

Trait interrelationships reveal root-mediated productivity and nitrate dynamics

Pearson correlation analysis revealed distinct patterns of association among physiological traits, yield components, quality parameters, and root characteristics across harvesting periods (Tables 7 and 8). During the first harvest, productivity was primarily associated with aboveground growth and physiological performance. Harvested yield (IY) exhibited strong positive correlations with spear number (NP; $r = 0.902$, $P < 0.01$) and spear weight (SW; $r = 0.760$, $P < 0.01$), indicating that early productivity was mainly determined by the combined contribution of spear emergence and biomass accumulation. Chlorophyll a (Chla) was positively correlated with both spear number ($r = 0.581$, $P < 0.01$) and harvested yield ($r = 0.651$, $P < 0.01$), while total chlorophyll content (Chla + b) also showed positive relationships with yield-related variables. Dry matter content (DM) exhibited a moderate positive correlation with harvested yield ($r = 0.592$, $P < 0.01$), suggesting a close association between biomass accumulation and productivity during the first harvest.

In contrast, quality traits appeared less strongly integrated with productivity during the early harvest stage. Spear Brix showed weak and non-significant relationships with yield variables, whereas nitrate concentration (NO_3^-) displayed only a moderate positive correlation with spear weight ($r = 0.365$, $P < 0.05$) and no significant association with total yield. These findings indicate that nitrate accumulation and sweetness were not major determinants of yield formation during the initial harvesting period.

During the second harvest, the correlation structure became more integrated and revealed a stronger contribution of root system development to productivity (Table 8). Harvested yield (IY2) remained strongly correlated with spear number (NP2; $r = 0.858$, $P < 0.01$) and spear weight (SW2; $r = 0.781$, $P < 0.01$), but additional significant associations emerged between yield and root morphological traits. Positive correlations were observed between harvested yield and total root length (TRL; $r = 0.555$, $P < 0.01$), average root diameter (AD; $r = 0.596$, $P < 0.01$), root volume (TV; $r = 0.562$, $P < 0.01$), and root surface area (SA; $r = 0.337$, $P < 0.05$). Root traits were also highly interrelated, particularly between total root length and root surface area ($r = 0.796$, $P < 0.01$), as well as between average root diameter and root volume ($r = 0.573$, $P < 0.01$), indicating coordinated root structural development under different nutrient regimes.

Furthermore, total chlorophyll content (Chla + b) was positively associated with both harvested yield ($r = 0.529$, $P < 0.01$) and root traits, particularly total root length ($r = 0.687$, $P < 0.01$) and root diameter ($r = 0.617$, $P < 0.01$), suggesting close linkages between photosynthetic performance and belowground development. In contrast, nitrate concentration (NO_3^-) tended to show weak or negative relationships with productivity and root variables, including root diameter ($r = -0.480$) and harvested yield ($r = -0.317$), implying that greater nitrate accumulation was not associated with improved productive performance during the later harvest stage. Soluble solids content (Brix2) was strongly correlated with dry matter (DM2; $r = 0.797$, $P < 0.01$), reflecting a close relationship between tissue dry matter accumulation and spear quality.

Principal component analysis during the first harvesting

Principal component analysis (PCA) was performed to explore the relationships among physiological, yield, and quality traits of asparagus during the first harvest (Fig. 6). The first two principal components (PCs) explained 55.5% of the total variation, with PC1 and PC2 accounting for 38.7% and 16.9%, respectively. PC1 was primarily associated with yield-related variables, including spear number (NP), spear weight (SW), and harvested yield (IY), indicating that productivity traits represented the major source of variation among fertilization treatments. Chlorophyll variables, particularly chlorophyll a (Chla) and total chlorophyll (Chla + b), were also positively aligned with PC1, suggesting their close association with yield formation during the first harvest (Fig. 6).

In contrast, PC2 was mainly characterized by quality-related and physiological traits, particularly nitrate accumulation (NO_3^-) and chlorophyll b (Chlb), indicating an independent physiological gradient among treatments. Spear Brix was weakly associated with yield variables and appeared separated from the main productivity cluster, suggesting a relatively limited relationship between soluble solids accumulation and harvested yield at this stage. Similarly, dry matter content (DM) showed moderate association with yield but occupied an intermediate position in the ordination space (Fig. 6).

Principal component analysis during the second harvesting

PCA of the second harvest revealed a more integrated relationship among yield, root system architecture, and physiological traits (Fig. 7). The first two principal components captured the major variation among treatments, with PC1 largely representing productivity and root development variables, while PC2 reflected quality and anatomical responses.

Along PC1, harvested yield (IY2) was closely associated with spear number (NP2), spear weight (SW2), and root morphological traits, including total root length (TRL), average root diameter (AD), root volume (TV), and root surface area (SA). The close alignment of these variables suggests that root system development became an important determinant of productivity during the later harvest stage. Root traits were strongly grouped together, indicating coordinated structural responses to nutrient supply.

In contrast, quality-related traits, particularly nitrate concentration (NO_3^-) and Brix, were distributed separately from the main productivity cluster along PC2, suggesting a degree of independence between yield formation and quality regulation. Nitrate accumulation showed an opposite orientation relative to yield-associated traits, indicating a potential trade-off between excessive nitrogen accumulation and productive performance.

Discussion

Effects of N and Mg on plant growth, physiology, and yield formation

The results indicate that asparagus growth and yield were strongly influenced by nitrogen supply, but the response was dependent on the application rate and its interaction with magnesium. Increasing N levels enhanced plant height, chlorophyll content, and spear production (Figs. 2 and 3; Table 1), which is consistent with the fundamental role of nitrogen in chlorophyll synthesis and vegetative growth (Zhang et al., 2015; Nicola, 2000). However, the highest yield was not observed at the highest N level, but rather at the moderate level of 4.5 g pot^{-1} (Table 2), supporting previous findings that optimal asparagus yield is achieved at moderate N inputs (Hikasa, 2000; Xikang et al., 2005).

The improvement in yield under moderate N was further enhanced by Mg application, particularly at 1 g pot^{-1}, indicating a synergistic interaction between these two nutrients. Magnesium plays a critical role in stabilizing chlorophyll and facilitating carbohydrate transport (Hermans et al., 2004), which may explain the higher chlorophyll content and improved spear performance observed under combined N and MgO treatments (Table 1). In contrast, excessive nitrogen (6 g pot^{-1}) increased nitrate accumulation (Table 3) and did not significantly improve yield, suggesting reduced nutrient use efficiency and potential metabolic imbalance (Hu et al., 1992; Ji et al., 2006). The increased nitrate accumulation observed under high nitrogen levels in this study is consistent with previous findings that excessive nitrate supply can exceed the plant's assimilation capacity, resulting in nitrate accumulation due to limited nitrate reductase activity and metabolic constraints (Hermans et al., 2004; Chen et al., 2004). However, this interaction suggests that Mg plays a crucial role in balancing nitrogen uptake and utilization, reducing the risk of nitrate accumulation under high N conditions.

The superior performance observed under the moderate nitrogen treatment suggests that asparagus productivity depends not solely on nutrient availability but also on the efficiency with which absorbed nutrients are assimilated and allocated to productive organs. In perennial crops such as asparagus, excessive nitrogen may stimulate vegetative growth while disrupting the balance between carbon assimilation and reserve accumulation, ultimately limiting productive efficiency across harvesting cycles (Hikasa, 2000; Elmer, 2018). The moderate N level (4.5 g pot^{-1}) therefore appears to provide a more favorable balance between shoot growth and metabolic efficiency than excessive N application.

The beneficial response to magnesium supplementation further highlights the importance of nutrient interactions in greenhouse asparagus systems. Magnesium is directly involved in chlorophyll stabilization, ATP synthesis, and phloem transport of carbohydrates, thereby contributing to improved nitrogen assimilation and carbon partitioning (Cakmak & Yazici, 2010; Hermans et al., 2013). In the present study, the higher chlorophyll content and yield performance observed under combined N-Mg treatments suggest that Mg enhanced physiological efficiency rather than simply acting as a supplemental nutrient. This interaction is particularly important in asparagus because spear development depends heavily on stored assimilates in crowns and roots. Consequently, balanced N-Mg fertilization may improve not only short-term growth responses but also the long-term productivity potential of perennial asparagus systems.

The increased nitrate accumulation observed under excessive nitrogen supply further indicates that nutrient availability exceeded the assimilation capacity of the plants. Similar responses have been reported in intensively fertilized vegetable systems, where nitrate accumulation results from insufficient nitrate reduction relative to uptake, leading to nitrate storage in edible tissues (Santamaria, 2006; Wang et al., 2022). Although nitrate concentration increased under high nitrogen conditions, yield improvement remained limited, suggesting reduced nitrogen-use efficiency. This finding reinforces the importance of optimizing nutrient supply rather than maximizing fertilizer inputs in protected cultivation systems.

Root system architecture as a key driver of yield and nutrient efficiency

A major finding of this study is the central role of root system architecture in mediating the effects of fertilization on yield. Root traits such as total root length, root volume, and root diameter were significantly enhanced under the $N_{4.5}M_1$ treatment (Table 4), which also corresponded to the highest yield, indicating improve nutrient acquisition capacity (Lynch, 2013; Rogers & Benfey, 2015) (Table 2). This indicates that balanced N and Mg supply promotes both root expansion and structural development, thereby improving the plant's capacity for nutrient and water uptake. The strong positive relationships between root traits and yield further support this mechanism. Total root length and root diameter were significantly correlated with harvested yield (Fig. 5), while correlation analysis showed significant associations between yield and root traits in the second harvest (e.g., TRL–IY2, r = 0.555**; AD–IY2, r = 0.596**) (Table 8). These results are consistent with previous studies demonstrating that root system development is a key determinant of productivity in perennial crops (Suralta et al., 2018). Root anatomical traits also exhibited coordinated responses to fertilization (Table 5; Fig. 4), suggesting that nutrient management influences not only root size but also internal structure. Such structural adaptations may enhance transport efficiency within the root system, contributing to improved nutrient uptake and plant performance. In contrast, excessive nitrogen reduced root development, likely due to physiological stress or nutrient imbalance, as reported in previous studies (Seethepalli et al., 2021).

The strong positive relationships between yield and root traits observed in the second harvest suggest that productivity became increasingly dependent on belowground development over time. This response is biologically meaningful because asparagus is a perennial crop whose productive potential largely depends on the accumulation and remobilization of carbohydrate reserves in underground organs (Elmer, 2018). Treatments promoting root expansion and anatomical development may therefore improve not only immediate nutrient uptake but also long-term yield stability. Similar relationships between root architecture and nutrient-use efficiency have been reported in perennial and horticultural crops, where extensive root systems enhance both nutrient capture and resilience to nutrient limitations (Lynch, 2019; York et al., 2022).

In addition to morphological responses, root anatomical modifications observed in this study further support the role of nutrient-mediated structural adaptation. Increased pericycle area and diameter under balanced nutrient combinations may improve internal transport efficiency within the root system, facilitating movement of nutrients and assimilates between roots and shoots. Such coordinated responses suggest that root development should be considered an active driver of productivity rather than a passive consequence of fertilization.

Integration of multivariate responses: yield–quality trade-offs and system dynamics

The integration of correlation and principal component analyses provided further insights into the relationships among growth, yield, quality, and root traits. In the first harvest, yield was primarily associated with aboveground traits, particularly spear number and weight (r = 0.902** and 0.760**, respectively) (Table 7), while chlorophyll content also showed positive correlations with yield. However, Brix was weakly related to yield (r = -0.201), indicating that quality attributes were relatively independent from productivity at this stage.

In contrast, the second harvest exhibited a more integrated system response, where yield was closely associated with root traits and chlorophyll content (Table 8). PCA analysis further confirmed this pattern, showing that yield and root variables were aligned along the same principal component in the second harvest (Fig. 7), whereas physiological and quality traits were separated along another axis. This indicates a shift from aboveground-driven productivity in the early stage to a root-dependent system in later stages. Additionally, nitrate content tended to be separated from yield variables in the PCA (Fig. 7) and showed negative or weak correlations with yield (Table 8), suggesting a trade-off between high nitrogen input and product quality.

The multivariate analyses further revealed a dynamic transition in the determinants of asparagus productivity across harvesting periods. During the first harvest, productivity was primarily associated with aboveground traits, particularly spear number, spear weight, and chlorophyll content, suggesting that early growth responses were largely regulated by immediate physiological performance. However, during the second harvest, yield became increasingly associated with root morphological traits, including root length, root diameter, and root volume, as confirmed by both correlation and PCA analyses.

This shift from shoot-driven productivity to root-mediated productivity represents an important mechanistic finding of the study. The close alignment of root traits and harvested yield in the second PCA suggests that nutrient responses became increasingly dependent on belowground resource acquisition and reserve dynamics over time. Since asparagus productivity relies heavily on stored carbohydrates and nutrient remobilization, treatments promoting root system development may provide greater benefits during repeated harvesting cycles than treatments stimulating vegetative growth alone.

Interestingly, nitrate accumulation was separated from yield-associated traits in the PCA and exhibited weak or negative relationships with productivity variables. This pattern suggests a potential trade-off between excessive nitrogen availability and productive efficiency, whereby greater nitrate accumulation does not necessarily result in improved yield performance. Similar findings have been reported in sustainable horticultural systems, where excessive nitrogen inputs increased nitrate accumulation without proportional gains in productivity (Ji et al., 2006; Savvas & Gruda, 2018).

Ecological and practical implications for sustainable greenhouse asparagus production

These results highlight the importance of integrated nutrient management in balancing productivity, quality, and environmental sustainability. The optimal combination of moderate N and Mg not only maximized yield but also improved root development and reduced the risk of nitrate accumulation, thereby supporting a more efficient and sustainable production system.

Taken together, the findings of this study suggest that balanced nitrogen and magnesium fertilization improves asparagus productivity through coordinated effects on physiological performance, root system architecture, and nutrient-use efficiency. Rather than maximizing nitrogen input, the combination of moderate nitrogen and magnesium promoted more efficient nutrient assimilation, stronger root development, and lower nitrate accumulation. These responses are particularly relevant for greenhouse asparagus production, where excessive fertilization remains common and environmental sustainability is becoming increasingly important. The integration of root phenotyping and multivariate analysis further provides new insight into nutrient-response mechanisms in asparagus, supporting balanced N–Mg fertilization as a practical and ecologically sound nutrient management strategy for sustainable protected cultivation.

Conclusion

This study demonstrated that nitrogen and magnesium fertilization significantly influence growth, yield, spear quality, and root system architecture of asparagus under greenhouse conditions. The optimal combination of 4.5 g N pot^{-1} and 1.0 g MgO pot^{-1} achieved the highest yield and improved quality, indicating the importance of balanced nutrient management. Excessive nitrogen increased vegetative growth and nitrate accumulation without yield benefits, whereas moderate Mg enhanced chlorophyll content, carbohydrate allocation, and root development. Notably, root system architecture was identified as a key factor linking nutrient supply to productivity, supported by strong correlations and PCA results. These findings highlight that integrated N-Mg management improves nutrient use efficiency and reduces environmental risks. The study provides a scientific basis for sustainable fertilization strategies and practical recommendations for asparagus production under protected cultivation. Nevertheless, because the experiment was conducted under controlled greenhouse pot conditions and limited harvesting cycles, further long-term field validation is needed to confirm the stability and broader applicability of root-mediated productivity responses under commercial asparagus production systems.

Declarations

Funding:

This research was partially funded by the Ministry of Agriculture and Rural Development (MARD), Vietnam, through the ministerial-level project “Research and Select Asparagus Varieties Suitable for the Conditions of Northern Vietnam”. The authors gratefully acknowledge this financial support.

Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest.

Availability of data and material

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Alva AK, Paramasivam S, Fares A, Delgado JA, Mattos D (2006) Nitrogen and irrigation management practices to improve nitrogen uptake efficiency and minimize leaching losses. J Crop Improv 15(2):369–420. https://doi.org/10.1300/J411v15n02_15
2. Cakmak I, Yazici AM (2010) Magnesium: A forgotten element in crop production. Better Crops 94(2):23–25
3. Chen BM, Wang ZH, Li SX, Wang GX, Song HX, Wang XN (2004) Effects of nitrate supply on plant growth, nitrate accumulation, metabolic nitrate concentration and nitrate reductase activity in three leafy vegetables. Plant Sci 167(3):635–643
4. Elmer WH (2018) Asparagus decline and replant problem: a look back and a look forward at strategies for mitigating losses. Acta Hort 1223:195–204. https://doi.org/10.17660/ACTAHORTIC.2018.1223.27
5. Guo W, Nazim H, Liang Z, Yang D (2016) Magnesium deficiency in plants: An urgent problem. Crop J 4(2):83–91. https://doi.org/10.1016/j.cj.2015.11.003
6. Hermans C, Johnson GN, Strasser RJ, Verbruggen N (2004) Physiological characterisation of magnesium deficiency in sugar beet: acclimation to low magnesium supply. J Exp Bot 55(404):879–891. https://doi.org/10.1093/jxb/erh094
7. Hermans C, Conn SJ, Chen J, Xiao Q, Verbruggen N (2013) An update on magnesium homeostasis mechanisms in plants. Metallomics 5(9):1170–1183. https://doi.org/10.1039/C3MT20223B
8. Hikasa Y (2000) Effects of nitrogen fertilizer application on asparagus spear yield and nutrient uptake. Japanese J Soil Sci Plant Nutr 71(1):77–82
9. Hu WH, Xu HL, Wang JQ (1992) Effects of nitrogen levels on nitrate accumulation and quality of asparagus. Acta Horticulturae Sinica 19(4):297–301
10. Ji YH, Yuan ZY, Lu WX (2006) Excessive nitrogen application and nitrate accumulation in vegetables in China. J Agro-Environment Sci 25(1):121–125
11. Lynch JP (2013) Steep, cheap and deep: an ideotype to optimize water and N acquisition by maize root systems. Ann Botany 112(2):347–357
12. Lynch JP (2019) Root phenotypes for improved nutrient capture: An underexploited opportunity for global agriculture. New Phytol 223(2):548–564. https://doi.org/10.1111/nph.15738
13. Nguyen Hong Hanh, Nguyen Thi Ngoc Dinh, Pham Thi Thu Huong, Do Thi Huong, Phan Thi Thuy, Nguyen Thi Ai Nghia, Nguyen Trung Duc, Tran Anh Tuan (2024). Variation of morpho-agronomical characteristics and genetic diversity of imported asparagus cultivars in Vietnam. Aust J Crop Sci, *18*(2), 107–115
14. Nicola S (2000) Nutrient uptake in asparagus: responses to nitrogen fertilization. Acta Hort 533:197–204. https://doi.org/10.17660/ActaHortic.2000.533.27
15. Rogers ED, Benfey PN (2015) Regulation of plant root system architecture: implications for crop advancement. Curr Opin Biotechnol 32:93–98
16. Santamaria P (2006) Nitrate in vegetables: Toxicity, content, intake and EC regulation. J Sci Food Agric 86(1):10–17. https://doi.org/10.1002/jsfa.2351
17. Savvas D, Gruda N (2018) Application of soilless culture technologies in the modern greenhouse industry—A review. Eur J Hortic Sci 83(5):280–293. https://doi.org/10.17660/eJHS.2018/83.5.2
18. Seethepalli A, Dhakal K, Griffiths M, Guo H, Freschet GT, York LM (2021) RhizoVision Explorer: Open-source software for root image analysis and measurement standardization. AoB Plants 13(6):plab056. https://doi.org/10.1093/aobpla/plab056
19. Suralta RR, Kano-Nakata M, Niones JM, Inukai Y, Kameoka E, Tran TT, Menge D, Mitsuya S, Yamauchi A (2018) Root plasticity for maintenance of productivity under abiotic stressed soil environments in rice: Progress and prospects. Field Crops Res 220:57–66. https://doi.org/10.1016/j.fcr.2017.06.023

20. Tränkner M, Tavakol E, Jákli B (2018) Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. Physiol Plant 163(3):414–431. https://doi.org/10.1111/ppl.12747
21. Wang X, Wang X, Sheng H, Wang X, Zhao H, Feng K (2022) Excessive nitrogen fertilizer application causes rapid degradation of greenhouse soil in China. Pol J Environ Stud 31(2):1527–1534. https://doi.org/10.15244/pjoes/143293
22. Wilson DR, Sinton SM, Butler RC, Drost DT, Paschold PJ, van Kruistum G, Poll JTK, Garcin C, Pertierra R, Vidal I, Green KR (2008) Carbohydrates and yield physiology of asparagus—A global overview. Acta Hort 776:413–428. https://doi.org/10.17660/ActaHortic.2008.776.54
23. Wintermans JFGM, De Mots A (1965) Spectrophotometric characteristics of chlorophylls a and b and their pheophytins in ethanol. Biochim Biophys Acta 109(2):448–453. https://doi.org/10.1016/0926-6585(65)90170-6
24. Xikang L, Zhong C, Quansheng C, Zucai H (2005) Effect of amount of nitrogen fertilizer applied on green asparagus. Shanghai Nongye Xuebao 21(4):75–77
25. Zhang Y, Yang J, Guo J (2015) Effects of nitrogen application on spear yield and nitrate content in asparagus. J Plant Nutr 38(9):1371–1381. https://doi.org/10.1080/01904167.2015.1014581

Tables

Table 1. Effect of nitrogen and magnesium level on Chlorophyll content of asparagus in 17MAP

Treatments		**Chl.a**	**Chl. b**	**Chl a +b**
	N_3	28.3b	66.8a	94.4b
N	$N_{4.5}$	28.6ab	67.1a	95.3a
	N_6	29.0a	65.0a	94.9c
P-value		*	ns	**
	M_0	28.3b	65.6a	93.9b
Mg	M_1	28.9a	66.6a	95.3a
	M_2	28.8a	66.8a	95.3a
P-value		*	ns	**
	N_3M_0	28.3b	66.3a	93.0c
N x Mg	N_3M_1	28.5ab	67.0a	95.1a
	N_3M_2	28.4ab	67.1a	95.1a
	$N_{4.5}M_0$	28.3b	67.2a	95.1a
	$N_{4.5}M_1$	29.0ab	67.2a	95.6a
	$N_{4.5}M_2$	28.6ab	67.0a	95.3a
	N_6M_0	28.5ab	63.2a	93.8b
	N_6M_1	29.0ab	65.6a	95.3a
	N_6M_2	29.4a	65.6a	95.5a
P-value		ns	ns	**

In a column, means followed by the same letter are not significantly different at P < 0.05

*ns, not significant; *,** significant at P <0.05 and 0.01, respectively. MAP: months after planting.*

N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (no MgO applied), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}).

Table 2. Effect of nitrogen and magnesium level on yield and component yield of asparagus in the first harvesting (10MAP)

Treatments		The number of spear	Spear weight (g)	Harvested yield (g $plant^{-1}$)
N	N_3	6.1b	11.7^{a}	72.7b
	$N_{4.5}$	6.9ab	11.7^{a}	81.8a
	N_6	7.8a	12.9^{a}	77.7b
P-value		*	ns	**
Mg	M_0	5.9b	10.7^{b}	74.2b
	M_1	7.8a	12.9a	90.8a
P-value	M_2	7.1ab	12.8a	100.6a
		**	**	**
NxMg	N_3M_0	5.3b	10.2a	50.4b
	N_3M_1	6.7ab	12.3a	81.0ab
	N_3M_2	6.6ab	13.0a	86.6ab
	$N_{4.5}M_0$	6.0ab	9.4b	56.4b
	$N_{4.5}M_1$	8.0ab	13.5a	108.5a
	$N_{4.5}M_2$	6.7ab	12.1a	80.6ab
	N_6M_0	7.0ab	12.5a	85.7ab
	N_6M_1	8.7a	12.9a	112.2a
P-value	N_6M_2	8.0ab	13.2a	105.3a
		ns	ns	ns

In a column, means followed by the same letter are not significantly different at $P < 0.05$

*ns, not significant; *,** significant at $P<0.05$ and 0.01, respectively. MAP: months after planting.*

N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (no MgO applied), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}).

Table 3. Effect of nitrogen and magnesium level on yield and component yield of asparagus in the first harvesting (14MAP)

Treatments	The number of spear	Spear weight (g)	Harvested yield (g $plant^{-1}$)

	N_3	3.4b	8.09b	26.7b
N	$N_{4.5}$	4.0a	9.0a	36.1a
	N_6	3.9a	7.78b	29.7b
P-value		**	**	**
	M_0	3.8a	8.11a	29.5a
Mg	M_1	3.9a	8.34a	32.8a
	M_2	3.7a	8.21a	30.8a
P-value		ns	ns	ns
	N_3M_0	3.0b	7.81abc	22.4c
NxMg	N_3M_1	3.7ab	8.4abc	30.8abc
	N_3M_2	3.3ab	8.06abc	26.8c
	$N_{4.5}M_0$	4.0a	8.90ab	35.6ab
	$N_{4.5}M_1$	4.0a	9.16a	37.1a
	$N_{4.5}M_2$	4.0a	8.9ab	35.6ab
	N_6M_0	4.0a	7.62bc	30.5abc
	N_6M_1	4.0a	7.46c	30.4abc
	N_6M_2	3.7ab	7.66bc	28.2bc
P-value		ns	ns	ns

In a column, means followed by the same letter are not significantly different at $P < 0.05$

*ns, not significant; *,** significant at $P<0.05$ and 0.01, respectively. MAP: months after planting.*

N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (no MgO applied), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}).

Table 4. The quality parameters of asparagus as affected by various combinations of nitrogen (N) and magnesium (Mg) levels.

Treatments		Dry matter (%)		Spear Brix		NO_3^- (mg g^{-1})	
		10MAP	14MAP	10MAP	14MAP	10MAP	14MAP
N	N_3	8.57a	7.0a	5.6b	5.7a	81.9b	63.2b
	$N_{4.5}$	10.18a	8.1a	6.3a	5.8a	86.2b	72.4ab
	N_6	10.47a	4.6b	5.4c	5.7a	92.0a	80.2a
P-value		ns	*	**	ns	**	*
Mg	M_0	7.4b	7.1a	5.6b	5.7a	82.7b	72.4a
	M_1	10.26ab	7.5a	5.5b	5.9a	86.4ab	68.9a
	M_2	11.5a	6.2a	6.2a	5.6a	91.0a	74.6a
P-value		*	ns	*	ns	**	ns
NxMg	N_3M_0	6.05a	7.5a	5.3cd	5.76a	78.3b	83.7a
	N_3M_1	9.29a	7.2a	6.7b	6.03a	81.3ab	74.3a
	N_3M_2	10.85a	6.1a	4.7de	5.3a	86.0ab	82.7a
	$N_{4.5}M_0$	8.12a	7.6a	6.2b	6.17a	81.0b	64.3a
	$N_{4.5}M_1$	10.85a	9.9a	4.5e	5.73a	87.0ab	60.7a
	$N_{4.5}M_2$	11.57a	6.8a	7.3a	5.6a	90.7ab	64.7a
	N_6M_0	8.08a	6.1a	5.18d	5.2a	88.7ab	69.3a
	N_6M_1	10.69a	5.3a	5.2cd	5.97a	91.0ab	71.7a
	N_6M_2	12.69a	5.8a	5.7c	5.9a	96.3a	76.3a
P-value		ns	ns	*	ns	*	ns

In a column, means followed by the same letter are not significantly different at $P < 0.05$

*ns, not significant; *,** significant at P<0.05 and 0.01, respectively. MAP: months after planting.*

N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (no MgO applied), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}).

Table 5. Root length, area and volume of asparagus as affected by various combinations of nitrogen (N) and magnesium (Mg) levels.

Treatments		Total root length (mm)	Root diameter (mm)	Surface area (mm^2)	Root volume (mm^3)
	N_3	63353.7b	2.84c	662021a	566042c
N	$N_{4.5}$	99678.7a	3.12a	664478a	854659a
	N_6	63887.3b	3.03b	602281b	642618b
P-value		**	**	*	**
	M_0	55753.7c	2.93b	510403c	526345c
Mg	M_1	89524.7a	3.04a	754089a	838276a
	M_2	81641.3a	3.02a	664288b	698697b
P-value		**	**	**	**
	N_3M_0	46101h	2.76d	465305h	497413h
NxMg	N_3M_1	82001c	2.83c	932827a	613944d
	N_3M_2	61958f	3.01b	587929e	586768f
	$N_{4.5}M_0$	61557f	3.08b	491047g	491345i
	$N_{4.5}M_1$	123578a	3.28a	675027c	1122779a
	$N_{4.5}M_2$	113900b	3.00b	827360b	949852b
	N_6M_0	59602g	3.05b	574856f	590278e
	N_6M_1	62994e	3.01b	654413d	778105c
	N_6M_2	69065d	3.04b	577573f	559471g
P-value		**	**	**	**

In a column, means followed by the same letter are not significantly different at P < 0.05

*ns, not significant; *,** significant at P<0.05 and 0.01, respectively.*

N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (no MgO applied), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}).

Table 6. Root pericycle area, perimeter and diameter as affected by various combinations of nitrogen (N) and magnesium (Mg) levels.

Treatments		Pericycle area (µm)	Pericycle perimeter (µm)	Pericycle diameter (µm)
	N_3	463072b	2594a	755.9b
N	$N_{4.5}$	477445ab	2768a	767.8b
	N_6	560718a	2824a	854.8a
P-value		*	ns	**
	M_0	496141a	2642a	788.7a
Mg	M_1	516124a	2748a	807.1a
	M_2	488971a	2796a	782.6a
P-value		ns	ns	ns
NxMg	N_3M_0	377041bc	2303a	683.3b
	N_3M_1	410884abc	2557a	714.8ab
	N_3M_2	601293a	2922a	869.6a
	$N_{4.5}M_0$	519036abc	2718a	804.3ab
	$N_{4.5}M_1$	542397abc	2772a	822.2ab
	$N_{4.5}M_2$	370902c	2815a	677.0b
	N_6M_0	592345	2906a	878.6a
	N_6M_1	595092a	2915a	884.3a
	N_6M_2	494717abc	2651a	801.3ab
P-value		**	ns	**

In a column, means followed by the same letter are not significantly different at P < 0.05

*ns, not significant; *,** significant at P<0.05 and 0.01, respectively.*

N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (no MgO applied), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}).

Table 7. Pearson correlation matrix among growth, yield, quality, and root traits of asparagus under different N and Mg treatments in the first harvesting

	Chla	Chlb	Chla+b	NP	SW	IY	Brix	DM	NO_3^-
Chla	1								
Chlb	-0,446	1							
Chla+b	0,434*	0,359*	1						
NP	0,581**	-0,220	0,386*	1					
SW	0,499**	-0,241	0,373*	0,416*	1				
IY	0,651**	-0,300	0,407*	0,902**	0,760**	1			
Brix	-0,007	0,104ns	0,183ns	-0,024	-0,365	-0,201	1		
DM	0,271ns	0,019ns	0,398*	0,683**	0,292ns	0,592**	0,140ns	1	
NO_3^-	0,320ns	0,116ns	0,413*	0,242ns	0,365*	0,329	-0,124	0,178ns	1

NP: number of spears, SW: spear weight, IY: individual yield, DM: dry matter, NO_3^-: nitrate accumulation

*ns, not significant; *,** significant at P<0.05 and 0.01, respectively.*

Table 8. Pearson correlation matrix among growth, yield, quality, and root traits of asparagus under different N and Mg treatments in the second harvesting

	NP2	SW2	DM2	Brix2	NO_3.2	IY2	Chla	Chlb	Chla+b	STA	SP	SD	TRL
NP2	1												
SW2	0,353*	1											
DM2	-0,179	0,430*	1										
Brix2	-0,021	0,348*	0,797**	1									
NO3	-0,210	-0,338	-0,277	-0,367	1								
IY2	0,858**	0,781**	0,127ns	0,185ns	-0,317	1							
Chla	0,123ns	-0,101	-0,041	-0,233	-0,320	0,026ns	1						
Chlb	0,226ns	0,334*	0,182ns	0,365*	-0,178	0,333*	-0,446	1					
Chla+b	0,403*	0,495**	0,086ns	-0,035	-0,284	0,529**	0,434*	0,359*	1				
STA	0,336*	-0,180	-0,246	-0,319	0,048ns	0,119ns	0,082ns	0,217ns	0,124ns	1			
SP	0,405*	-0,018	-0,071	-0,066	-0,159	0,256ns	0,051ns	0,244ns	0,216ns	0,602**	1		
SD	0,358*	-0,211	-0,195	-0,279	0,032ns	0,115ns	0,107ns	0,223ns	0,152ns	0,973**	0,635**	1	
TRL	0,393*	0,552**	0,170	0,122ns	-0,298	0,555**	0,276ns	0,268ns	0,687**	-0,128	0,195ns	-0,120	1
AD	0,511**	0,481*	0,116ns	-0,060	-0,480	0,596**	0,411*	0,227ns	0,617**	0,489**	0,356*	0,480**	0,420*
TV	0,398*	0,540**	0,248ns	0,179ns	-0,381	0,562**	0,311ns	0,190ns	0,494**	0,005ns	0,186ns	-0,012	0,611**
SA	0,241ns	0,342*	0,031ns	0,139ns	-0,163	0,337*	0,092ns	0,207ns	0,4609*	-0,285	0,061ns	-0,294	0,796**

NP: number of spears, SW: spear weight, IY: individual yield, DM: dry matter, NO_3^-: nitrate accumulation, Chla,b,a+b: chlorophyll a, b and total chlorophyll (a+b), STA: stele area, SP:stele perimeter, SD:stele diameter, TRL: total root length, AD: Average root diameter, TV: Total root volume, SA: root surface area

*ns, not significant; *,** significant at P<0.05 and 0.01, respectively.*

Figures

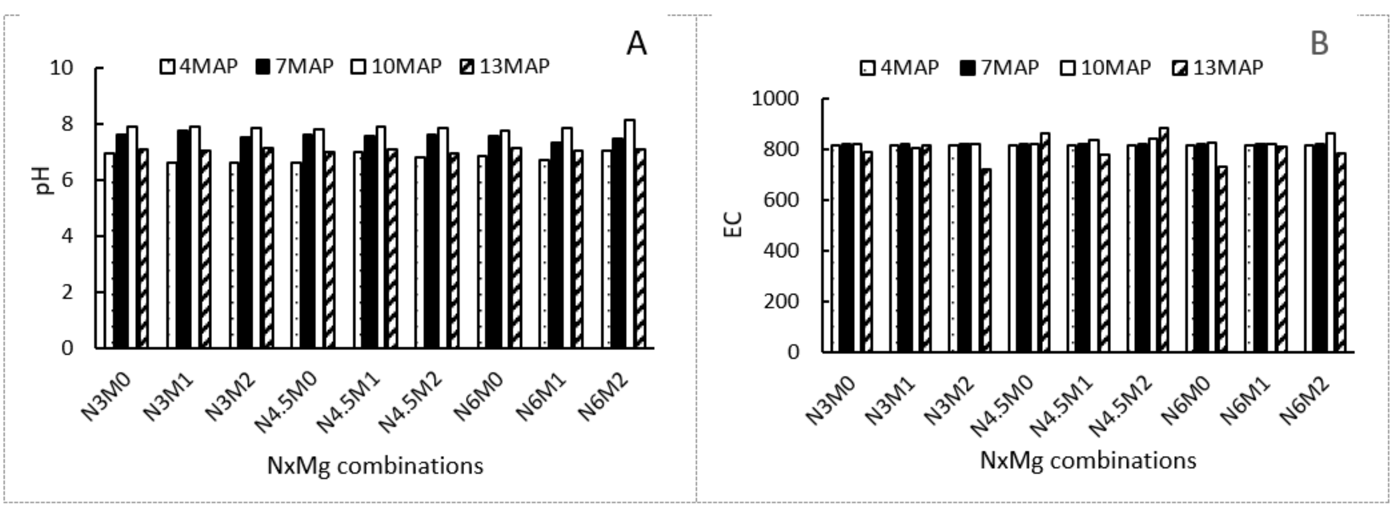

Figure 1

The soil pH (A) and EC (B) as affected by various combinations of nitrogen (N) and magnesium (Mg) levels.

Note: N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (0g MgO pot^{-1}), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}); MAP - months after planting

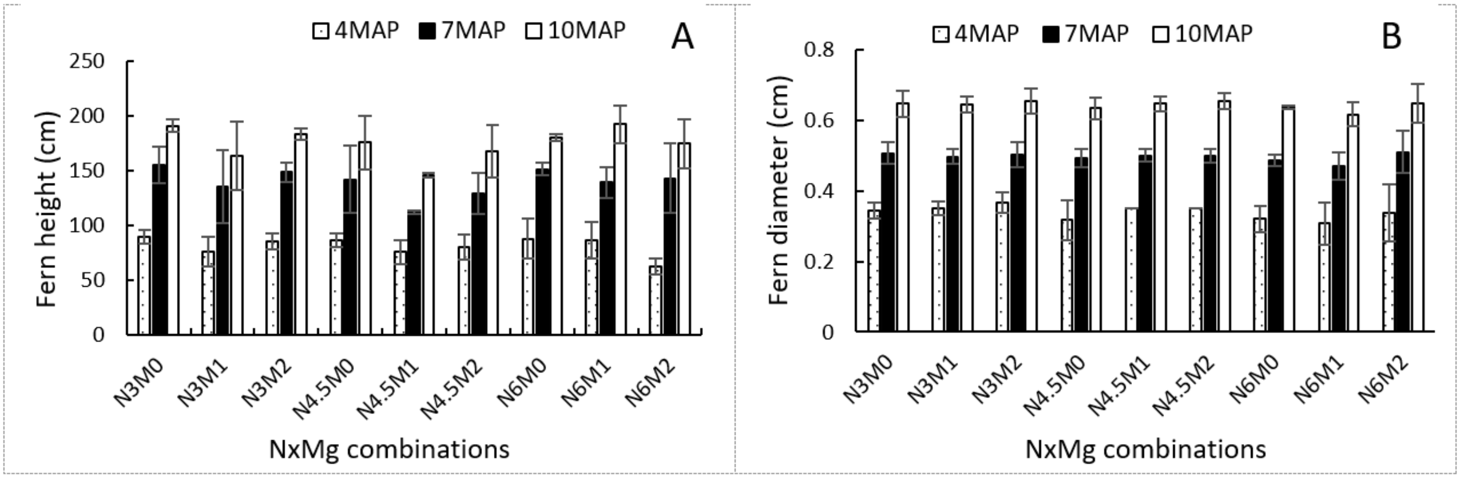

Figure 2

Plant height (A) and diameter (B) of mother stem of asparagus as affected by various combinations of Nitrogen (N) and Magnesium (Mg) levels.

Note: N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (0g MgO pot^{-1}), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}); MAP- months after planting

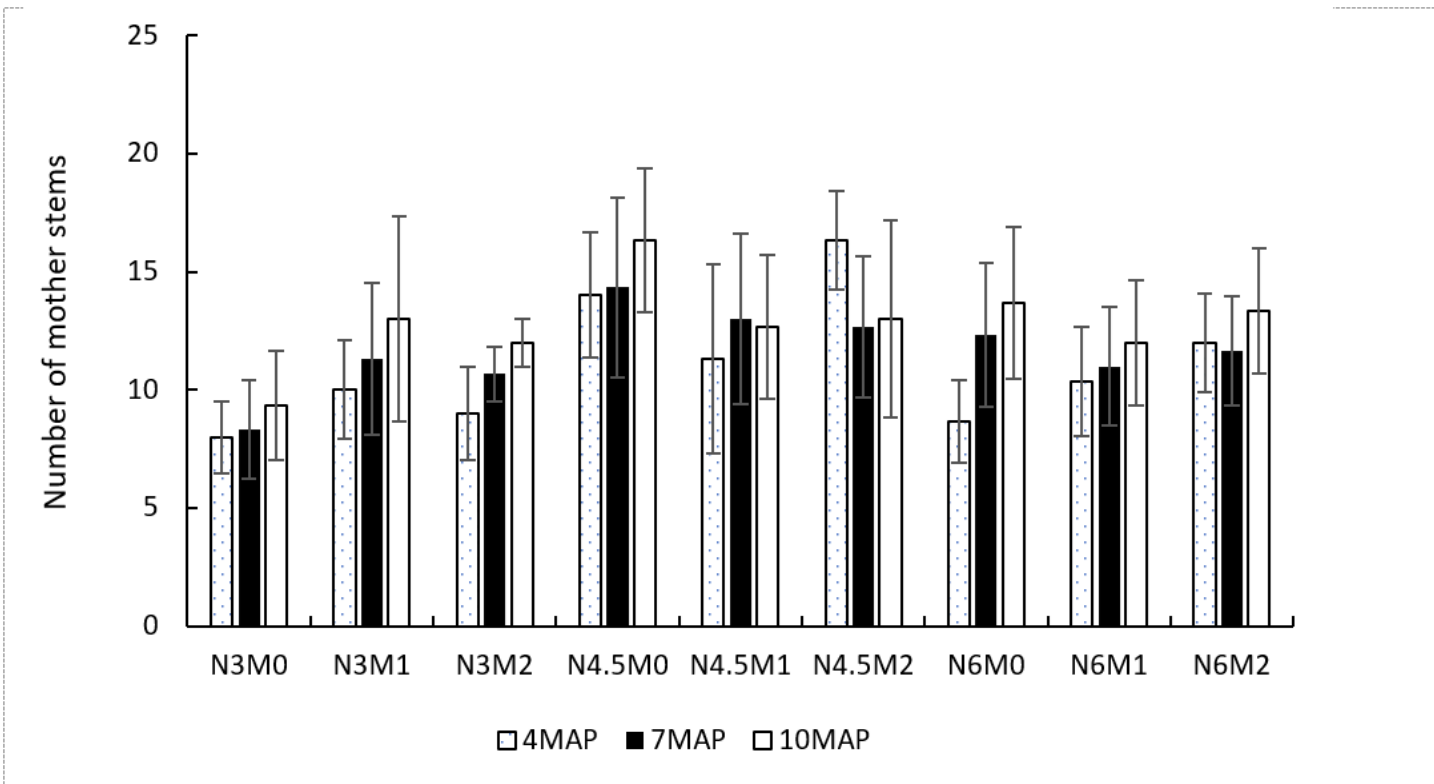

Figure 3

Number of mother stems of asparagus under various combintaions of Nitrogen (N) and Magnesium (Mg) levels.

Note: N_3 (3g N pot-1), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (0g MgO pot^{-1}), M_1 (1gMgO pot^{-1}) and M_2 (2g MgO pot^{-1}). MAP- months after planting.

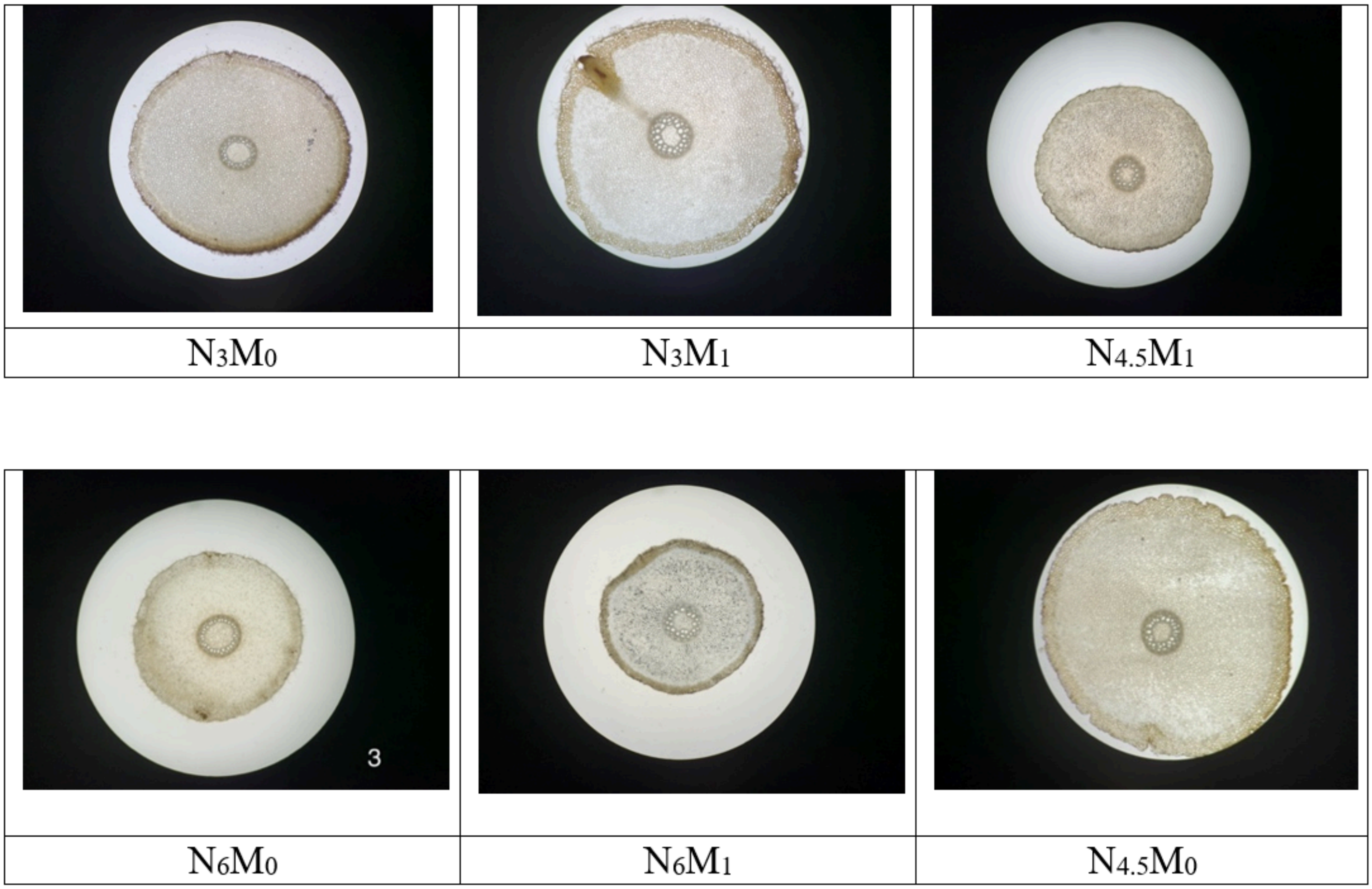

Figure 4

Root anatomical structure as affected by various combinations of Nitrogen (N) and Magnesium (Mg) levels.

Note: N_3 (3g N pot^{-1}), $N_{4.5}$ (4.5gN pot^{-1}) and N_6 (6g N pot^{-1}); M_0 (no MgO applied), M_1 (1g MgO pot^{-1}) and M_2 (2g MgO pot^{-1}).

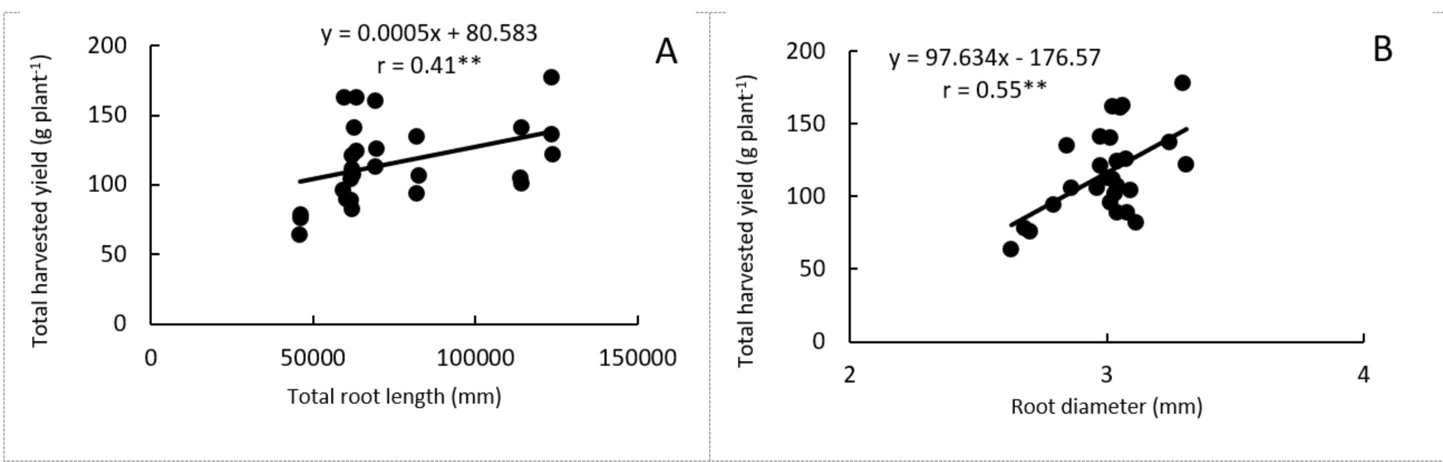

Figure 5

Relationship between total root length and total harvested yield (A), root diameter and total harvested yield (B).

*Note: ns, not significant; *,** significant at P<0.05 and 0.01, respectively.*

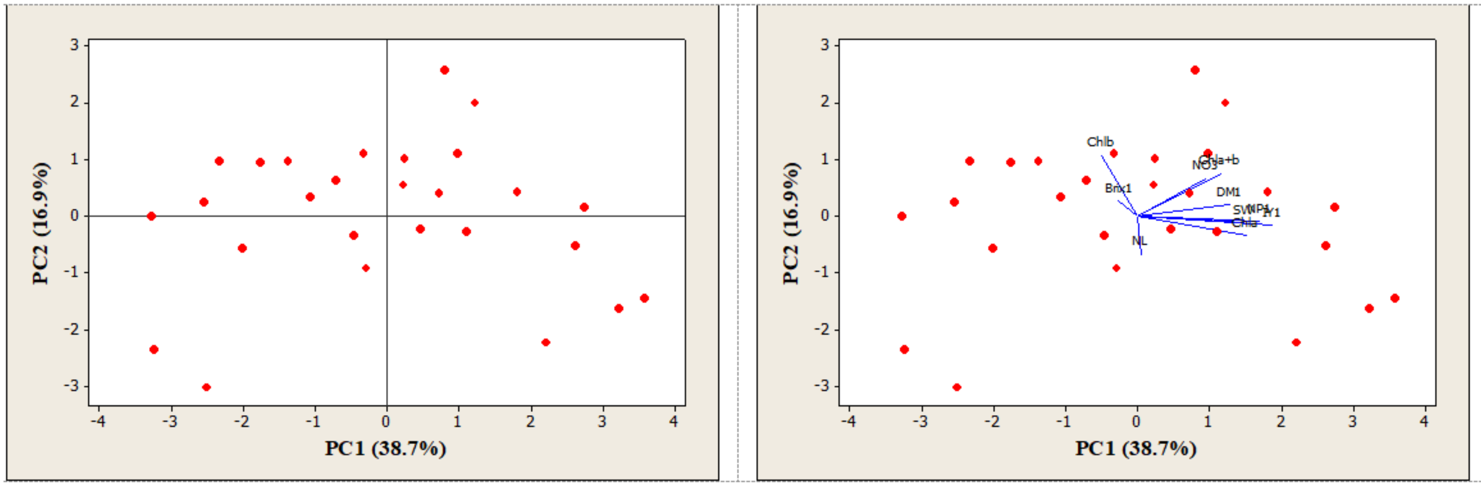

Figure 6

Principal component analysis (PCA) of measured variables in the first harvesting: score plot (left) and biplot (right)

Note: *NP: number of spears, SW: spear weight, IY: individual yield, DM: dry matter,* NO_3^-*: nitrate accumulation, Chla,b,a+b: chlorophyll a, b and total chlorophyll (a+b).*

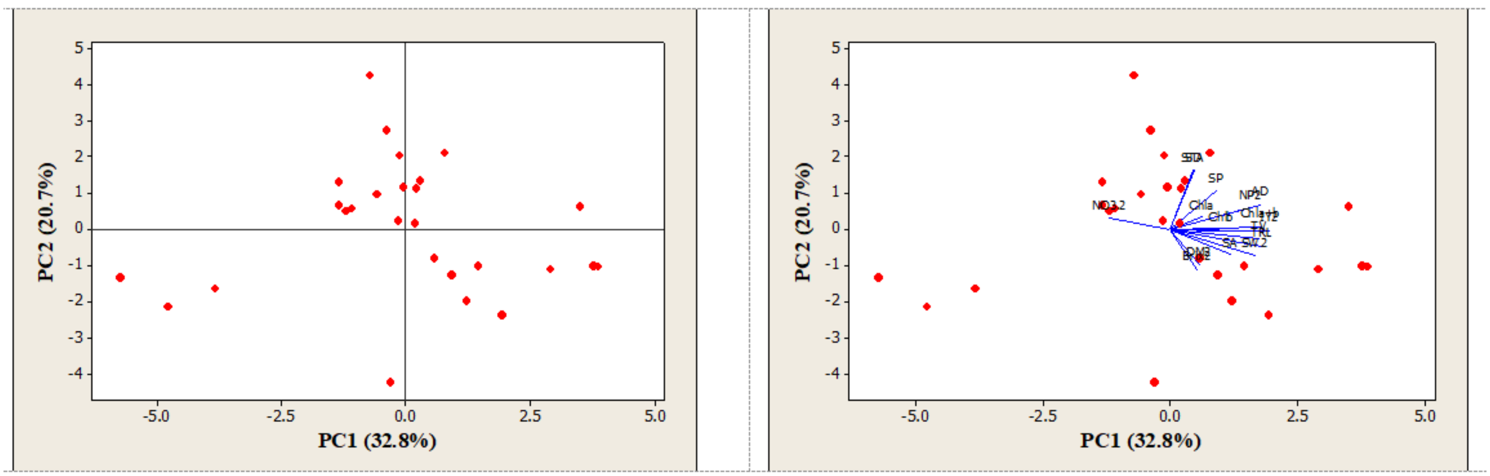

Figure 7

Principal component analysis (PCA) of measured variables in the second harvesting: score plot (left) and biplot (right)

Note: *NP: number of spears, SW: spear weight, IY: individual yield, DM: dry matter,* NO_3^-*: nitrate accumulation, Chla,b,a+b: chlorophyll a, b and total chlorophyll (a+b), STA: stele area, SP:stele perimeter, SD:stele diameter, TRL: total root length, AD: Average root diameter, TV: Total root volume, SA: root surface area*