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Oxygen enrichment of nutrient solution of substrate-grown vegetable crops under Mediterranean greenhouse conditions: oxygen content dynamics and crop response

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Abstract

This work assessed the seasonal dynamics of the substrate oxygen content and the response to oxygen enrichment of nutrient solution (oxyfertigation) of autumn-winter sweet pepper and spring melon crops grown on rockwool slabs (2003/04 season) and perlite grow-bags (2004/05), compared to non-enriched crops. Dissolved Oxygen (DO) values in the nutrient solution were higher for all the oxygen enriched treatments (>20 mg L^{-1}) than for the non-enriched ones (~4 mg L^{-1}), but no significant differences were found in the substrate solution. For pepper crops, DO values were highest at the onset and, especially, at the end of the cycle in winter, while the lowest DO values (3 to 4 mg L^{-1}) occurred during September and October. For melon, DO values decreased progressively from the onset of the cycles to values ≤ 3 mg L^{-1} during the second half of the cycles. For pepper crops, there were no significant differences between oxygen treatments for fruit production, which could be attributed to the fact that DO values were >3 mg L^{-1} throughout each crop cycle. However, a significant 7% increase in total and marketable yield, associated with a higher fruit number, was observed for the oxygen enriched melon grown on rockwool slabs, whereas no significant differences were found for the melon grown on perlite grow-bags. In conclusion, the use of inexpensive systems of substrate oxygen enrichment should be restricted to rockwool substrates and to crop periods when a high oxygen demand coincides with low oxygen availability, such as the period from melon flowering phase.

Additional key words: *Capsicum annuum*; *Cucumis melo;* dissolved oxygen; hypoxia; melon; perlite grow-bag; rockwool slab; sweet pepper.

Resumen

Contenido de oxígeno y respuesta de cultivos hortícolas en sustrato e invernadero al enriquecimiento de oxígeno de la solución nutritiva

Se estudió la dinámica del contenido de oxígeno disuelto (OD) en la solución del sustrato y la respuesta de cultivos de pimiento y melón en planchas de lana de roca (campaña 2003/04) y sacos de perlita (2004/05) al enriquecimiento de oxígeno de la solución nutritiva (oxifertirrigación), comparándolos con cultivos no enriquecidos. El OD en la solución nutritiva fue mayor en los tratamientos enriquecidos (>20 mg L^{-1}) que en los no enriquecidos (~4 mg L^{-1}) en los cuatro cultivos, pero no hubo diferencias significativas entre tratamientos en el OD en la solución del sustrato. En melón, el OD en la solución del sustrato disminuyó progresivamente desde el inicio de ambos ciclos hasta valores ≤ 3 mg L^{-1} durante la segunda mitad de los mismos. En pimiento, el OD fue mayor al principio y, sobre todo, al final del cultivo, en invierno, y los valores más bajos (3-4 mg L^{-1}) ocurrieron en septiembre-octubre. En pimiento no se encontraron diferencias significativas en producción entre tratamientos de oxígeno, lo que puede atribuirse a que el OD fue normalmente >3 mg L^{-1}. En melón, no hubo diferencias en la producción en perlita, pero el rendimiento comercial en lana fue un 7% mayor en el cultivo con oxifertirrigación, asociado a un mayor número de frutos. Como conclusión, debe considerarse el enriquecer de oxígeno la solución nutritiva en cultivos en lana de roca y en periodos

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cuando coincidan alta demanda y baja disponibilidad de oxígeno, caso que ocurre a partir de la floración del melón en ciclos de primavera.

Palabras clave adicionales: *Capsicum annuum; Cucumis melo;* hipoxia; lana de roca; melón; oxígeno disuelto; perlita; pimiento.

Introduction

Soilless-grown vegetable crops represent around 20% of the total area of greenhouse crops in the southeast of the Spanish Mediterranean coast, a mild winter climate area (Montero *et al.*, 1985) with one of the largest concentrations of greenhouses in the world (Castilla and Hernández, 2005). Most of these greenhouses are low-cost structures covered with plastic film and without active climatic control systems. Crops are normally grown under suboptimal climatic conditions (Montero *et al.*, 1985): solar radiation and air temperature are below the optimum during the winter period, and air temperature is often too high from March to October. Sweet pepper (*Capsicum annuum* L.) and melon (*Cucumis melo* L.) are two of the major greenhouse crops in this area, mostly grown in autumn-winter and spring cycles, respectively.

Soilless vegetable crops from this area are most often grown on limited volumes of two inert growing media: perlite and rockwool (Castilla and Hernández, 2005). Although these substrates usually have high air-filled porosity values, vegetable roots can experience suboptimal oxygen conditions as a result of various factors (Schröder and Lieth, 2002; Raviv *et al.*, 2004), especially in the non-controlled climatic conditions of Mediterranean greenhouses (Guri, 2002; Bonachela *et al.*, 2005; Urrestarazu and Mazuela, 2005). Most substrate-grown crops in Mediterranean areas have long periods of high temperatures in both growing media and greenhouse air, which usually lead to high rates of crop growth and root respiration. During these periods, plants normally require frequent and ample irrigation, which could reduce the oxygen diffusion rate and the root oxygen availability. Moreover, substrates under long cultivation periods: i) usually increase organic matter content and micro-organism activity, which could increase the competition for oxygen in the root environment; and ii) roots are densely matted within the substrate, which could alter oxygen diffusion and supply. The situation may be further complicated by the tendency of roots to grow downwards, which frequently results in a dense layer of roots at the bottom of the container. Roots at the bottom may experience water contents near-saturation for prolonged periods. However, little is known about the oxygen content dynamics in commercial substrate-grown vegetable crops (Schröder and Lieth, 2002), especially in areas where low-cost plastic greenhouses without climate control systems predominate and high air temperatures for long cropping periods are common, such as the Mediterranean basin and some central and south American countries. At present, most studies have been carried out on hydroponically-grown crops but not under commercial growing conditions (Gislerod and Kempton, 1983; Rivière *et al.*, 1993; Chun and Takakura, 1994; Walter *et al.*, 2004).

Several methods have been tested for improving the oxygen supply to crop roots (Bhattarai *et al.*, 2005; Marfà *et al.*, 2005; Urrestarazu and Mazuela, 2005). The supply of pure, pressurized oxygen gas to the nutrient solution is an oxygen-enriched method often used for research purposes (Chun and Takakura, 1994). This technique, called oxyfertigation, has been adapted to commercial horticultural greenhouses on the Spanish Mediterranean coast and has been described by Marfà *et al.* (2005). Overall, conflicting results have been found regarding the use of oxygen-enriched methods on substrate-grown greenhouse crops in Mediterranean areas: significant increases in marketable yield were found for a commercial greenhouse cucumber crop grown on rockwool slabs with oxyfertigation (Marfà and Guri, 2001) and for a spring melon grown on rockwool slabs with chemical oxygen enrichment (Urrestarazu and Mazuela, 2005), whereas no marketable yield differences were observed by Bonachela *et al.* (2005) for a watermelon crop grown on perlite grow-bags. The main aim of this work was to study, under Mediterranean greenhouse conditions: i) the seasonal dynamics of the substrate oxygen content and

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Abbreviations used: AFP (air-filled porosity, %, v/v), DO (dissolved oxygen content, mg L^{-1}), EC (electrical conductivity, dS m^{-1}), HI (harvest index, g g^{-1}), L (leaf length, cm), LA (leaf area, cm^2), LAI (leaf area index, m^2 m^{-2}), VAC (volumetric air content, %, v/v), VWC (volumetric water content, %, v/v).

ii) the response of sweet pepper and melon crops, grown on rockwool slabs and perlite grow-bags, to the oxygen enrichment of the nutrient solution.

Material and methods

Experiments

Four experiments were carried out throughout the 2003/04 and 2004/05 cropping seasons at the *Cajamar Foundation* Research Station (36° 48' N, 2° 3' W, 155 m a.s.l.), on the Almería coast, southeast Spain. They were conducted in a E-W oriented greenhouse («parral» type) of 500 m^2, with asymmetrical roofs of 27° (North) and 15.8° (South) slope, covered with plastic film (a three-layer of 0.2 mm thickness), without heating equipment and passively ventilated by opening gable and roof vents (Pérez-Parra *et al.*, 2004).

An autumn-winter California-type sweet pepper (cv. Bárdenas) and a spring muskmelon-type melon crop (cv. Sirio) were grown in each of the two cropping seasons. They were grown in new and two-year-old reused rockwool slabs of Med Horizontal Grodan® (T502, Grodan Med SA, Almería, Spain) of 100 cm (length) × 10 cm (height) × 15 cm (width) in 2003/04 and in new and four-year-old reused 40 L perlite grow-bags (100 cm long and with a mean height of 16 cm) of type B12 (particle size ∅ 0.1–5.0 mm) in 2004/05. Both substrates were tightly wrapped in white plastic, with holes made in the upper part into which the transplanting cubes were inserted and a small slit in the lower part to allow drainage.

In sweet pepper plants, the two main stems were vertically guided with polypropylene cords supported by wires to a height of 2 m, the axillary shoots were topped above the first leaf and fruits were mostly harvested red. Transplanting was carried out on 1 August, 2003 and 3 August, 2004, respectively, at a plant density of 3.08 m^{-2}. Crops ended on 21 February, 2004 and 25 February, 2005, respectively. In melon, the main stem was vertically guided with a polypropylene cord supported by wires to a height of 2 m, axillary shoots were pruned at the second leaf and bees (*Apis mellifera*) were used for pollination. Transplanting was carried out on 3 March, 2004 and 11 March, 2005, at a plant density of 1.59 and 2.05 m^{-2}, respectively. Crops ended on 21 June, 2004 and 9 June, 2005, respectively. Local crop management practices were applied to each crop.

The irrigation water had an electrical conductivity (EC) of 0.4 dS m^{-1}. The same nutrient solution was supplied to all the treatments by a drip irrigation system automatically controlled by a fertigation computer (NX-3000, Xilema®, Almería, Spain). The irrigation system was non-recirculating. The nutrient solution was transported from the irrigation pipes directly into the rockwool slab or the perlite grow-bag by drippers inserted in the media (three drippers of 3 L h^{-1} per slab or bag). Nutrient solution composition was adapted to the main growth phases of melon crops following local recommendations. Irrigation was activated automatically by a water level sensor located in a tray holding two representative rockwool slabs in 2003/04 or two perlite grow-bags in 2004/05 (Medrano *et al.*, 2008). At the onset of each crop cycle, until the roots reached the bottom of the container, the irrigation frequency was programmed according to the measured drainage water. This activation irrigation system is commonly used by greenhouse growers of soilless crops in the area.

A 2 × 2 factorial experiment, with 6 (2003/04) and 4 (2004/05) replications per treatment combination, was arranged in a completely randomized experimental design. The experimental unit consisted of a complete crop row. Two main factors were studied: the dissolved oxygen concentration in the nutrient solution and the substrate age (new and reused). No interactions were found between the two main factors for the parameters evaluated throughout the four crop cycles. This work only focuses on crop response to the dissolved oxygen content and, therefore, the data presented are average values of the two substrate age levels. For each crop, two levels of dissolved oxygen content in the nutrient solution were compared: an over-saturated nutrient solution ($+O_2$) and a standard nutrient solution with a dissolved oxygen concentration below saturation (O_2). During each irrigation event, pure, pressurized oxygen gas was dissolved in the nutrient solution of the $+O_2$ treatment with a gas injector within the irrigation pipe. This technique is named oxyfertigation and was described by Marfà *et al.* (2005). Data were statistically analyzed with the Stat graphics plus (v5.1) software and means were compared with the LSD test ($p \leq 0.05$).

Measurements

Dry and wet greenhouse air temperatures were measured with a ventilated psychrometer (mod. 1.1130, Thies Clima, Germany) located 2 m aboveground in the middle of the greenhouse. Solar radiation inside the greenhouse was measured with a pyranometer (SP Lite, Kipp and Zonen, The Netherlands) located 2.5 m aboveground, just above the crop canopy, in the south part of the greenhouse. Substrate temperature was also measured with a thermistor (T-107, Campbell Scientific, USA), located in the central part of one rockwool slab (2003/04) and one perlite bag (2004/05 season). Data were read every 5 min, averaged every 30 min and registered by a data logger system (CR-10X, Campbell Scientific, USA). Greenhouse climate for the two crops studied was, in general, within the range of normal conditions for the area (Montero *et al.*, 1985).

Dissolved oxygen (DO) was measured with an oxygen probe (550A YSI, Ohio, USA) with ± 0.1 mg L^{-1} resolution and automatic temperature compensation. DO values were periodically measured in the nutrient and substrate solution, except for part of the sweet pepper cycle in the 2003/04 season due to technical problems. Substrate solution was extracted from 4 replications per treatment every 2-4 weeks in the central part (just below the plant) of rockwool slabs and perlite grow-bags 1 cm above the substrate bottom. Extractions were carried out between 12:00 and 14:00 h, when DO values are theoretically lowest (Schroeder and Lieth, 2004). Solution samples were extracted with a moisture sampler (Rhyzon SMS, Eijkelkamp, Giesbeek, The Netherlands), which had been previously calibrated (Acuña, 2007). Extractions were obtained by connecting the sampler with a needle to a closed vial of 60 mL capacity subjected to a suction of 60 kPa. Vials were covered with foil to avoid exposure to the sun and DO measurements were conducted immediately after extraction by introducing the probe within the vial.

Volume of nutrient solution from two drip emitters and leached nutrient solution from two representative rockwool slabs (2003/04) and two perlite grow-bags (2004/05), located in the middle of the greenhouse, was measured daily for each treatment. Simultaneously, EC and pH values of the supplied and leached nutrient solution were measured.

Water release characteristic curves and main physical properties (total porosity, air-filled porosity and easily available water) of rockwool slabs and perlite grow-bags were determined (De Boodt *et al.*, 1974) before and after each cropping season. Air-filled porosity (AFP) values of the new and reused substrates, measured by Acuña (2007), were around or higher than 30% and 45% (v/v) for rockwool slabs and perlite grow-bags, respectively.

Volumetric water content (VWC) of rockwool slabs was measured periodically throughout the 2003/04 melon cycle with a FDR-type sensor (WMC, Grodan, Roermond, The Netherlands), specifically calibrated for this substrate. Measurements were taken at eight different points in four rockwool slabs per treatment. Volumetric air content (VAC) values were estimated from VWC measurements assuming that changes in total porosity during the cropping period were negligible (Acuña, 2007).

Crop transpiration rate was measured using two weighing lysimeters (Van Meurs and Stanghellini, 1992) located in the centre of a row to form a continuous canopy at the middle of the greenhouse. Each lysimeter consisted of a tray with a drainage collector carrying one rockwool slab or one perlite grow-bag and placed on an electronic balance (KCC150, Mettler Toledo, Giesen, Germany) with ± 0.001 kg resolution and 150 kg measurement range. This system was located in a 70 cm deep pit thermally insulated on the sides and top. Considering that the evaporation loss from the substrate was negligible (the substrate container was covered with a white plastic film), the weight loss measured by the balance every five minutes was assumed to be equal to crop transpiration.

Plant height and leaf length (L, cm) were measured during the crop cycles every 3-4 weeks from one plant per replication, except for the final crop phase, when L measurement became too difficult. A narrow curvilinear relationship between leaf area (LA, cm^2), measured with an electronic planimeter (AM7626, Delta T Device Area Meter, UK), and L was found for sweet pepper ($LA = 0.363 \times L^{1.93}$; $R^2 = 0.99$) and melon crops ($LA = 0.463 \times L^{2.137}$; $R^2 = 0.97$). Total aboveground, leaf, stem and fruit biomass, as well as leaf area index (LAI) values, were measured in 4 plants per replication at the onset and end of each cycle. An intermediate measurement was also carried out at flowering. Axillaries stems and young fruits pruned before the sample date were included in the corresponding biomass fraction. Total and marketable yield, and yield components (fruit number and mean fruit weight) were measured in 18 (sweet pepper), 9 (melon in 2003/04 season) and 12 (melon in 2004/05 season) plants per replication. Two fruits per replication were selected during each harvest to measure fruit dry matter. Marketable fruits were classified in two categories, according to the official journal of the European Communities (OJ, 2001).

Results and discussion

Dissolved oxygen (DO) content in the nutrient and substrate solution

Values of DO in the nutrient solution supplied were higher for the oxygen enriched treatment than for the non-enriched one throughout the four studied crop cycles. The mean DO value, averaged over the crop cycle, was significantly higher for the oxygen-enriched nutrient solutions (values slightly above 20 mg L^{-1}) than for the non-enriched ones (values about 4 mg L^{-1}, Table 1). However, no significant differences in the substrate DO values were found between the two oxygen treatments for any measurement date and crop (Fig. 1). Neither was any significant difference found between oxygen treatments for the average seasonal substrate DO values (Table 1), although they were slightly higher for the oxygen enriched treatments. This behaviour could be explained, at least partially, as follows: i) both substrates presented high AFP values, which usually gives rise to a high oxygen diffusion rate between substrate and atmosphere considering the relationship between oxygen diffusion rate and AFP values found by Bunt (1991); besides, when the over-saturated oxygen solution passes through the substrate pores (especially those in the upper parts) under nearly atmospheric conditions, part of the dissolved oxygen is liberated to the substrate, whereas the opposite process appears to occur with the under-saturated oxygen solution (Rivière *et al.*, 1993; Marfà *et al.*, 2005); ii) only around 5-12% of the substrate solution is renewed with new nutrient solution during each irrigation and, therefore, the effects on the substrate DO values are limited (Morard and Silvestre, 1996), especially when the irrigation frequency is low. For example, the number of daily irrigations in melon crops ranged from 2 at the beginning of both cycles to 20 and 18 at the generative phase of the crop grown on rockwool slabs and perlite grow-bags, respectively.

Substrate DO values were clearly below saturation level for all the treatments and crops, especially throughout the spring crop cycles (Fig. 1). For sweet pepper crop grown on perlite grow-bags, the substrate DO values were lowest (3 to 4 mg L^{-1}) during the second half of September and the first half of October, when high oxygen demand coincided with low oxygen availability. In this period, air and substrate temperatures were still high (Fig. 1), which decreased the oxygen saturation values and, therefore, the oxygen availability (Morard and Silvestre, 1996), and crops had already developed most of their roots and vegetative biomass, and were more active [*e.g.* rates of crop transpiration (Fig. 2) and growth (Fig. 3) were highest at this time], which usually implies a high oxygen demand. By contrast, the substrate DO values were highest just at the beginning of the crop cycle (in August), when plants were small, and during the winter period, when the air and substrate temperatures, and the solar radiation, were lower (Fig. 1). For melon crops, the lowest substrate DO values (below or around 3 mg L^{-1}) occurred from flowering throughout the second half of the cycle, when the oxygen demand and the air temperature were high. In this period, melon crops had already developed most of their roots and vegetative biomass, and were more active [*e.g.* rates of crop transpiration (Fig. 2) and growth (Fig. 3) were highest at this time]. By contrast, the substrate DO values were highest at the beginning of each melon cycle when plants were small. Previous work has shown that the most important factors

Table 1. Average seasonal dissolved oxygen values (mg L^{-1}) in the nutrient and substrate solution of sweet pepper and melon crops grown with (+O_2) and without (O_2) oxygen enrichment of the nutrient solution. Almería coast, southeast Spain

Oxygen treatments		2003/04 season (rockwool slabs)		2004/05 season (perlie slabs)	
		Sweet pepper	Melon	Sweet pepper	Melon
Nutrient solution	+O_2	23.8^b	21.1^b	21.8^b	21.7^b
	O_2	4.0^a	3.7^a	4.2^a	3.7^a
Substrate solution	+O_2	6.3^a	3.1^a	4.9^a	2.8^a
	O_2	6.2^a	3.0^a	4.4^a	2.6^a

Values with different letter within the same column and solution type are significantly different ($p < 0.05$).

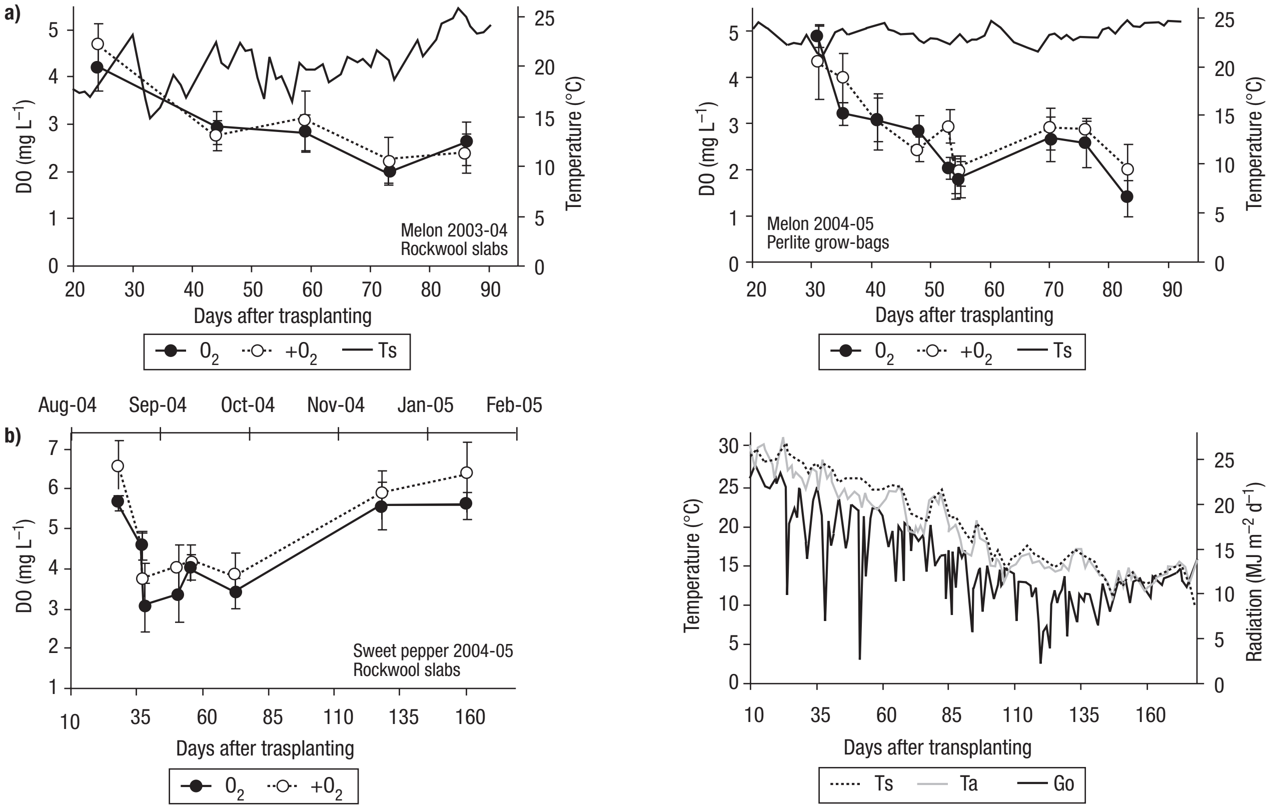

Figure 1. a) Seasonal dynamics of dissolved oxygen (DO) in the substrate solution (mean ± standard error) and substrate temperature (Ts) values of melon crops grown with (+O_2) and without (O_2) oxygen enrichment. b) Seasonal dynamics of substrate DO, substrate and greenhouse air (Ta) temperatures and outside solar radiation (Go) values of a sweet pepper crop grown on perlite grow-bags with (+O_2) and without (O_2) oxygen enrichment.

influencing root respiration are root biomass, root temperature and supply of photosynthates to roots from the aerial part of the plant (Morard and Silvestre, 1996).

Fertigation and crop transpiration

In the four studied crops, the total amount and the seasonal dynamics of the supplied, uptake and leached nutrient solution was similar for both oxygen treatments. The average seasonal values of cumulative crop water uptake were 265 (+O_2) *vs.* 276 mm (O_2) for sweet pepper grown on rockwool slabs; 248 (+O_2) *vs.* 242 mm (O_2) for sweet pepper grown on perlite grow-bags; 206 (+O_2) *vs.* 191 mm (O_2) for melon grown on rockwool slabs; and 241 (+O_2) *vs.* 242 mm (O_2) for melon grown on perlite grow-bags. Average seasonal percentages of leached nutrient solution were slightly higher than 30% for most crops and similar for both oxygen treatments. Daily crop transpiration values were also similar for oxygen enriched and non-enriched nutrient solutions throughout the four crop cycles (Fig. 2). Transpiration values in sweet pepper crops increased progressively from 0.3 L m^{-2} at the beginning of the cycle until reaching maximum values of around 2.5 L m^{-2} in October. Hereafter, they decreased to 1-1.5 L m^{-2} during the winter period. In melon, transpiration values increased progressively throughout the cycles, reaching maximum values during May: about 5 L m^{-2} in 2003/04 and 6 L m^{-2} in 2004/05. At the end of the cycles, transpiration values decreased due to the whitewashing of the external plastic cover (a common cooling practice) at the beginning of crop senescence. Neither were significant differences between oxygen treatments observed for VAC values: 39.5% for +O_2 *vs.* 33.1% for O_2 for the melon grown on rockwool slabs throughout the 2003/04 season. However, VAC values were higher for the enriched melon treatment around flowering and fruit set (Fig. 4), associated to a lower volumetric water content value (data not shown). VAC values were below 30% at the beginning of the cycle, but they stayed above this value for the remaining crop cycle (Fig. 4).

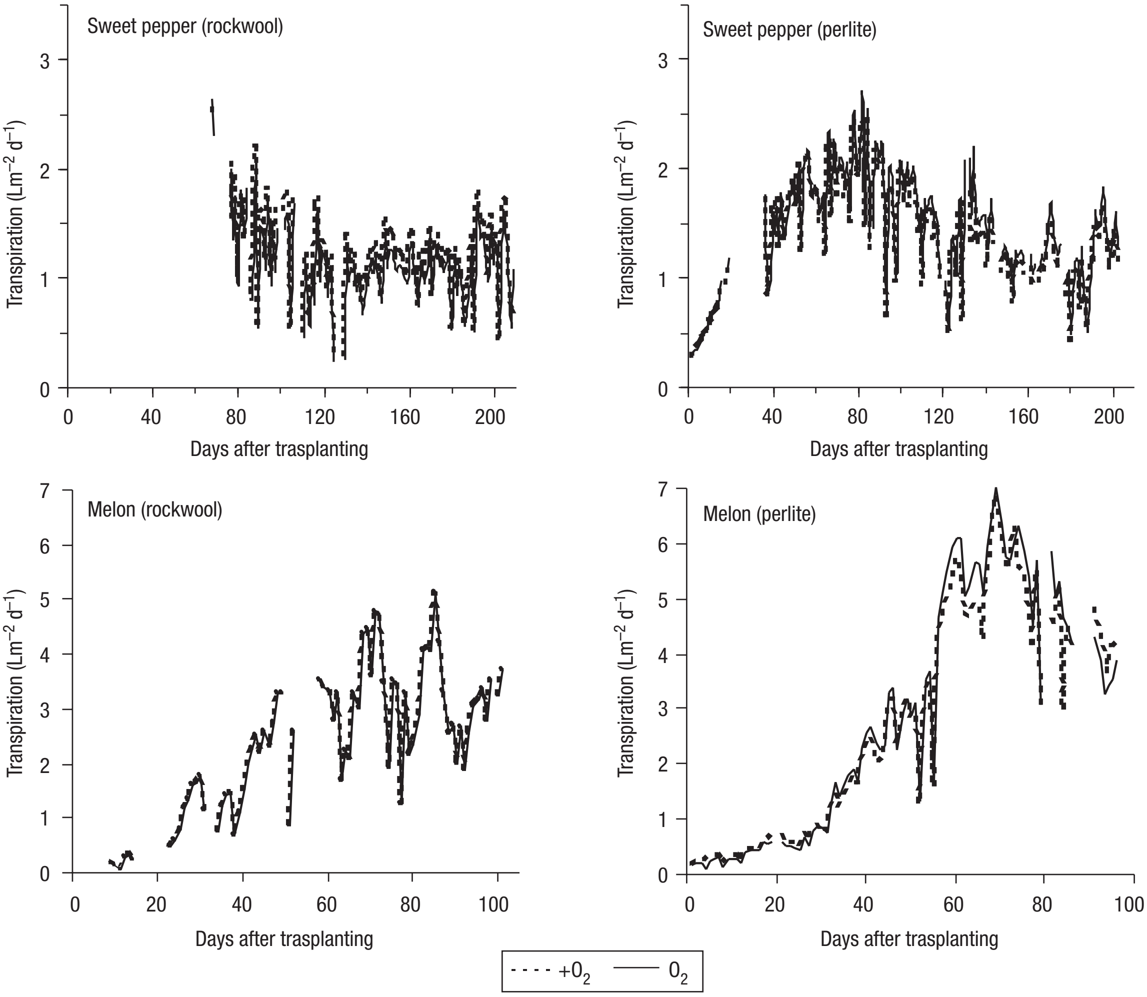

Figure 2. Seasonal dynamics of daily crop transpiration values (L m^{-2} d^{-1}) of sweet pepper and melon crops grown with (+O_2) and without (O_2) oxygen enrichment.

The uptake of nutrients, estimated from data on supplied and leached nutrient solutions, did not appear to be affected by oxygen enrichment of the nutrient solution either, as the supplied nutrient solution was the same and the nutrient concentration in the leached solution was similar for both treatments. Similar dynamics and average seasonal values of EC and pH in the leached nutrient solution were measured for the two oxygen treatments. Average seasonal substrate solution EC values were equal for both oxygen treatments: 2.6 dS m^{-1} for the sweet pepper grown on rockwool slabs, 3.2 dS m^{-1} for the sweet pepper grown on perlite grow-bags, 3.5 dS m^{-1} for the melon grown on rockwool slabs and 2.9 dS m^{-1} for the melon grown on perlite grow-bags. Average seasonal substrate solution pH values were around 6 for all crops and treatments. These values are slightly higher than those recommended for this irrigation water, but they are common values for local soilless commercial crops.

In general, nutrient uptake, an energy dependant process, and water uptake are reduced under hypoxic root environments (Morard and Silvestre, 1996), but related information on substrate grown crops is scarce and inconclusive. For a spring watermelon crop grown on perlite grow-bags in a commercial greenhouse on the Almería coast, Bonachela *et al.* (2005) did not observe any differences in water uptake or in EC and pH of the leached solution between oxygen over-saturated and non-enriched nutrient solution. However, in a commercial greenhouse in the same area, Urrestarazu and Mazuela (2005) found a higher water uptake for an autumn-winter sweet pepper cycle with chemical oxygen enrichment by application of potassium peroxide, but not in a spring melon cycle nor in an autumn-

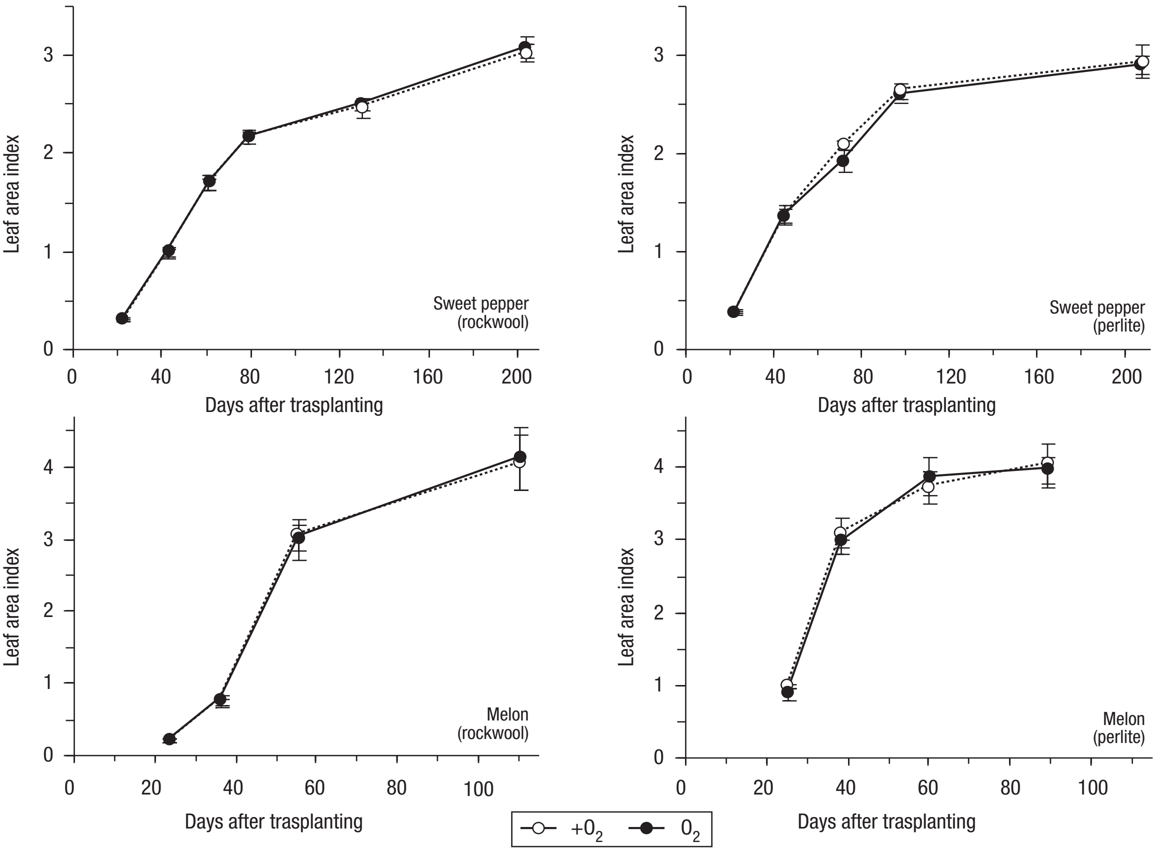

Figure 3. Seasonal dynamics of leaf area index (LAI, m^2 m^{-2}) values (mean ± standard error) of sweet pepper and melon crops grown with ($+O_2$) and without (O_2) oxygen enrichment.

winter cucumber crop. Therefore, the absence of differences between the oxygen treatments in most of the fertigation parameters evaluated in this work could be attributed to: i) the absence of clear differences between treatments in substrate oxygen content; ii) no oxygen deficiency in either treatment; iii) hypoxic periods of insufficient intensity or duration to affect significantly the measured parameters.

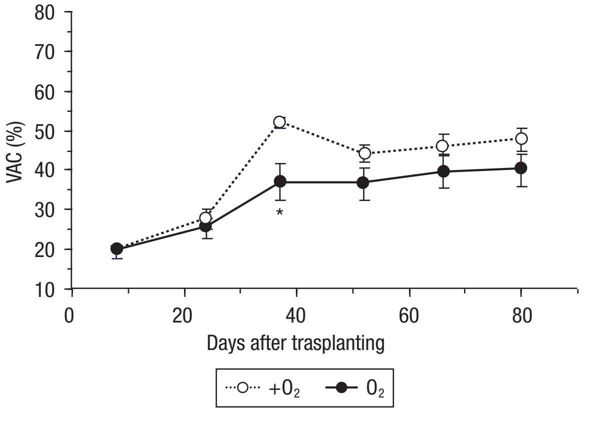

Figure 4. Seasonal dynamics of the volumetric air content (VAC, %) values (mean ± standard error) in rockwool slabs throughout a melon crop grown with ($+O_2$) and without (O_2) oxygen enrichment.

Growth and crop productivity

The oxygen enrichment of the nutrient solution did not affect the growth parameters evaluated in the four studied crops: length, diameter and number of plant internodes, crop height (data not shown), LAI values throughout the crop cycle (Fig. 3) and aboveground biomass and its partitioning at the end of cycle (Table 2). LAI values were similar for both oxygen treatments throughout the sweet pepper and melon cycles. Maximum LAI values were found at the end of the cycles for both treatments, and were around 3.0 m^2 m^{-2} for sweet pepper and around 4.0 m^2 m^{-2} for melon. Values of aboveground biomass were similar to those measured by Bonachela *et al.* (2006) in the same area but with crops grown in sand mulched soils. Neither did oxygen enrichment modify the crop harvest index

Table 2. Values of aboveground biomass, biomass partitioning and harvest index (HI) at the end of the sweet pepper and melon crop cycles grown with (+O_2) and without (O_2) oxygen enrichment

Crops	Oxygen treatment	Aboveground biomass (g m^{-2})					HI (g g^{-1})
		Leaf	Stem	Fruit	Vegetative	Total	
Sweet pepper (rockwool)	+O_2	246^a	327^a	918^a	573^a	$1,491^a$	0.62^a
	O_2	243^a	324^a	919^a	567^a	$1,486^a$	0.62^a
Melon (rockwool)	+O_2	298^a	153^a	665^a	451^a	$1,116^a$	0.60^a
	O_2	287^a	147^a	666^a	434^a	$1,100^a$	0.61^a
Sweet pepper (perlite)	+O_2	232^a	312^a	806^a	544^a	$1,350^a$	0.60^a
	O_2	234^a	297^a	810^a	531^a	$1,340^a$	0.60^a
Melon (perlite)	+O_2	264^a	178^a	474^a	442^a	916^a	0.52^a
	O_2	269^a	184^a	507^a	453^a	960^a	0.53^a

Values with different letter within the same column and crop cycle are significantly different ($p < 0.05$).

(Table 2). In hydroponically-grown crops, oxygen deficiency usually reduces root and shoot biomass, and leaf area (Yoshida *et al.*, 1996), but information on substrate-grown vegetables is scarce. For sweet pepper and lettuce (*Lactuca sativa* L.) greenhouse crops grown on perlite grow-bags on the North-Eastern Spanish Mediterranean coast, Guri (2002) did not find significant differences in the crop LAI values when the crops were irrigated with an over-saturated nutrient solution, although she did find a lower root hydraulic resistance and a higher weight of thin roots (diameter < 2 mm) for the oxygen enriched solution.

The seasonal evolution of the total fresh fruit weight of sweet pepper crops was similar for both oxygen treatments at both crop cycles. At the end of the cycle, values of 9.6 kg m^{-2} were measured for both oxygen treatments in the crop grown on rockwool slabs, and values of 8.4 (+O_2) and 8.6 (O_2) kg m^{-2} in the crop grown on perlite grow-bags (Table 3). Moreover, no significant differences were found between oxygen treatments for the fresh weight of marketable, first and second class sweet pepper fruits, nor for the marketable yield components: mean fruit weight and fruit number (Table 3). However, the yield response of melon crops to oxyfertigation depended on the type of substrate. No significant differences were found between oxygen treatments for any productivity parameter for the melon grown on perlite grow-bags (Table 3), whereas a significant 7% increase in total and marketable yield, associated with a higher fruit number, was observed for the oxygen enriched treatment grown on rockwool slabs. For hydroponically-grown vegetable crops, the critical

Table 3. Fresh weight of total, marketable, first and second class fruits (kg m^{-2}), and yield components [fruit number (fruits m^{-2}) and mean fruit weight (g $fruit^{-1}$)] at the end of the sweet pepper and melon crop cycles grown with (+O_2) and without (O_2) oxygen enrichment

Crops	Oxygen treatment	Fresh fruit weight				Yield components	
		Total	Marketable	First class	Second class	Fruit number	Fruit weight
Sweet pepper (rockwool)	+O_2	9.6^a	8.6^a	6.1^a	2.5^a	44.2^a	195^a
	O_2	9.6^a	8.6^a	6.0^a	2.6^a	45.4^a	190^a
Sweet pepper (perlite)	+O_2	8.4^a	7.7^a	5.5^a	2.2^a	37.8^a	203^a
	O_2	8.6^a	7.7^a	5.4^a	2.3^a	39.5^a	194^a
Melon (rockwool)	+O_2	6.1^b	6.1^b	5.2^b	0.9^a	10.0^b	616^a
	O_2	5.7^a	5.7^a	4.7^a	1.0^a	9.0^a	634^a
Melon (perlite)	+O_2	5.7^a	5.5^a	4.8^a	0.7^a	7.6^a	723^a
	O_2	5.6^a	5.5^a	5.0^a	0.5^a	7.5^a	733^a

Values with different letter within the same column and crop cycle are significantly different ($p < 0.05$).

oxygen partial pressure of the nutrient solution was between 4-6% (Schapira *et al.*, 1990; Morard, 1995), which corresponds to DO concentration values of around 3 mg L^{-1} (Gislerod and Kempton, 1983; Zeroni *et al.*, 1983; Holtman *et al.*, 2005). However, the critical DO value should be considered with caution. Oxygen depletion within the root media usually occurs progressively under field conditions, and the critical oxygen content or pressure at which deficiency is first experienced is difficult to determine, depending upon oxygen demand, the magnitude of the oxygen sources (Armstrong and Drew, 2002) and the location where measurements are carried out. For sweet pepper crops, DO values at the bottom of the substrate were always higher than 3 mg L^{-1} throughout each crop cycle (Fig. 1), whereas substrate DO values for melon crops were slightly below or around 3 mg L^{-1} from flowering in both substrates. Overall, the yield response to oxyfertigation in the spring melon grown on rockwool slabs appears to be inconclusive, although the lower yield observed for the non-enriched treatment could be associated to events of slight oxygen deficiency in the lower part of the substrate container occurred around midday during the flowering and fruit setting periods, when the oxygen enriched treatment presented better oxygen and aeration substrate conditions (Figs. 1 and 4). The application of oxygen-enriched nutrient solution at high frequency (15 to 20 daily irrigation events) from flowering could improve the oxygen substrate conditions for the roots, although no significant differences were detected between treatments for the substrate DO content in measurements taken around midday each 2-4 weeks. In the same area, a 9% increase in marketable yield was found for a commercial greenhouse cucumber crop grown on rockwool slabs with oxyfertigation (Marfà and Guri, 2001); a 17% increase in marketable yield was also found for spring melon grown on rockwool slabs with chemical oxygen enrichment (Urrestarazu and Mazuela, 2005), but substrate DO values were not measured in either of these experiments. However, we believe that further research is required to confirm the effectiveness of this technique for commercial spring melon crops grown on rockwool slabs, including a better characterization of oxygen status and availability within the medium. The latter, could be achieved by increasing the number of measurement points and/or with continuous measurements (Holtman *et al.*, 2005). By contrast, the absence of yield response to oxyfertigation in the melon crop grown on perlite grow-bags appears to be clear, as no differences were found between oxygen treatments for any of the oxygenation, growth and productivity parameters assessed. Similar results were previously observed by Bonachela *et al.* (2005) for a spring watermelon crop grown on perlite grow-bags irrigated with oxygen enriched nutrient solution. This response could be due to the higher volume and height of the perlite grow-bags and, therefore, to the higher water and air availability per plant, compared to rockwool slabs. Moreover, the oxygen diffusion rate was theoretically higher in the perlite grow-bags than in the rockwool slabs considering the higher air-filled porosity values of the former medium and the relationship of oxygen diffusion rate to air-filled porosity values found by Bunt (1991).

In conclusion, based on our results, the effectiveness of the oxyfertigation technique for improving productivity or fruit quality of sweet pepper and melon crops grown on inert substrates in Mediterranean greenhouses is not clear. In autumn-winter cycles of sweet pepper crops it does not appear to be of interest, since no visual plant symptoms of oxygen deficiency were observed and no improvements of the major fertigation, growth and yield parameters were found. In spring melon cycles, however, conflicting results were obtained, although the yield increase associated to the oxygen enrichment observed for the crop grown on rockwool slabs was relatively small. In any case, the use of inexpensive systems of substrate oxygen enrichment should be restricted to rockwool substrates and to crop periods when a high oxygen demand coincides with low oxygen availability, such as the period from melon flowering phase.

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References

ACUÑA R., 2007. Oxigenación en cultivos hortícolas en sustratos de lana de roca y perlita en el litoral de Almería. Técnicas de la mejora y efecto de los sustratos. Doctoral thesis. Universidad de Almería, Almería. Spain. 214 pp. [In Spanish].

ARMSTRONG W., DREW M.C., 2002. Root growth and metabolism under oxygen deficiency. In: Plant roots. The hidden half (Waisel Y., Eshel A., Kafkafi U., eds). M. Dekker, NY, USA. pp. 729-761.

BHATTARAI S., SU N., MIDMORE D., 2005. Oxygation unlocks yields potentials of crops in oxygen-limited soil environments. Adv Agron 88, 313-377.

BONACHELA S., VARGAS J., ACUÑA R., 2005. Effect of increasing the dissolved oxygen in the nutrient solution to above-saturation levels in a greenhouse watermelon crop grown in perlite bags in a Mediterranean area. Acta Hortic 697, 25-32.

BONACHELA S., GONZÁLEZ A.M., FERNÁNDEZ M.D., 2006. Irrigation scheduling of plastic greenhouse vegetable crops based on historical weather data. Irr Sci 25, 53-62.

BUNT A.C., 1991. The relationship of oxygen diffusion rate to air-filled porosity of potting substrates. Acta Hortic 294, 215-224.

CASTILLA N., HERNÁNDEZ J., 2005. The plastic greenhouse industry of Spain. Chron Hortic 45(3), 15-20.

CHUN C., TAKAKURA T., 1994. Rate of root respiration of lettuce under various dissolved oxygen concentrations in hydroponics. Environ Control in Biol 32(2), 125-135.

DE BOODT M., VERDONCK O., CAPPAERT I., 1974. Method for measuring the water release curve of organic substrates. Acta Hortic 37, 2054-2062.

GISLEROD H., KEMPTON R., 1983. The oxygen content of flowing nutrient solutions used for cucumber and tomato culture. Sci Hortic 20(4), 23-33.

GURI S., 2002. Fertirrigació carbònica i oxigenació del medi radicular en cultius hortícoles. Doctoral thesis. Universidad de Lleida, Lleida, Spain. 147 pp. [In Catalan].

HOLTMAN W., VAN DUIJN B., BLAAKMEER A., BLOK C., 2005. Optimization of oxygen levels in root systems as effective cultivation tool. Acta Hortic 697, 57-64.

MARFÀ O., GURI S., 2001. Efectos de la aplicación de oxígeno en el agua de riego en cultivos sin suelo. Agrícola Vergel 239, 593-596. [In Spanish].

MARFÀ O., CÁCERES R., GURI S., 2005. Oxyfertigation: a new technique for soilless culture under Mediterranean conditions. Acta Hortic 697, 65-72.

MEDRANO E., ALONSO J.F., SÁNCHEZ-GUERRERO M.C., LORENZO P., 2008. Incorporation of a model to predict crop transpiration in commercial irrigation equipment as a control method for water supply to soilless horticultural crops. Acta Hortic 801, 1325-1330.

MONTERO J.I., CASTILLA N., GUTIÉRREZ DE RAVE E., BRETONES F., 1985. Climate under plastic in the Almería area. Acta Hortic 170, 227-234.

MORARD P., 1995. Étude de l'oxygénation du systeme racinaire. In: Les cultures végétales hors-sol. Pub Agricoles, Agen, France. pp. 245-252. [In French].

MORARD P., SILVESTRE J., 1996. Plant injury due to oxygen deficiency in the root environment of soilless culture: a review. Plant Soil 184(2), 243-254.

OJ, 2001. Directive 1615/2001/CE of the Council of August 07. Official Journal of the European Communities L 224 08/08/2001. pp. 21-25.

PÉREZ-PARRA J., BAEZA E., MONTERO J.I., BAILEY B., 2004. Natural ventilation of parral greenhouses. Biosyst Eng 87, 355-366.

RAVIV M., WALLACH R., BLOM T.J., 2004. The effect of physical properties of soilless media on plant perfomance. A review. Acta Hortic 644, 251-259.

RIVIÈRE L., CHARPENTIER B., JEANNIN B., KAFKA B., 1993. Oxygen concentration of nutrient solution in mineral wools. Acta Hortic 342, 93-101.

SCHAPIRA A., MORARD P., MAERTENS C., 1990. Échanges gazeux racinaires du concombre et de la tomate en culture hydroponique. CR Acad Agric Fr 76(4), 59-66. [In French].

SCHRÖDER F.G., LIETH H., 2002. Irrigation control in Hydroponics. In: Hydroponic production of vegetables and ornamentals (Savvas D., Passam H. eds). Embryo Pub Athens, Greece. pp. 263-298.

SCHROEDER F.G., LIETH H., 2004. Gas composition and oxygen supply in the root environment of substrates in closed hydroponic systems. Acta Hortic 644, 299-305.

URRESTARAZU M., MAZUELA P., 2005. Effect of slow-release oxygen supply by fertigation on horticultural crops under soilless culture. Sci Hortic 106, 484-490.

VAN MEURS W., STANGHELLINI C., 1992. Use of an off-the-shelf electronic balance for monitoring crop evapotranspiration. Acta Hortic 304, 219-225.

WALTER S., HEUBERGER H., SCHNITZLER W., 2004. Sensibility of different vegetables to oxygen deficiency and aeration with H_2O_2 in the rizosphere. Acta Hortic 659, 499-508.

YOSHIDA S., KITANO M., EGUCHI H., 1996. Water uptake of cucumber plants (*Cucumis sativus* L.) under control of dissolved O_2 concentration in hydroponics. Acta Hortic 440, 199-204.

ZERONI M., GALE J., BEN ASHER J., 1983. Root aeration in a deep hydroponic system and its effect on growth and yield of tomato. Sci Hortic 19, 213-220.