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# Leaf Physiological and Root Morphological Responses of Some Fruit Bearing Vegetables as Affected by Different Rates of Nitrogen

Firdes ULAS[1] Saliha ERDOGDU[1] Yusuf Cem YUCEL[2] Abdullah ULAS[2]* Halit YETISIR[1]
[1]Department of Horticulture, Faculty of Agriculture, Erciyes University, Kayseri, TURKEY
[2]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, Kayseri, TURKEY

*Corresponding Author
E-mail:agrulas@erciyes.edu.tr

**Abstract**
The aim of the present study was to determine genotypic differences in shoot growth, leaf physiological and root morphological development of some fruit bearing vegetables at different rates of nitrogen supply. A short-term hydroponic experiment was conducted between January and February in 2018 by using a non-flow nutrient film technique (NFT) in a controlled growth chamber for 28 days. Four different fruit bearing vegetable species (eggplant, tomato, watermelon and pumpkin) were evaluated under three different nitrogen levels (low: 0.3 mM, medium: 1.5 mM and high: 3.0 mM N) in a completely randomized block design with four replications. Results indicated that shoot and root growth, leaf physiological development and root morphology of four plant species were significantly ($P<0.001$) affected by different rates of N supply. Highly significant ($P<0.001$) genotypic differences were found between plant species and the growth response to supplied N, i.e. the interaction between N rate and plant species was also highly significant ($P<0.001$). Increasing N supply, had a substantial positive effect on the shoot growth and leaf physiological development, while the root growth and morphology was negatively affected. Based on shoot biomass yield pumpkin was characterized as 'N-efficient' whereas eggplant as the 'N-inefficient' species under low N supply. Similar genotypic variation existed at medium or high N rates between species and thus pumpkin was characterized as 'N-responsive' whereas eggplant as 'N-nonresponsive'. The results clearly indicated that 'N-efficiency' and 'N-responsiveness' of pumpkin are more closely related to vigorous and active root system occurred with a uniform assimilate allocation to the roots that contributed to high shoot N uptake and high photosynthesis.

**Keywords:** N-efficiency, Species, SPAD, Chlorophyll, Photosynthesis

## INTRODUCTION

### Significance of Nitrogen For Crops and Vegetables

A Nitrogen (N) is one of the most common and widely used fertilizer nutrient for production of stable crops and vegetables [1]. Although being an important resource and essential input for crop growth and yield, the available N is more often a limiting factor influencing plant growth than any other nutrient in both high-input and low-input agriculture systems [2]. As a result of reduced cost of synthetic N fertilizers produced by Haber-Bosch process, the mineral N fertilizer application enhanced over 7 folds in the past 40 years [3]. Based on the reported data, the total N fertilizer application in agricultural use in between 2002 and 2016 increased by almost 32% in the world while the increase reached to 58% in Turkey [4]. In general, due to a short growing period and weak root system the N requirement of some vegetables can be large (300-400 kg N $ha^{-1}$) as compared to some cereals such as wheat, barley or maize [5].

However, the efficiency of N fertilizers is frequently low, since, plants taken up often less than 50% of the applied N [6], and the proportion of fertilizer N not utilized by the crop is left in the soil and/or lost from the plant/soil system through volatilisation, leaching and denitrification [7] and [8].

Due to low levels of N fertilizer used by the small-scale farmers, soil fertility is declining dramatically in low-input agriculture. On the other hand, the concerns are rising on environmental pollution of both air and water due to use of intensive N fertilizer in high-input agriculture [9].

Therefore, to improve N efficiency in agriculture, integrated N management strategies that take into consideration improved fertilizers and soil and crop management practices are necessary [10]. Among these, breeding and cultivation of N-efficient cultivars would contribute to increase N efficiency of crops and thus sustain higher yields in low-input agriculture, and to minimize the environmental impact in high-input agriculture [11]. However, to facilitate the breeding of N-efficient cultivars, the identification of suitable plant traits contributing to genotypic variation for N efficiency is necessary.

Unlike the intense studies on genotypic differences in N efficiency of some cereal crops such as wheat [12], maize [13] and barley [14] and rice [15], research on fruit bearing vegetable crops seemed to be much more scarce in the literature. Therefore, the aim of this study was to determine the genotypic differences in N efficiency of some fruit bearing vegetable species (eggplant, tomato, watermelon and pumpkin) in relation in to shoot growth at agronomical, root growth at morphological and leaf development at physiological levels under three different nitrogen levels.

## MATERIALS AND METHODS

### Plant Material and Experimental Design

A hydroponic experiment was conducted between January and February in 2018 by using a non-flow nutrient film technique (NFT) in a controlled growth chamber situated in the Plant Physiology Laboratory of Erciyes University, Faculty of Agriculture, Kayseri in Turkey. Four different species of fruit bearing vegetables [eggplant (Aydın Siyahı- *Solanum melongena* L.), tomato (Töre F1- *Lycopersicon esculentum*), watermelon (Crimson sweet- *Citrullus lanatus*) and pumpkin (*Cucurbita pepo*)] were used as plant materials. To produce homogenous plantlets for hydroponic growth medium, seeds of four species were sown in petri dishes on 14 January 2018 and then germinated seeds were transplanted to the multi-pots in a mixture of peat (pH: 6.0-6.5) and perlite in a 2:1 ratio for almost 2 weeks. The seedlings with 2-true-leaves were carefully freed from the peat-perlite growth medium with no root damage and then transferred into 8 L plastic pots filled with nutrient solution in growth chamber on 28 January 2018. Total vegetation period from transplanting into 8 L plastic pots up to final harvest was almost 4 weeks. The average day/night temperatures was 25/22 °C, the relative humidity was 65-70% and about 350 µmol $m^{-2}$ $S^{-1}$ photon flux was supplied in a photoperiod of 16/8 h of light/dark regimes in the controlled growth chamber. Hydroponic experiment was arranged in a completely randomized block design with four replications and three plants in each pot (replication). In experiment, all nutrients were supplied to the plants by using a non-flow nutrient film technique (NFT) that experienced in a 8 L plastic pots. The nutrient solution was prepared by using distilled water contained analytical grade (99% pure) chemicals according to modified Hoagland and Arnon formulation. The nutrient solution in each 8 L pot was continuously aerated with the aid of an air pump.

In hydroponic experiment, nitrogen was supplied in three different concentrations (Low N: 0.3 mM N, Medium N: 1.5 mM N, High N: 3.0 mM N) by using two different proportional N sources (75% Ca(NO3)2 and 25% (NH4)2SO4). The basic nutrient solution had the following composition (µM): K2SO4 (500); KH2PO4 (250); CaSO4 (1000); MgSO4 (325); NaCl (50); H3BO3 (8.0); MnSO4 (0.4); ZnSO4 (0.4); CuSO4 (0.4); MoNa2O4 (0.4); Fe-EDDHA (80). All nutrients were replaced when the N concentration of the nutrient solution in the 3.0 mM N rate pots fell below 0.3 mM, as measured daily with nitrate test strips (Merck, Darmstadt, Germany) by using a NitracheckTM reflectometer. The experiment was terminated on 28.02.2018.

**Harvest, Shoot and Root Dry Biomass Measurements**

In hydroponic experiment three plants per pot were harvested 28 days after treatment (DAT). Plants were separated into shoot and roots. Plant height (cm) was measured by using a ruler. For the fresh and then after dried weight determination shoot was fractioned into the leaf, stem and roots. Plant materials were dried in a forced-air oven for 48 h at 70 °C to determine shoot and root dry weights.

**Root Morphological Measurements**

In hydroponic experiment, the root morphological parameters such as root length (m), root volume (cm3) and average root diameter (mm) of the four vegetable species were measured by using a special image analysis software program WinRHIZO (Win/Mac RHIZO Pro V. 2002c Regent Instruments Inc. Canada) in combination with Epson Expression 11000XL scanner. From each harvested fresh root samples almost 5.0 g sub-samples were taken. The samples were each (one after the other) placed in the scanner's tray. Water is added and with the aid of a plastic forceps, the roots are homogenously spread across the tray; and the scanning and analysis done from the WinRhizo system's interface on a computer connected to the scanner. The total plant root length and volume was then determined as the ratio of sampled root fresh weight to the total root fresh weight.

**Leaf Physiological Measurements**

At the end of the hydroponic experiment the leaf area (LA) of plants was measured destructively with a leaf area measuring device (LI-COR LI-3100C, Inc., Lincoln, NE, USA). The measurements were recorded in centimeter square ($cm^2$). On the other hand, the leaf chlorophyll content (SPAD) was determined non-destructively by using a portable chlorophyll (SPAD) meter (Minolta SPAD-502). During the growth period, SPAD readings were performed on $3^{th}$ and $4^{th}$ week of the vegetation period at the centre of the leaves on the fully expanded youngest leaf of whole plants for each treatment. The leaf-level $CO_2$ gas exchange (µmol $CO_2$ $m^{-2}$ $s^{-1}$) measurements were done in controlled growth chamber by using a portable photosynthesis system (LI-6400XT; LI-COR Inc., Lincoln, NE, USA). The leaf photosynthesis measurement was performed on the most recent fully expanded leaves, using four replicate leaves per treatment on $3^{th}$ and $4^{th}$ week of the vegetation period.

**Statistical Analysis**

Statistical analysis of the nutrient solution experiments data was performed using SAS Statistical Software (SAS 9.0, SAS Institute Inc., Cary, NC, USA). A two-factorial analysis of variance was performed to study the effects of species and nitrogen and their interactions on the plants. Levels of significance are represented by $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, and ns means not significant. Multiple comparisons of treatment means were made separately for each N rate by Duncan's Multiple Range Test ($P \leq 0.05$).

## RESULTS AND DISCUSSION

**Shoot Growth and Leaf Physiological Development**

Shoot dry matter, shoot N uptake, plant height, total leaf area, leaf chlorophyll content (SPAD), and photosynthetic activity of leaves of four different vegetable species were significantly (P<0.001) affected by different rates of N supply (Table 1, Fig. 1). Plants under high N supply showed significantly higher shoot dry matter, shoot N uptake, plant height, total leaf area, SPAD value, and photosynthesis than plants grown under medium or low N rates. Increasing N supply, increased the shoot dry matter production by almost 38% at medium N and 70% at high N rate. A considerable increase in shoot N uptake was recorded at medium (74%) and high (123%) N rates with increasing N supply. Furthermore, pronounced nitrogen effect was observed on the leaf and stem growth and thus the total leaf area and plant height increased by almost 40% and 23% at medium N and 64% and 41% at high N rate, respectively. Interestingly, increasing N supply increased the leaf SPAD value by almost 10% at medium N and 18% at high N rates indicating a weak nitrogen impact on leaf chlorophyll content. On the other hand, despite of low enhancement in SPAD value, the photosynthetic activity of leaves substantially increased with increasing N supply and reached to 28% at medium N and 49% at high N rates (Fig. 1).

**Table 1.** Mean Shoot Dry Matter, Plant Height, Total Leaf Area, Leaf Chlorophyll Index (SPAD) and Photosynthesis of Four Vegetable Plant Species Grown under Three N Rates (Low N: 0.3 mM, Medium N: 1.5 mM, High N: 3.0 mM) in Nutrient Solution at 28 DAT. Means Between N Rates with the Same Letter (Lowercased: Low N, Underlined-Uppercased: Medium N, Uppercased: High N ) are not Significantly Different at P < 0.05 (Duncan's Test); Symbols with *, **, *** Denote Significant Differences at P < 0.05, 0.01, 0.001, Respectively; Ns, Non-Significant (F Test).

| Plant Species | N rate | Shoot Dry Matter (g $plant^{-1}$) | Shoot N Uptake (mg $plant^{-1}$) | Plant Height (cm) | Total Leaf Area ($cm^2$ $plant^{-1}$) | Leaf Chlorophyll Index (SPAD) |
|---|---|---|---|---|---|---|
| Eggplant | Low | 0.07 d | 1.27 d | 5.50 d | 57.91 d | 25.98 c |
| | Medium | 0.18 $\underline{D}$ | 5.05 $\underline{D}$ | 8.00 $\underline{D}$ | 97.65 $\underline{D}$ | 28.63 $\underline{D}$ |
| | High | 0.19 D | 5.78 D | 11.00 D | 119.34 D | 30.21 D |
| Tomato | Low | 0.39 c | 8.94 c | 15.00 c | 193.53 b | 32.44 b |
| | Medium | 0.44 $\underline{C}$ | 14.59 $\underline{C}$ | 18.08 $\underline{C}$ | 264.20 $\underline{B}$ | 36.09 $\underline{B}$ |
| | High | 0.54 C | 17.59 C | 19.25 C | 275.47 B | 38.55 B |
| Watermelon | Low | 0.45 b | 12.34 b | 17.50 b | 144.19 c | 39.48 a |
| | Medium | 0.53 $\underline{B}$ | 18.72 $\underline{B}$ | 20.75 $\underline{B}$ | 195.33 $\underline{C}$ | 41.55 $\underline{A}$ |
| | High | 0.68 B | 24.59 B | 22.50 B | 219.66 C | 43.73 A |
| Pumpkin | Low | 0.57 a | 15.44 a | 19.00 a | 257.75 a | 26.03 c |
| | Medium | 0.89 $\underline{A}$ | 27.58 $\underline{A}$ | 23.50 $\underline{A}$ | 359.50 $\underline{A}$ | 30.35 $\underline{C}$ |
| | High | 1.12 A | 36.65 A | 27.85 A | 459.25 A | 34.18 C |
| Species | *** | *** | | *** | *** | *** |
| N Rate | *** | *** | | *** | *** | *** |
| Species x N | *** | *** | | *** | ** | *** |

This can be attributed to an increase in shoot growth and shoot N uptake which might be contributed to a high leaf area formation and thus a high photosynthetic activity of leaves. Since, the N availability during growth and development plays a major role in establishing and maintaining a photosynthetic active canopy [10]. In general, an optimal external N supply has a substantial effect on the leaf area index (LAI) and the amount of N per unit leaf area ([16]. Furthermore, according to [17], the higher plant growth is due to the increase in leaf area and to the relationship between photosynthesis and leaf area. On the other hand, a suboptimal supply of N usually limits the leaf growth rate and thus the LAI due to low rates of net photosynthesis or insufficient cell expansion or both these factors [18]. In agreement with these studies, our results clearly indicated that an increase in N supply has an encouraging contribution to shoot growth, N uptake, leaf area development, leaf chlorophyll content (SPAD) and photosynthesis.

Highly significant (P<0.001) differences were found between four plant species in shoot dry matter, shoot N uptake, plant height, total leaf area, leaf SPAD value and photosynthetic activity (Table 1, Fig. 1). Growth response to supplied N, i.e. the interaction between N rate and plant species, was also highly significant (P<0.001). The shoot dry matter differences between plant species were relatively narrow under low N (6.0 g plant$^{-1}$), but enlarged with increasing N supply at medium (7.8 g plant$^{-1}$) and high N (11.6 g plant$^{-1}$) rates. The highest shoot dry matter production was recorded with pumpkin, while the lowest was found with eggplant at low, medium and high N rates. As well, tomato and watermelon usually showed an above-average dry matter production at low, medium and high N rates. Based on the shoot dry biomass, our result clearly showed significant genotypic variation in N efficiency between four different plant species under different N rates. Genotypic difference in nutrient efficiency of crop plants is not a new issue, since it has been well known for at least 92 years [19]. Recently, several studies widely reported the existence of genotypic differences in N efficiency between various field crops [20], [21], and [22] and vegetable crops species [23] and [24].

A genotype can be characterized as N-efficient either when realizing a yield above average under conditions of low or suboptimal N supply [22] or when converting N fertilizer efficiently into yield under conditions of high N supply [20]. In this present work, "N-efficient" species are defined as those realizing an above-average yield (shoot dry biomass) under suboptimal (low) N supply [22], while species having a high yield under optimal (medium) or high N supply are called "N-responsive".

Based on the shoot dry matter production at low N supply, pumpkin, tomato and watermelon can be classified as 'N-efficient', while eggplant as 'N-inefficient' species. Since, pumpkin usually produced significantly highest shoot dry matter, while tomato and watermelon had almost moderate, and eggplant a lowest at low N rate. Interestingly, only pumpkin and watermelon can be classified as 'N-efficient' and tomato 'N-inefficient' if comparison will be done only between three plant species by excluding eggplant. However, the question remains unanswered which morphological an physiological characteristics contribute to this plant trait. Moreover our results indicated that discussion of genotypic variation in N efficiency is quite complicated and the term can be used in different research objectives in different ways [20].

At non limiting N condition, pumpkin, tomato and watermelon produced an above-average shoot dry matter and therefore were called as 'N-responsive' and eggplant 'N-nonresponsive' species at medium N rate. However, only pumpkin retained the N-responsiveness in shoot dry matter at high N rate and the other three species were N-nonresponsive. By the way, at medium and high N rates only pumpkin can be classified as 'N-responsive' and watermelon and tomato as 'N-nonresponsive' if the comparison will be done only between three plant species by excluding eggplant.

A low performance in shoot dry matter production by eggplant, tomato and watermelon compared to pumpkin can be explained by severe yield depression due to high N supply which is partially in agreement with the study of [24] who recorded similar severe yield reduction on several vegetable species grown under high N supply.

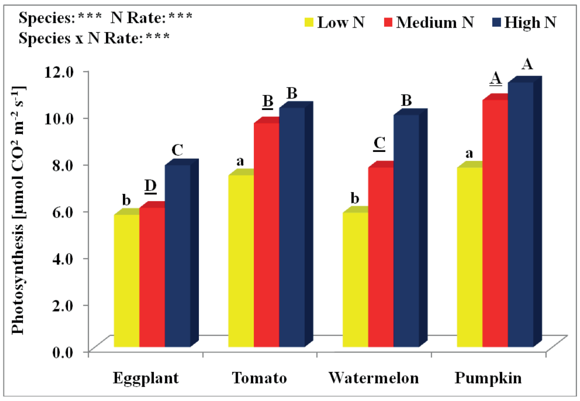


**Figure 1.** Photosynthesis of Four Vegetable Plant Species Grown under Three N Rates (Low N: 0.3 mM, Medium N: 1.5 mM, High N: 3.0 mM) in Nutrient Solution at 28 DAT. Means Between N Rates with the Same Letter (Lowercased: Low N, Underlined-Uppercased: Medium N, Uppercased: High N ) are not Significantly Different at $P < 0.05$ (Duncan's Test); Symbols with *, **, *** Denote Significant Differences at $P < 0.05, 0.01, 0.001$, Respectively; Ns, Non-Significant (F Test).

Since, the author [24] reported that tomato was superior and did not negatively influenced by high N rate while pumpkin, cabbage, lettuce and potato had a severe yield reduction. The contradictory results between two studies might be due to growth medium of the plants, since we conducted an hydroponic experiment whereas the other study [24] was a sand experiment.

In our study another subject is waited to explain why the growth performance of eggplant was significantly lowest as compared to other three plant species under different rates of N supply. The reason might be the eggplant is a relatively slow growing crop that usually accumulates maximum shoot biomass and N uptake during early and mass fruiting [25]. A study by [26] revealed that, relative growth rate of eggplant plants at the 1th 60 days was substantially low. Another study by [27] who reported that, the N uptake of eggplants was most intensive during early and mass fruiting. Our hydroponic experiment was conducted for a period of 28 DAT and may be the results and the response of eggplant grown under different rates of N supply could be different if we had a longer experimental period.

In terms of plant height the variation between species was about 13.5, 15.5 and 16.9 cm at low, medium and high N rates, respectively. Averaged over N rates the plant height ranked between species as pumpkin> watermelon > tomato > eggplant. Total leaf area between four species varied in the range of 199.8, 261.9, 339.9 cm$^2$, at low, medium and high N rates, respectively. Highest leaf area was developed by pumpkin and tomato, while the lowest was shown by watermelon and eggplant at three N rates.

Almost same variation was found in SPAD value (13.5) at low and high N rates, while the variation at medium N was slightly lower (12.9) than both N rates. Interestingly, N-efficient plant species (pumpkin) has similarly lowest SPAD value as N-inefficient plant species (eggplant) at three N rates. However, despite of showing a lowest SPAD value, a highest photosynthetic activity was recorded with pumpkin, while the lowest was found with eggplant at three N rates. This can be attributed to a negative correlation between leaf area development and SPAD value of leaves. In general, the plants which have a great leaf area formation usually show a decline in accumulation of N per unit of leaf area [28]. Also similar negative correlation between leaf area and SPAD value and a positive correlation between leaf area and photosynthesis can be easily seen in the results of watermelon at three N rates. By the way, the variation between four plant species in photosynthetic activity was by almost 2.0, 4.6 and 3.5 µmol $m^{-2}$ $s^{-1}$ at low, medium and high N rates, respectively.

**Root Growth and Morphological Development**

Root dry matter, root:shoot ratio, total root length, total root volume and average root diameter of four plant species was significantly (P<0.001) affected by different rates of N supply (Table 2). Opposite to shoot growth, plants under low N supply showed significantly higher root dry matter, root:shoot ratio, total root length, total root volume and thicker root than plants grown under medium and high N conditions. Increasing N rate, reversely decreased the root dry matter production by almost 29.8% at medium N and 42.2% at high N rate. The decline in root:shoot ratio was much higher than root dry matter when the N rate was increased from low to medium (53.7%) or to high (69.5%) N. Furthermore, the decline in total root length was about 22.9% at medium N and 32.1% at high N rate, while a much higher reduction in total root volume was recorded when the N rate was increased from low to medium (30.1%) or to high (42.1%) N. Average root diameter decreased with increasing N supply almost by 4.2% at medium N and 8.0% at high N rates and thus plants showed usually thick roots at low N, whereas roots elongated and became thin at medium and high N rates.

Nitrogen uptake is regulated by the demand of the growing crop if N supply is not limited [29]. In contrast, if the required N is limited in the soil, N uptake depends on the extent and effectiveness of the root system [30] and also morphological root characteristics such as maximum rooting depth, and root length density at deeper soil layers [20]. Root production depends on the carbohydrate supply from the shoots [31] and nutrient supply in the growth medium [32].

This is in agreement with our study that clearly indicated plants grown under low N condition had more vigorous root system (root dry matter, root length and volume) than plants grown under medium or high N conditions. A highest root:shoot ratio result under low N than medium or high N rates also confirmed by the several studies [33] and [34].

This was mainly due to differences in partitioning of dry matter within the plant that allocated a higher proportion of its total dry matter to the root system under low N condition [20] and [35]. An increased carbohydrate sink strength of the roots under N deficiency usually leads to greater allocation of assimilates to the roots for new root formation [36]. Since, newly developed roots are of particular importance for nutrient uptake [37]. A higher root formation under low N supply than under high N supply was also found by [38] and [39] who worked with various plant species.

Highly significant (P<0.001) differences were found between four plant species in root dry matter, root:shoot ratio, total root length, total root volume and average root diameter (Table 2). Also, growth response to supplied N, i.e. the interaction between N rate and species, was highly significant (P<0.001). Interestingly, the variation between plant species in root dry matter was relatively large under low N (0.09 g $plant^{-1}$), but a sharp decline occurred with increasing N supply at medium (0.06 g $plant^{-1}$) and high N (0.05 g $plant^{-1}$) rates.

**Table 2.** Mean Root Dry Matter, Root:Shoot Ratio, Total Root Length, Total Root Volume and Averaged Root Diameter of Four Vegetable Plant Species Grown under Three N Rates (Low N: 0.3 mM, Medium N: 1.5 mM, High N: 3.0 mM) in Nutrient Solution at 28 DAT. Means Between N Rates with the Same Letter (Lowercased: Low N, Underlined-Uppercased: Medium N, Uppercased: High N ) are not Significantly Different at P < 0.05 (Duncan's Test); Symbols with *, **, *** Denote Significant Differences at P < 0.05, 0.01, 0.001, Respectively; Ns, Non-Significant (F Test).

| Plant Species | N Rate | Root Dry Matter (g $plant^{-1}$) | Root:Shoot Ratio (g $g^{-1}$) | Total Root Length (m $plant^{-1}$) | Total Root Volume ($cm^3$ $plant^{-1}$) | Averaged Root Diameter (mm) |
|---|---|---|---|---|---|---|
| Eggplant | Low | 0.04 d | 0.55 a | 5.54 d | 0.38 d | 0.29 a |
| | Medium | 0.03 D | 0.19 A | 4.32 D | 0.31 C | 0.28 A |
| | High | 0.02 C | 0.12 A | 3.54 D | 0.27 C | 0.27 A |
| Tomato | Low | 0.12 b | 0.30 b | 30.44 b | 1.86 a | 0.25 c |
| | Medium | 0.08 B | 0.18 A | 24.16 B | 1.18 A | 0.24 C |
| | High | 0.06 B | 0.11 A | 21.68 B | 0.97 A | 0.23 C |
| Watermelon | Low | 0.09 c | 0.18 d | 24.82 c | 1.36 c | 0.26 b |
| | Medium | 0.07 C | 0.12 B | 21.19 C | 1.06 B | 0.25 B |
| | High | 0.06 B | 0.09 B | 19.19 C | 0.88 B | 0.24 B |
| Pumpkin | Low | 0.13 a | 0.23 c | 37.72 a | 1.72 b | 0.24 d |
| | Medium | 0.09 A | 0.10 C | 28.11 A | 1.18 A | 0.23 D |
| | High | 0.08 A | 0.07 C | 26.66 A | 0.98 A | 0.22 D |
| Species | *** | *** | *** | *** | *** | *** |
| N rate | *** | *** | *** | *** | *** | *** |
| Species x N | *** | *** | *** | ** | *** | *** |

Our results clearly indicate that plants grown under low N stress condition exhibit a higher genotypic variation in root morphology than plants grown under favorable N conditions. The highest root dry matter was recorded with N-efficient species pumpkin, while the lowest was found with N-inefficient species eggplant consistently at low, medium and high N rates. As well, tomato showed almost similar root dry matter as pumpkin, while a moderate root dry matter was exhibited by watermelon at three N rates. The variation in root:shoot ratio between four species was about 0.37, 0.09 and 0.05 g $g^{-1}$ at low, medium and high N rates, respectively. The highest root:shoot ratio was recorded with eggplant, while the lowest and almost similar was shown by pumpkin and watermelon at low N rate. At medium and high N rates, eggplant and tomato showed the highest root:shoot ratio, while the lowest was shown by watermelon and pumpkin. Showing usually a high shoot (Table 1) and root (Table 2) dry matter production, but reversely having a relatively low root:shoot ratio confirmed that assimilate partitioning of N-efficient sp. pumpkin was uniformly between shoot and roots particularly at low N rate. However, this was not true for eggplant, since due to a high carbohydrate sink strength of roots under N deficiency, great assimilates might have been allocated from shoot to the roots and thus showed a highest root:shoot ratio at low N rate. Consequently, it explains why the shoot growth of eggplant was the lowest as compared to other three plant species. Moreover, due to relatively slow shoot growth and N uptake [25], [26] and [27] plant characteristics and also unequally assimilate partitioning between shoot and roots might be the reasons that led to characterize eggplant as N-inefficient species. Genotypic differences in total root length between four plant species clearly confirmed that ps. pumpkin has an equivalent assimilate distribution between shoot and roots. Since, the highest total root length was produced by ps. pumpkin while the lowest was produced by ps. eggplant at three N rates. Almost similar and moderate total root length was shown by tomato and watermelon at three N rates. Total root length varied between species by almost 32.2, 23.8 and 23.1 m plant$^{-1}$ at low, medium and high N rate, respectively. Significantly highest total root volume was recorded with tomato at low N rate, while the lowest was shown by eggplant. A higher root volume, but a lower root length production of tomato than pumpkin at low N rate can be explained due to variation in thickness (root diameter) of individual roots. On the other hand, at medium and high N rates tomato and pumpkin produced similar and highest total root volume, whereas the lowest was shown by the eggplant. A moderate root volume was exhibited by watermelon at three N rates. Total root volume varied between species by almost 1.48, 0.87 and 0.70 cm$^3$ plant$^{-1}$ at low, medium and high N rate, respectively. Almost in all measured root morphological parameters, eggplant showed usually the lowest results as compared to other three species at low N rate. But in terms of average root diameter this species showed significantly highest result than other three species at low, medium and high N rate. This result can be explained by having a short but a thick roots of eggplant than the other three species. Average root diameter varied between species by almost 0.050, 0.049 and 0.052 mm at low, medium and high N rate, respectively. The root diameter between four species under three N rates ranked consistently as eggplant > tomato > watermelon > pumpkin.

# CONCLUSION

The results indicated increasing N supply, had significantly positive effects on the shoot growth and leaf physiological development, while the root growth and morphology were negatively affected. Based on shoot biomass yield performance pumpkin was characterized as ‘N-efficient’ whereas eggplant as the ‘N-inefficient’ species under low N supply. Similar genotypic variation existed at medium or high N rates between species and thus pumpkin was characterized as ‘N-responsive’ whereas eggplant as ‘N-nonresponsive’. All results clearly indicated that ‘N-efficiency’ and ‘N-responsiveness’ of pumpkin are more closely related to vigorous and active root system occurred with a uniform assimilate allocation to the roots that contributed to high shoot N uptake and high photosynthesis. Consequently, we can suggest that the root traits which are contributing to N efficiency of pumpkin should be investigated under field conditions with various N fertilizer doses.

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