

NDT, a new soilless growing system without substrate suitable for Mediterranean conditions

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Abstract

Nutrient film technique (NFT) is characterized by the reduction of the dissolved oxygen concentration (DOC) in the recirculating nutrient solution along the gully; this is most intense in warm climates like the Mediterranean region. In this case, plant's roots at the end of gully suffer from oxygen deficiency. The aim of this study was to develop a new soilless system without substrate which eliminates this NFT drawback and the cost of the substrate. Therefore, a new soilless system was designed. This new system associated the continuous drip irrigation along the gully with the recirculation of the nutrient solution and it was defined as Nutrient Drip Technique (NDT). In addition, the root gully was modified and shaped as W to provide better drainage of the nutrient solution in NDT system compared to NFT system. This system was tested for a tomato crop and compared with an NFT system and for a cucumber crop and compared with a media-based perlite and an NFT system. DOC measurements were taken along the gullies of the different systems. The results indicated that DOC of the nutrient solution along the gullies of NDT was higher and more uniform compared to NFT. Both tomato and cucumber plants grown in NDT system had higher Leaf Area Index (LAI) and were more productive compared to the conventional NFT system. Cucumber crop in NDT system had similar growth and productivity as in the perlite system. Water Use Efficiency (WUE) was higher in NDT compared to NFT system. Consequently, NDT system provides a better control of the root environment and the independence of porous substrates.

Keywords: drip irrigation; hydroponic systems; oxygen; root environment; water potential

Introduction

Growing plants in solution culture, allows accurate control of nutrients and water supplies for plants (Adams, 1981; Epstein and Bloom, 2005). It creates less emission, increases water and nutrient use efficiencies and is therefore a more sustainable method than growing in porous substrate. Growing without porous substrate can also lead to higher yields, because all conditions can be better controlled. Growing plants without porous substrate exhibits, also, several advantages, for plant research applications, such as salinity and water-deficit stresses, which can be applied evenly and accurately to the cultivated plants.

In NFT system, as the roots are constantly in the nutrient solution (Cooper, 1975) and the same nutrient solution runs from the upper end of the gully through the roots of many plants across the length of the gully, dissolved oxygen concentration (DOC) in the nutrient solution is possible to be depleted and electric conductivity (EC) may be differed some meters after the entrance in the gully. Plants exhibit reduced number of growth points and root death mainly at the end of the long gullies, caused by oxygen deficiency (Vlugt, 1986). Oxygen deficiency has an immediate effect on the water and nutrient uptake, and on the yield of the whole plant under different soilless culture conditions (Morard and Silvester, 1996; Morard *et al.*, 2000; Adams, 2002). Physiological effects of hypoxia on roots of many plant species have been well documented (Engelaar *et al.*, 1993; Thomas *et al.*, 2005). A good oxygen supply to the roots depends on sufficient replacement across the gullies. Sufficient oxygen supply could be satisfied from a higher flow rate of nutrient solution. However, this is not useful in NFT system, because at the end of the gullies the water level rises too much, creating more waterlogging problems to the plants at these points. Usually, oxygen deficiency in solution culture mainly occurs as the result of high solution temperature, because molecular oxygen has a slow rate of diffusion from air to water and of high respiration rates of roots. Except for temperature, oxygen concentration in the root environment is greatly affected by root biomass and supply of photosynthates to roots, from the aerial part of the plant (Morard and Silvestre, 1996).

Several methods have been tested for improving the oxygen supply to crop roots (Bhattarai *et al.*, 2005). Ehret *et al.* (2010) used an oxygen microbubble diffuser in nutrient solution tank. Marfà *et al.* (2005) used a sealed injection chamber to dissolve oxygen in pressurized water. The supply of pure, pressurized oxygen gas to the nutrient solution is an oxygen-enriched method used usually for research purposes (Chun and Takakura, 1994). Moreover, additional oxygen may be provided directly into the rhizosphere during irrigation with hydrogen peroxide injection (Huber, 2000) or potassium peroxide (Urrestarazu and Mazuela, 2005) into the irrigation stream. Nevertheless, conflicting results have been found regarding the use of oxygen-enriched methods on various hydroponic systems for greenhouse crops in Mediterranean areas (Urrestarazu and Mazuela, 2005).

In most porous substrates, the roots are well oxygenised via dissolving air from the pores of the substrate in the water film around the roots. However, in many cases, root aeration in crop production may be elusive because of the complexity of interactions among plant roots, substrate physical properties and irrigation practices. In porous substrates, the periodic variation in the amount of nutrient solution which is contacted the roots can cause an undesirable variable stem water potential to the plants (Wheatley *et al.*, 2009). Holtman *et al.* (2005) stated that if the control of oxygen levels in root systems is technically feasible, it may become a new tool for growers to manage cultivation in horticulture, in addition to light, temperature, carbon dioxide, nutrition and water.

Consequently, the major problem of the NFT system is the depletion of the dissolved oxygen along the gully, particularly in long-term cultivations and during the hot periods. On the other hand, the major problem of the substrates systems is the cost of their supply. Therefore, a new hydroponic recycling system, without the disadvantages of the NFT system, should be developed. The aim of the current study is the design and the operation of a new hydroponic recycling system, without substrate, which has to supply nutrient solution with saturated oxygen concentration along of the whole gully.

The essential features of the new hydroponic system and results, which were recorded throughout the duration of the two experiments, about variations in oxygen content of the nutrient solutions and the effects of the system on the growth and yield of the tomato and cucumber plants are presented.

Materials and Methods

The hydroponic set up

The basic features of the new hydroponic system, named Nutrient Drip Technique (NDT) are similar to NFT system and include: (1) a tank of nutrient solution; (2) a pump to deliver the solution, via pipes, to the upper ends of (3) the sloped gullies in which the plants are grown; (4) one irrigation line with emitters, which lay in the middle of each gully, across the length of the gully and (5) a means of collecting the solution as it flows from the lower ends of the drainage water-courses and of returning it to the tank for recirculation. The means of fertigation in NDT are similar to NFT system.

The gullies that are made from sheet-metal, differ from that of NFT, forming in both sides a U type drainage water-course (Figure 1). The gullies were 0.3 m wide plus 0.05 m for each drainage water-course. NDT gullies are laid on metal scaffold, with a slope of 1%. Each gully is covered with a double face white-black PE plastic sheet of 0.25 mm thick, waterproofing the gully. The two edges of the PE are clipped together to form a channel. The black colour is on the inside and the white on the outside, thus reducing heat absorption in bright sunshine and increasing the reflection of light during winter. In both sides of the gully, in the water-course and across of its whole length, PVC perforated pipes are placed (0.05 m wide), in order to prevent the roots from developing in the drainage water-course and facilitate the drainage. The diameter of the perforated pipes used was 42mm. The holes on the perforated pipes were located on the upper side, every 0.4 m, their width was 4 mm and their length was equal to a quarter of the diameter of the pipes. The pipes were covered by a net with very small holes (0.10 mm) to permit water passage but avoiding the roots to go in the drainage pipes. The nutrient solution is delivered in the gullies by the drip irrigation system. The emitters (Strimon, Palaplast Ltd.) are two for each plant, delivering nutrient solution at the rate of 8 litres per hour. The solution flowing continuously from the centre of the gully is allowed to flow into the drainage pipes in both sides of the gully under gravity and the leached solution is transported to the nutrient solution tank, for recirculation (Figure 1).

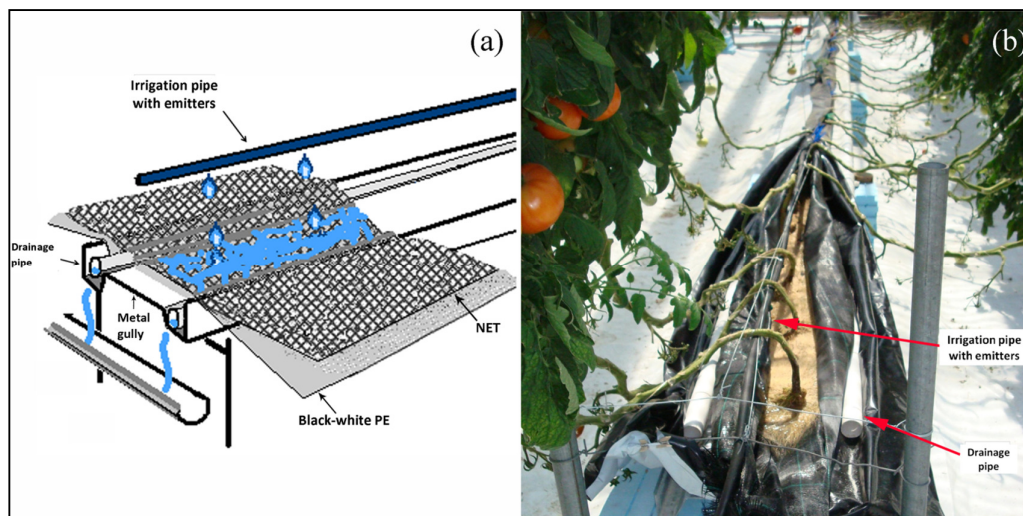


Figure 1. (a) A schematic layout of the tested soilless growing system (NDT) and (b) Photograph of a greenhouse where NDT system was tested in the experiment with tomato plants

Experiments

The experiments were carried out for cluster tomato crop and for long cucumber crop in an experimental greenhouse located at the Agricultural University of Athens campus (37° 59' N, 23° 42' E and 38 m altitude), Greece. Both experiments were conducted in a venlo-type greenhouse of 200 m², covered with a 1 mm thick polycarbonate sheets. The greenhouse had air heater equipment and it was passively ventilated by opening

side and roof vents. Greenhouse temperature was ranged from 14 to 32 °C, while the relative humidity in greenhouse was ranged between 50 and 80%.

During the first experiment the NDT system and an NFT system were compared. The NFT system included all the features as above in NDT system except the gullies which were without side drainage water-courses and the irrigation system in which the nutrient solution was released at the upper end of the NFT gullies, flowed by gravity to the lower end of the gullies and returned into the tank for recirculation. Tomato seedlings (*Solanum lycopersicum*, cv. 'Rally F1') raised in perlite were transplanted at the stage of 6-8 true leaves (5 weeks after sowing) and were grown in NFT and NDT at a plant density of 2.5 plant m⁻². Plants were started in the gullies in January and the cycle ended in May. For the NFT, the gullies were 10 m long, 0.3 m wide and had a slope 2%.

In the second experiment, cucumbers (*Cucumis sativus* L. Prevely F1) were grown at a plant density of 2 plants m⁻². NDT, NFT and perlite bag systems were compared. Each perlite bag (Perloflor Hydro®) was 1m long and 33 L in volume with 95% total porosity. The grain size ranged from 0.5 to 2.5 mm. Three plants were planted in each bag. The perlite bags were placed on 10 m long gullies with 0.3 m width and 1% slope. Plants were transplanted in the gullies and perlite bags in the beginning of December and the cycle ended in the beginning of May.

In both experiments, each gully represented a treatment and accommodated 30 plants. Each treatment was duplicated. Thus, there were 60 replicate plants per treatment. The gullies were randomly arranged in six rows. Additional plant rows were placed around the experimental installation to prevent margin effects.

The nutrient solution was continually recirculating day and night using suitable pumps. The composition of the tomato nutrient solution was as follows: 10.00 mM K⁺, 5.35 mM Ca²⁺, 1.43 mM Mg²⁺, 0.72 mM NH₄⁺, 15.00 mM NO₃⁻, 1.50 mM H₂PO₄⁻, 3.90 mM SO₄²⁻, 40 μM Fe, 20 μM Mn, 5 μM Zn, 20 μM B, 0.5 μM Cu and 0.5 μM Mo. Furthermore, the composition of the cucumber nutrient solution was as follows: 7.15 mM K⁺, 3.55 mM Ca²⁺, 1.10 mM Mg²⁺, 0.65 mM NH₄⁺, 15.28 mM NO₃⁻, 1.25 mM H₂PO₄⁻, 1.49 mM SO₄²⁻, 40 μM Fe, 20 μM Mn, 4 μM Zn, 20 μM B, 0.5 μM Cu and 0.5 μM Mo. The same nutrient solution was applied for the different growing systems. In average for the first experiment (tomato), a flow rate in the gully of 2.3 L min⁻¹ for NFT, and 7.8 L min⁻¹ for NDT was used. For the second experiment (cucumber) it was used 2.9 L min⁻¹ for NFT and 8 L min⁻¹ for NDT. A higher flow rate for NDT system was used, utilizing the advantage of the NDT system to have better drainage, in order to serve more oxygen and nutrients to the roots.

Irrigation of the perlite bag system was controlled by equipment based on integrated solar radiation, performed when a preset amount of accumulated radiation (600 kJ m⁻²) was reached. Solar radiation was measured by a pyranometer (CM11, KIPP & ZONEN, Holland). This solar energy level for the activation of irrigation was too low because the irrigation system was recirculating and losses of nutrients did not occur. The application of this strategy ensured that plants grown in perlite bags did not face any water availability problem.

In both experiments, every morning and evening, EC and pH values of the nutrient solution in the solution tank were measured by a portable equipment (PC10, CyberScan) and adjusted. Conductivity was maintained at 2 - 2.5 dS m⁻¹ and pH of 5.5-6.5. Water lost by evapotranspiration was replaced automatically by a float valve. Water consumption was measured daily by flow meters.

The productive part of the main stem of each tomato plant was vertically guided with polypropylene cords, supported by wires at a height of 2.7 m. Each cucumber plant was trained to grow vertically up to a wire used for support, following the umbrella system.

Growth and yield measurements

For both experiments (tomato and cucumber), eleven plants per gully (22 plants per treatment) were randomly chosen for growth measurements. During the experiments in each selected plant, height, leaf number per plant, as well as leaf dimensions were measured. In each experiment, the area of 72 leaves with known length and width was estimated by means of an imaginary computer program (Delta-T Scan). Using this data and applying linear regression analysis, the following equations were established: $y = 0.3289X - 40.3$ ($R^2=0.95$) for

tomato and $y = 0.8408X + 10.5$ ($R^2=0.95$) for cucumber, and used to estimate the leaf area (y) as a function of the product length \times width (X). Using these equations, the leaf area of each sampled plant was estimated. Furthermore, the total number of leaves was counted in each sampled plant. Hence, the total leaf area of each sampled plant was estimated by multiplying the mean area per leaf by the total number of leaves per plant.

Fruits were harvested from the same selected plants and weighted, two times per week. Fruit number was also determined. Tomato experiment was carried out until the harvest of 8th cluster (128 days after transplanting). Harvest period in second experiment (cucumber) began 49 days after transplanting and ended 154 days after transplanting.

Season-long water use of each species was obtained by summing the weekly water consumption over the entire season assuming that the evaporative loss from the gullies was insignificant. The season-long water use efficiency, WUE was calculated by dividing the total fruit yield by the season-long water use. Thus, WUE represents the amount of accumulative yield over the season for each unit of water transpired by the plant (g fresh weight $L^{-1} H_2O$).

Oxygen measurements

DOC was measured with a dissolved oxygen sensor (CellOx 325, CRISON, Spain) connected to a handheld DO meter (OXI 45P, CRISON, Spain) of ± 0.01 $mg L^{-1}$ resolution, with temperature compensation. Measurements were taken at the upper end of the gullies (1m from the inlet), at the middle (5m from the inlet) and at the lower end (9m from the inlet), in all tested systems. DOC was measured every day between 12:00 to 14:00 p.m., when DOC values are theoretically lowest (Gislerod and Adams, 1983). DOC measurements were conducted immediately in the gully. In the perlite bags DOC measurements were conducted 0.5 cm above the bags bottom, half an hour after irrigation, between 12:00 to 14:00 pm.

Nutritional status

In the first experiment, with tomatoes, during the growing period and for four different dates (47, 55, 89 and 96 days after the planting), samples of 8 - 10 leaves at the 5th knot from the top were randomly sampled from each treatment, in different plants from those selected for growth measurements. Leaf samples were oven-dried at 70 °C to constant weight and were grounded for mineral analysis, after ashing at 500 °C and extraction with 1N HCl solution. The concentrations of K^+ and Ca^{2+} were determined by atomic absorption spectrophotometry (Varian, SpectrAA-200, Australia). Total nitrogen was determined by means of Kjeldahl digestion using a Gerhard Vapodest 30 apparatus.

Statistical analyses

The data were subjected to repeated measurements or single factor analyses of variance using the STATISTICA 7.0 work package and, when a significant F-test was obtained, means were separated using LSD-test ($P < 0.05$).

Results

Dissolved oxygen concentration (DOC)

In both experiments values of DOC in the nutrient solution supplied at the upper end of the gullies were similar for NDT and NFT systems, but at the downstream of the middle and just downstream of the last plant in the gully were clearly different, throughout the tomato (Figure 2) and cucumber cycle (Figure 3).

In tomato, the DOC in the solution tank at the pump inlet was 7.3 $mg L^{-1}$. The mean seasonal DOC value, at the last plant in the gully, was significantly higher for the NDT system 7.1 $mg L^{-1}$ (89% saturation) than for the NFT system 5.1 $mg L^{-1}$ (64% saturation).

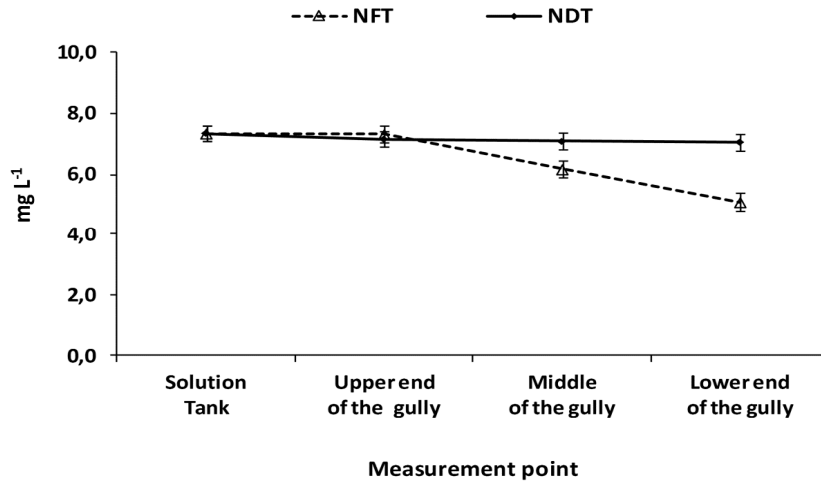


Figure 2. Dissolved Oxygen Concentration (mg L^{-1}) in tomato nutrient solution in the solution tank and across the length of the gullies for NDT and NFT systems. Vertical bars depict \pm S.E.s of means of 20 measurements

In cucumber, the DOC in the solution tank at the pump inlet was 7.3 mg L^{-1} . The mean seasonal DOC value, at the last plant in the gully, was significantly higher for the NDT system 7.3 mg L^{-1} (90% saturation) than for NFT (5.7 mg L^{-1}) and perlite bags (5.7 mg L^{-1}) (0.5cm above the bottom) (Figure 3). DOC in the NDT nutrient solution was maintained adequate across the entire length of the gully, over the whole period of cultivation. DOC of nutrient solution in perlite bags was recorded low along the length of the gully.

Greenhouse conditions (including air temperature) were normal during the course of the experiments. High temperatures sometimes fluctuated as much as $32 \text{ }^{\circ}\text{C}$, while low temperatures fluctuated to $10 \text{ }^{\circ}\text{C}$. The greater DOC values in winter were associated with lower greenhouse air temperature and solar radiation values and therefore with lower nutrient solution temperature and lower crop activity. Day temperatures of the nutrient solution along NDT, during the experiment, tended to be slightly lower than those of NFT (data not presented).

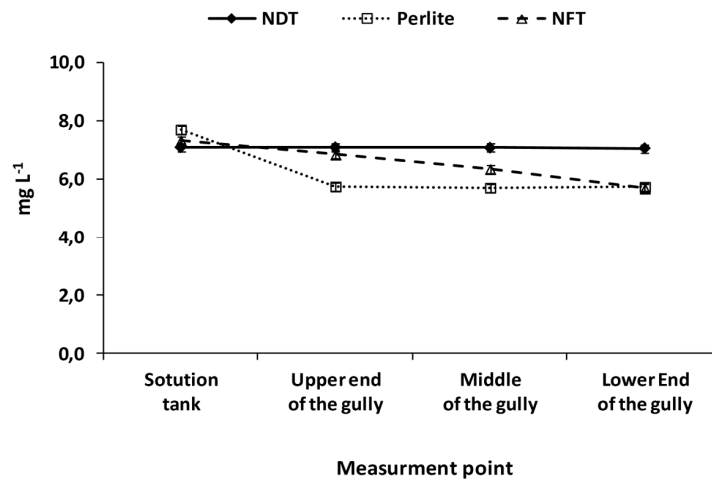


Figure 3. Dissolved Oxygen Concentration (mg L^{-1}) in cucumber nutrient solution in the solution tank and across the length of the gullies for NDT, perlite and NFT systems. Vertical bars depict \pm S.E.s of means of 45 measurements

Growth parameters and nutrient status

Roots of tomato plants grown in the NDT at day 90 appeared healthy and white, whereas those of plants in NFT were yellowish. During the second experiment with cucumber, root death appeared in NFT, after 130 days, and plants were wilted. Various micro-organisms were isolated from roots of NFT, but none of those were determined to be the causal agent of root death. For this reason, the measurements were stopped in NFT. In NDT and perlite bags plants were vigorously developing until the end of the cultivation (154 days after transplanting). The nutrient solution and its temperature were similar in both systems.

For the tomatoes, no significant differences in plant height were found between growing systems (Figure 4a). However, a significant positive effect of NDT system was observed on leaf area index (Figure 4b). In NDT system the increase (30%) in leaf area index was due mostly to an increase in mean leaf size by 21% (Figure 4d) and secondarily to an increase in the leaf number per m² by 6% (Figure 4c).

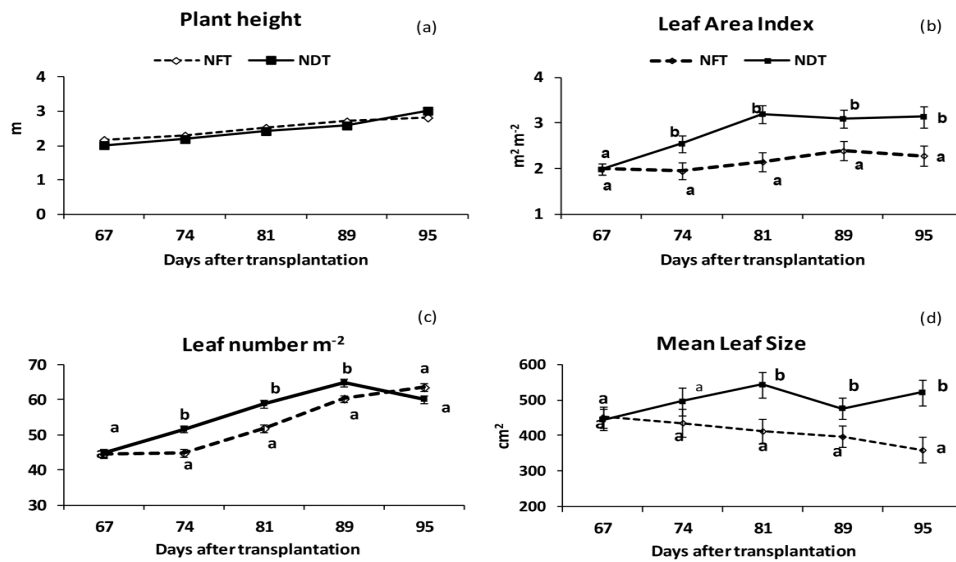


Figure 4. Effects of two different soilless growing systems (NFT and NDT) on a. plant height, b. leaf area index, c. leaf number per m² and d. mean leaf size of tomatoes plants. Vertical bars depict ±S.E.s of means of 11 measurements

In cucumber no significant differences were found in plant height (Figure 5a) and leaf area index between NDT and perlite bags growing systems, however, significantly lower (21%) leaf area index was observed in NFT growing system compared to NDT system (Figure 5b). In NFT system the decrease in leaf area index was largely attributed to the smaller leaf size (Figure 5d) and reduced leaf number per m² (Figure 5c).

Total N, K⁺ and Ca²⁺ concentration in tomato leaves were unaffected by the growing systems (Table 1).

Table 1. Concentrations (mmol g⁻¹ dry weight) of total N, K and Ca in young, fully developed leaves of tomato grown in recirculating nutrient solution as influenced by the growing system

Growing System	Mean Concentrations ± S.E. (mmol g ⁻¹ D.W.)		
	Total N	K	Ca
NFT	3.20 ± 0.05 a	1.20 ± 0.021 a	0.37 ± 0.016 a
NDT	3.28 ± 0.05 a	1.20 ± 0.021 a	0.39 ± 0.016 a

Values are means of 10 samples taken 47, 55, 89, and 96 days after transplanting. In each column, values followed by the same letter do not differ significantly (LSD test, P < 0.05).

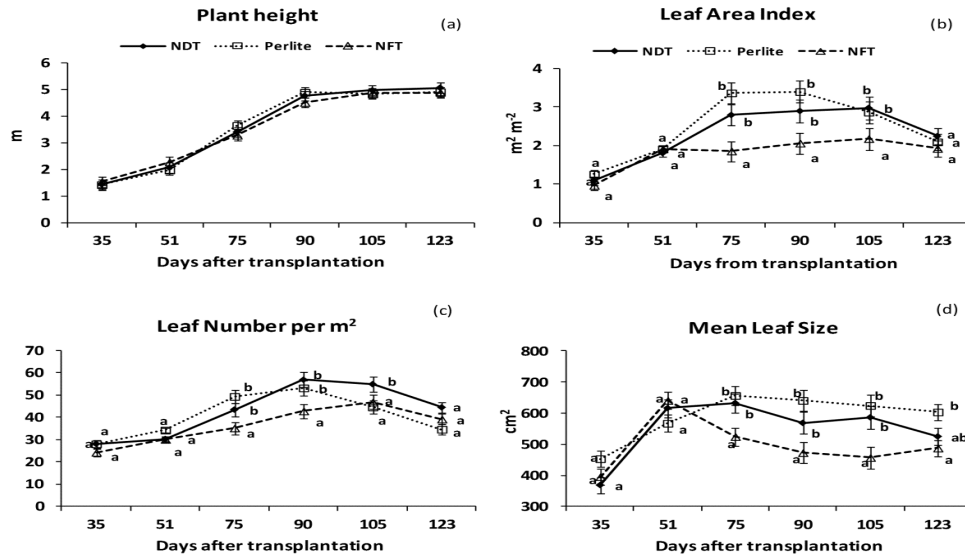


Figure 5. Effects of three different soilless growing systems (NFT, Perlite and NDT) on (a) plant height, b. leaf area index, c. leaf number per m² and d. mean leaf size of cucumber plants. Vertical bars depict ±S.E.s of means of 11 measurements

Yield components

Tomato fruit production showed a significant increase (34%) in the NDT system (Figure 6a) compared to NFT system. The number of fruits per m² was not affected by the growing system (Figure 6b). However, the individual fresh fruit weight was significantly higher (21%) in NDT compared to NFT (Figure 6c).

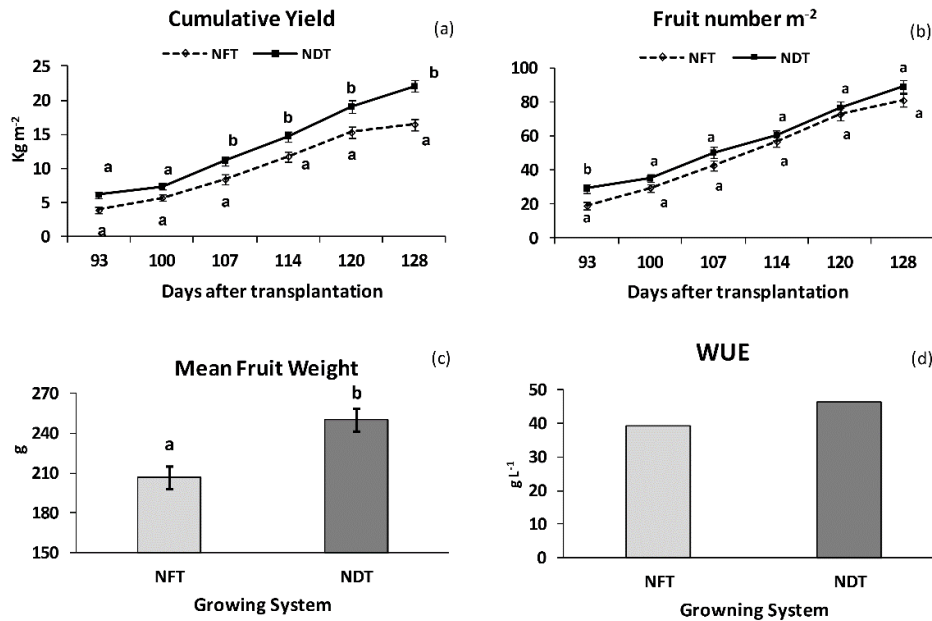


Figure 6. Effects of two different soilless growing systems (NFT and NDT) on a. Cumulative yield, b. fruit number per m², c. mean fruit weight and d. water use efficiency of tomatoes plants. Vertical bars depict ±S.E.s of means of 11 measurements

No significant differences in cucumber fruit yield were found between NDT and perlite bags growing systems; on the contrary, fruit yield was much lower (30%) in NFT growing system compared to NDT system (Figure 7a). The decrease in yield of cucumber plants in NFT growing system resulted by the fewer number of fruits per m² (21%) and by the lower weight of the individual fruit (10%).

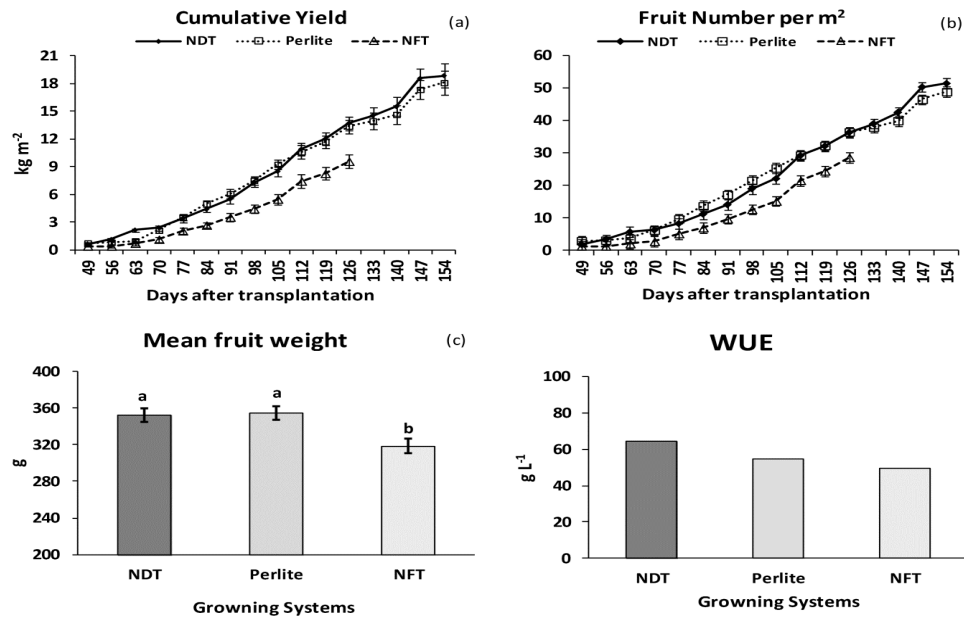


Figure 7. Effects of three different soilless growing systems (NFT, Perlite and NDT) on a. Cumulative yield, b. fruit number per m², c. mean fruit weight and d. water use efficiency of cucumbers plants. Vertical bars depict \pm S.E.s of means of 11 measurements

In the first experiment with tomato, each plant consumed 168 L of water in NFT system and 190.4 L in NDT system from January until May. Season-long water use efficiency (based upon commercial yield per unit volume of water consumed throughout the season) (from January until May) was 18% higher in NDT (46.4 g L⁻¹) compared to NFT (39.3 g L⁻¹) for tomato (Figure 6d). In cucumber experiment, each plant consumed 96.4 L of water in NFT, 106.1 L in NDT and 116.6 L in perlite system from December until April. Season-long water use efficiency (from December until April) was higher by 30% in NDT (64.4 g L⁻¹) system and 16% in perlite (57.3 g L⁻¹) compared to NFT (49.6 g L⁻¹) for cucumber (Figure 7d).

Discussion

Plants roots require dissolved oxygen for respiration, nutrient and water uptake. For high value crops, such as most soilless long-term vegetables crops, the understanding of the root zone oxygen dynamics and the factors influencing it may be of interest for improving soilless cultural practices. DOC in NFT nutrient solution began to drop following downstream across the length of the gullies. The drop was negligible on top of the gullies and 30% at the lowest part of the 10m long gullies in the case of tomato (Figure 2) and 17% in the case of cucumber (Figure 3), highlighting the influence of the plant activity. In solution cultures such NFT system, oxygen availability to plant roots may be improved via an increase in the nutrient solution flow rate. However, this practice may be caused stagnation problems. The stagnation of nutrient solution inside the channels of the NFT system due to excessive root biomass in long-term crops (Savvas and Gruda, 2018) causes low solubility of oxygen in solution. In NFT system, the decrease in DOC was lower in cucumber compared to

tomato due to the higher solution flow rate in the gully (2.9 L min^{-1} versus 2.3 L min^{-1}). Several researchers have reported oxygen deficiency in NFT system (Jackson, 1980; Puerta *et al.*, 2007). In NDT system, each plant was supplied with fresh, oxygen saturated nutrient solution through the emitters. Obviously, in NDT system the distance covered by the nutrient solution in its way through the bed is considerably shorter than the whole length of the channel, such as in NFT system. Thus, a uniform distribution of the nutrient solution was achieved, without reduction in DOC in NDT system.

DOC of nutrient solution 0.5cm above the bottom of perlite bags was maintained low, without any negative effect on the production. At the bottom of the perlite bags, a small reservoir of nutrient solution exists in a standing condition, which is not in favour of oxygen dilution. The physical properties of growing media are very important because they have a strong influence on air availability to the plant roots. Perlite is a growing media with high total pore space which ranges round 50-70% v/v (Savvas and Gruda, 2018). In a standard substrate-based hydroponic system, such as perlite, the plant root system is not just dependent on oxygen dissolved in the nutrient solution for respiration; oxygen is also present in the air-filled pores of the growing media. As nutrient solution is applied and flows through the growing media and then drains from the base, fresh air is pulled down into the root zone and fills the pores around the roots. Provided the media is permitted to actually fully drain and is not continually-or too frequently-irrigated with nutrient solution, air will remain in these pore spaces to provide some oxygen to the root system. Perlite substrate naturally drains freely and holds a lot of air. A large amount of the root system, in the perlite bags, is above of the nutrient solution which exists in bottom; thus, roots are well oxygenised via dissolving air from the pores of the substrate in the water film around the upper roots. In porous media the diffusion of oxygen from the air-filled porosity in the solution is continuous. In solution cultures, where mass flow of oxygen to the roots can be realized to minimize boundary layer effects around roots, a critical oxygen pressure - defined as the lowest partial pressure for a physiological process such as root extension to have its maximum activity. However, for roots grown in media, diffusion is the only significant process involved to reach the root surface, and boundary layer effects are therefore significant. The diffusion coefficient of oxygen increased strongly with the air-filled porosity (Baas *et al.*, 2001), in conventional perlite bags air-filled porosity (AFP) usually retain above 45% (Acuna *et al.*, 2013). Moreover, Baas *et al.* (2001) concluded that no oxygen depletion is expected in the perlite when AFP is above of 31%. Thus, the critical concentration level of dissolved oxygen in porous media may not be the same as in the solution culture systems.

Leaf area index was higher in NDT system compared to NFT in both experiments, which could suggest a better water availability in the plants. The better aeration of the nutrient solution in NDT system may reduce heat stress on the canopy, maintaining more positive leaf water potential and a smaller crop water stress index (Bhattarai *et al.*, 2005). More favourable plant water potential allows the greater leaf expansion (Figure 4d and Figure 5d). Holtman *et al.* (2005) reported for young cucumber plants, that largest leaf area was achieved at DOC in nutrient solution of 10 mg L^{-1} . In cucumber plants, depression of root water uptake, lower leaf water content and decrease in leaf expansion have been found at lower DOC (Yoshida *et al.*, 1996). Less water efficiency under oxygen deficiency is reported, also, by Morard *et al.* (2000) on tomato. In the experiment with cucumbers, leaf number per m^2 was reduced in NFT system compared to NDT and perlite system (Figure 5c). This reduction was due to the earlier senescence of the older leaves (Jackson, 1980), these leaves was cut during pruning. Leaf growth is restricted and older leaves senesce prematurely because of reallocation of phloem mobile nutrients to younger leaves, hence, a reduction in plant leaf area (Gorbe and Calatayud, 2010). Reduced water uptake related to the growing area and the leaf area was also reported by others authors (Schwarz and Kuchenbuch, 1998). For cut rose plants, Bar-Yosef and Lieth (2013) reported that the minimum favourable DOC was $\sim 5.5 \text{ mg L}^{-1}$, in late spring and summer. In the experiment with tomatoes, DOC in nutrient solution at the end of the gully was reaching the limit of 5.1 mg L^{-1} . Moreover, cut roses have smaller leaf area and smaller root system compared to tomato and cucumber plants hence adapting to lower DOC in nutrient solution. It is known that the larger the plant and the leaf area of the crop, the higher the demand for oxygen. Small plants

such as cut roses have a relatively low requirement for oxygen in the root zone, while larger, longer-term fruiting plants such as tomato and cucumber demand much greater oxygen on the root zone.

Tomato fruit production in NDT showed a pronounced increase (34%), for an average increase of dissolved oxygen 15% in the nutrient solution. Cucumber fruit production in NDT did not indicate significant difference from the perlite bags growing systems. Similarly, cucumber fruit production was significantly increased in NDT (43%), in comparison to NFT growing system. Cucumber plants are more susceptible to oxygen deficiency of root environment than tomato plants under soilless culture (Adams, 2002). The improvement in DOC in NDT system caused a higher yield increase in cucumber compared to tomato. In both experiments, mean fruit weight was reduced in NFT system. Yield increasing is attributed to better oxygenating of root environment has been reported in tomato (López-Pozos *et al.*, 2011), in cucumber (Ehret *et al.*, 2010), in pepper (Marfà *et al.*, 2005; Urrestarazu and Mazuela, 2005), and in melon (Urrestarazu and Mazuela, 2005).

Certainly, in our experiments all mean values of oxygen content at the downstream of the gully in NFT were higher than the values described as limiting oxygen concentration (3 mg L^{-1}) in the nutrient solution (Gislerod and Kempton, 1983) or 50% oxygen saturation critical level for tomato fruit production and 65% for both vegetative and reproductive growth (Zeroni *et al.*, 1983). However, other authors reported that a decrease in oxygen content of the nutrient solution, together with a corresponding increase in respiration rate at a certain time of the day could limit growth, at least for part of the day (Hansen, 1977). Veen (1988) reported that reduction of respiration to 40% caused change in water uptake for tomato. Moreover, Urrestarazu and Mazuela (2005) reported that more temporarily available oxygen probably could be a reason for better water absorption of pepper plants. Hence, a solution system like NDT, where higher water flow rate can be used, provides higher dissolved oxygen in the nutrient solution and uniform along the gully. Consequently, stress situations are avoided and a better buffer capacity at the time around midday is provided, which could be the reason for a better water absorption supporting a larger leaf area and consequently higher yield.

In regions with scarcity of good quality water, yield per unit of water applied is of paramount importance. The greater WUE (Figure 6d and Figure 7d) calculated on this basis associated for the tested system (NDT) was due to higher yields of fresh fruits in tomato and cucumber, and not to reduced water use by plants in NDT system. Increased WUE in tomato plants was reported by Bhattarai *et al.* (2006), in a field experiment, in which subsurface irrigation with aerated water was investigated.

Oxygen level of the nutrient solution has an immediate impact on nutrient uptake and the yield of the whole plant (Morard *et al.*, 2000). Although, the uptake of N, K and Ca has been shown to be significantly lower in crops grown under oxygen stress (McLaren and Cameron, 1996), in the current experiment with tomatoes, the growing system did not affect the concentration of total N, K^+ and Ca^{2+} in leaves. However, plant yield in NFT system was found significantly decreased in comparison to NDT system. Bar-Yosef and Lieth (2013) in experiment with cut rose found that the accumulation rate of K was inhibited when DOC was 1.7 mg L^{-1} but was unaffected in 5 mg L^{-1} compared to 7.5 mg L^{-1} . In another experiment with cut roses, Carazo *et al.* (2005) reported an increase in K^+ and Ca^{2+} leaf content under oxyfertilization treatment, while significant difference was not found for N leaf content. Morard *et al.* (2000) reported that N uptake was the least affected by oxygen deficiency.

Conclusions

The results of the current study revealed that plant yield in NDT system appeared to approximate the yield in a well-drained porous substrate and to provide independence of the cost of porous substrates. Moreover, physical, chemical and biological substrate properties can change and deteriorate with time and use, which may affect both crop management and behaviour. Mechanical degradation of substrates can alter the pore structure, which may in turn affect retention and movement of nutrient solution and root aeration. NDT

system has advantages over NFT, because irrigation, DOC and electric conductivity is uniform along the channel, thus limiting water stress occurring principally at midday. These improved conditions for root growth ensure high quality yields. Moreover, in NDT higher water flow rate can be used and the length of the gullies can be very long without causing waterlogging problems to the plants at the lower part of the gullies. NDT system ensures an optimal balance between water availability and root aeration for optimizing yield and quality in horticultural crops. In NDT system the plant density can differentiate so as to be suitable for various horticultural crops, during various growing seasons, with different available solar radiation load. Moreover, NDT system can be easily constructed by the growers and not only be provided by a company. In conclusion, further research is required to determine the favourable flow rate of the nutrient solution under different transpiration conditions and for each different plant species grown in soilless culture.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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