Gas composition and oxygen supply in the root environment of substrates in closed hydroponic systems.

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Abstract

The objective of this study was to get more information about the root zone, mainly the gas composition in substrates, which are used in closed hydroponic systems. For analyses of carbon dioxide (CO_2), ethylene (C_2H_4) and oxygen (O_2) different methods were proofed and used. For analyses of carbon dioxide and ethylene, a gas sampling system was used to get gas samples from the root zone. CO_2 gas samples of 20 ml were analyzed with an IR sensor by air diffusion into a measuring cuvette. C_2H_4 gas samples of 3 ml were analyzed using gas chromatography (GC). Gas sample cells were inserted into the substrates at 2 or 3 heights. Dissolved oxygen was determined with a membrane covered galvanic sensor, in the air, in the in the nutrient solution, and in the drain solution. To analyze the root zone, a hydroponic system with chrysanthemum cv. 'Snow' on 3 substrates was performed. The following substrates were used: Sawagrow (polyester fiber), polyester fleece (thin layer of fleece), and UC-mix (peat substrate).

Gas sampling at 2 or 3 heights from root zone did function well, results ranged from 350 ppm to 7700 ppm CO_2, and from 0.0088 ppm to 0.1147 ppm of C_2H_4. The organic substrates UC-mix contains more CO_2, from top to the bottom the CO_2 level increased. The CO_2 level is influenced by microbial and root respiration. The determined CO_2 concentration is no limiting growth factor.

Results of C_2H_4 shown an influence by the substrates and a gradient from the top to the bottom. But highest level was determined in the middle and at the bottom of the substrates. The time course shows during the day pattern according the photoperiod. The trend of C_2H_4 level was almost constant during the experiment.

The dissolved O_2 level in solution was about 57-82 % and in drain solution 78 % - 99 %. O_2 level of solution and drain can be an indicator for oxygen deficiency, but it is no direct measurement in root zone or roots. The O_2 content in air between 10.5 % to 20.4 %. During the experiment the O_2 concentration decreased; for CO_2 the opposite trend was found.

1. Introduction

Plant growth in closed hydroponic systems, with restricted root environment, and consequently, low buffering capacity is more related to water, nutrient solution, and oxygen supply. Water and nutrients are supplied with the nutrient solution, which is regulated by the composition of the solution and the irrigation control. Available oxygen

is mainly determined by the layout of the hydroponic system and the physical substrate properties. The oxygen diffusion rates into the water depends directly on volumetric air content, the partial oxygen pressure, and temperature. Within the hydroponic systems there is an oxygen gradient for design flow techniques and flow rates (Vestergaard, 1984; Bunt, 1991; Baas et al. 2000; Wever et al., 2000). In addition, the substrate parameters change at the end of each crop, mainly as result of decomposition of organic substrates or root and increasing root mass (Wever and van Leeuwen, 1995). Oxygen deficiency may be a limiting factor for plant growth. Oxygen deficiency can be tolerated by roots for a short time, even for several days (Buwalda, 1991; Gisler∅d et al., 1997; Yosida et al. 1997). The growth of chrysanthemum and ficus was reduced as dissolved oxygen in solution decreased however plants are able to adapt to low O_2 concentrations (Soffer et al., 1991).

But, if O_2 (as sink) is limited, CO_2 and $C_2 H_4$ (as source) will be increasing in the root zone. Accumulation of root respiration products, CO_2 and C_2H_4, can inhibit plant growth. Concentrations over 0.1 µl dm^{-3} can be harmful for plants (Abbeles, 1982). Strojny et al. (1998) described for chrysanthemum growth that CO_2 and C_2H_4 has been influenced by pot soil air composition and high soil moisture. Finally the complete gas composition in the root zone is important for plant growth (Jackson, 1980).

The objective of this study was to get more information about the root environment, mainly the gas composition in inert and organic substrates, which are used in closed hydroponic systems.

2. Material and Methods

The experiments were carried out at the University of California (UC) Davis, in the greenhouse of the Department Environmental Horticulture. To investigate the root zone a hydroponic system with chrysanthemum on 3 substrates was installed. Statistical analysis was analysis of variance using the program Statistica. A Tukey Test at $p<0.05$ was used for comparisons of means.

2.1 Greenhouse experiment

The cut chrysanthemums cv. 'Snow' were grown (Table 1) on a bench to control the nutrient solution supply and collect the drain water. The hydroponic system was performed like a bed or a thin substrate layer system. Three closed irrigation systems were installed for each setup (2mx1m). The substrates were covered with white plastic sheets to reduce evaporation and growth of algae. The chrysanthemum transplants rooted in Oasis blocks (4.5x4.5x4 cm) were inserted into holes of the cover sheets.

Nutrient solution (Table 2) was supplied from a nutrient solution tank (80l) via drip irrigation left and right of the bench. The solution passed the substrates (50cm) to a drainage channel in the middle of the bench. The slope of the bench to the channel was 1 %. Drain solution (about 30 % of applied solution) was collected in an additional tank and replaced to the solution tank one per day. The nutrient solution was adjusted by EC and pH figures. De-ionized water (DI) was used for preparing of nutrient solution thereby EC and pH value was reduced and dissolved oxygen level increased (Table 3).

For irrigation control a timer was used. The frequency was 6 times per day; the duration was changed according the measured drain. For control, chrysanthemums were

grown in 23l pots holding 15l UC-mix substrate with an open irrigation system, without cover sheets.

To analyze the root zone, a hydroponic system with chrysanthemum on 3 substrates was performed. The following substrates were used: Sawagrow (polyester fiber), polyester fleece (thin layer of fleece), and University of California (UC) -mix (peat substrate). Substrate properties and variants are shown in Table 4.

2.2 Gas measurements

For analyses of carbon dioxide (CO_2), ethylene (C_2H_4), and oxygen (O_2) different methods were proofed and used. For analyses of carbon dioxide and ethylene, a gas sampling system was used to get gas samples from the root zone. Gas analyses were performed for CO_2, C_2H_4, and O_2 in air weekly, 4 times per day. Dissolved oxygen in solution was measured daily. Oxygen in air was determined with a galvanic sensor 'Model 600' (Kernco Instruments Inc.). The cylindrical sensor was inserted in the substrates Sawagrow and UC-mix 2cm deep from the top. For the polyester fleece (3 mm) the sensor was used like an up side down bell to analyze the air under it.

The system of sampling gas consisted of gas sampling cells fixed in the growing system under greenhouse conditions (non air tight). The used gas sampling system was modified after Strojny et al. (1998) and Wever et al. (2000). The gas sampling cells of 20 ml were air tight at one end and the other and closed with a tape so a plastic syringe could used to take air samples. The cells was made by vinyl tubing of 25 cm length (ø 10 mm inside) with 4 holes (ø 5mm) at the bottom. Gas sample cells were inserted into the substrates at 2 or 3 heights, depending on the height of substrates (Table 5).

CO_2 gas samples of 20 ml were analyzed with an infra red (IR) sensor Multiwarn II (Dreager, Germany). The air penetrates by diffusion into a measuring cuvette. The IR sensor measures the CO_2 partial pressure by absorption of infrared radiation. The measuring range was 0 to 5 % by volume with a resolution of 0.01 %. Response time diffusion operating is $\leq$ 50 sec. Furthermore, the Bellmethod (Freytag and Lüttich,1985) was checked to get results about the CO_2 concentration of substrates. A cylinder of 100 cm^3 is placed up side down on the substrates. The collected air submitted from the substrates was analyzed by IR sensor.

C_2H_4- gas samples of 3 ml were analyzed by injecting into a gas chromatograph (GC). The Carle Analytical GC (Fullerton, USA) was fitted with a 1 m activated alumina column and operating at 70 °C. He was used as carrier gas.

Dissolved oxygen was determined of 200 ml probes of solution with a membrane covered galvanic sensor 'Oxy-meter 320' (WTW, Germany) in the in the nutrient solution (input) and in the drain solution (output).

3. Results and Discussion

To get results about the CO_2 concentration, 2 methods were compared. Results of the Bellmethod (Figure 1) shown an accumulation of CO_2 over 5000 ppm, if the bell is air tight. A daily time course light was observed using the Bellmethod as non air tight bell, thus a dilution or exchange with ambient air is possible. Both concentrations characterize submitted CO_2, as mixed air sample from the substrate. To characterize the actual CO_2 concentration, the gas sampling method is better suitable, even if small air

samples are taken off of the root zone (Table 6). The lowest CO_2 concentration was determined in Sawagrow for all heights. Highest CO_2 concentration (maximum 7700 ppm) was measured in organic substrate UC-mix and UC-mix control. Results of CO_2 are about ten times lower compared with other results (Strojny et al., 1998; Wewer et al. 2000). The reason for this is, that with measurement in a non air tight system, CO_2 can dilute through the substrate surface. But O_2 and C_2H_4 results are comparable (Table 6). From the top to the bottom, the concentration increased. For O_2 the opposite trend was found, highest concentrations are on top. Highest O_2 concentrations in substrates (17,9 5 and 18,5 %) were measured in the middle for both polyester fleece substrates.

For C_2H_4, the highest level (0.026 ppm) was found in Sawagrow at the bottom. There are significant differences between the C_2H_4 level at the top and the bottom. For UC-mix control there exist non difference between the middle and the bottom. The time course (8:00 to 18:00) shows a pattern according the photoperiod. The trend of C_2H_4 level was almost constant during the experiment (Figure 2). Thus there was no accumulation determined. For UC-mix control, a decreased trend of ethylene was determined.

Dissolved oxygen results in solution (input) and drain (output) shows for all substrates a positive balance (Table 7). For UC-mix substrates the highest oxygen consumption (0.4762 and 0.5290 mgO_2/plant*d) was measured. The oxygen consumption consisted of root and microbial respiration, the results represent both. The lowest excess was found for UC-mix control (0.0061 mg O_2/plant*d) as organic substrate, the highest was for the thin polyester fleece No. 6313 (0.0191 mg O_2/plant*d). It can be presumed that in all systems the oxygen excess results from the nutrient solution, which was prepared when oxygen reached DI-water (70%) and oxygen diffusion related to air filled porosity of substrates (Bass et al., 2000). The O_2 and CO_2 level changed over time. The trend over time was similar to results in other substrates (Wever et al., 2000). In Figure 3 the time course of dissolved oxygen is given, for UC-mix, No. 6313, and Sawagrow, the trend is decreasing. For the UC-mix (control) the trend is slightly increasing. This can be explained with reduced microbial respiration (output) over time, because the trend of CO_2 concentration of UC-mix control (Figure 4) is slightly too. During the day (8:00 to 18:00 h) the CO_2 and C_2H_4 concentrations increase, which reflect increased respiration during the day (data not shown).

4. Conclusions

The gas sampling system from the root zone is suitable to get information about the gas composition, even if small air samples are taken off. Methods for monitoring of the gas composition, like the 'bellmethod' are not suitable, because sensors are insufficiently developed for measurement under greenhouse conditions. From the top to the bottom, the O_2 concentrations decreased and CO_2 and C_2H_4 increased. In organic substrates like UC-mix higher CO_2 and lower O_2 concentrations were found compared with inert substrates like Sawagrow.

But in all substrates there exist a gradient for gas concentrations from the top to the bottom, even in thin layer substrates. Excess amount of dissolved oxygen was found in each substrate. Lowest excess was found in organic substrates; here a certain amount is consumed by micro organisms.

Due to O_2 excess, a shortage of oxygen did not occur at any time during the experiment, even with almost water-saturated substrates. It can be concluded that plants are able to take up optimal amounts of water, nutrients, and O_2 if the nutrient solution is almost saturated with O_2. During the period of 60 days the O_2 concentration was decreased and CO_2 increased. All results found in different substrates are in a range that does not limit for plant growth (Jackson, 1980; Strojny et al., 1998). Further investigations should be done with different O_2 input levels over a longer growing period, like year around or over even several years.

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Table 1: Dates of events during the experiment in 2001.

Events	Experiment
Planting	30. March
Density	96 plants/m^2
Flower initiation (dark, 17:00- 8:00)	5 April - 2 May
End of experiment	1 June

Table 2: Composition of the nutrient solution in a closed system.

Parameter	Units	Figure	Parameter	Units	Figure
EC	mS/cm^{-1}	1.0	Fe	ppm	1.6
pH		5.5	Mn	ppm	0.27
Ca	ppm	90	Cu	ppm	0.16
Mg	ppm	24	Zn	ppm	0.12
K	ppm	124	B	ppm	0.26
$N\text{-}NH_4$	ppm	6	Mo	ppm	0.016
$N\text{-}NO_3$	ppm	96			
P	ppm	26			

Table 3: Quality of water and solution.

Parameter	Tap water	DI-water	Nutrient solution
EC (dSm^{-1})	0.4	0.1	1.0
pH	7.83	5.3	5.5
Dissolved oxygen (%)	23,3	83.3	70.3

Table 4: Substrate characteristics and variants of the experiment.

Var.	Substrate	Components	Water-air-solid matter (%)	Volume (l/plant)
1.	UC-mix	41,7 % FIR bark : 33,3 % peat : 25% sand	73.3 : 10.2 : 15.5	0.335
2.	No. '6313'	100 % polyesterfleece	59 : 39 : 2	0.0335
3.	Sawagrow	100 % polyesterfleece	59 : 39 : 2	0.335
4.	UC-mix (pot)	control	73.3 : 10.2 : 15.5	1.509

Table 5: Place of gas sampling cells in substrates.

Substrate	Height (cm)	Place in substrate from the bottom (cm)		
1. UC-mix	3	bottom (0)	-	top (3) *
2. No. 6313	0.3	bottom (0)	-	top (0.3)*
3. Sawagrow	3	bottom (0)	middle (1.5)	top (3)*
4. UC-mix control	20	bottom (3)	middle (11)	top (19)

* gas sample cell was placed between the substrate and the covering plastic sheets

Table 6: Average results of gas measurement.

Substrate	CO_2 (ppm) lsd (5%) 250 ppm			O_2 (%) lsd (5%) 1,9 %			C_2H_4 (ppm) lsd (5%) 0.0063 ppm		
	bottom	middle	top	bottom	middle	top	bottom	middle	top
UC-mix	1898	-	722	-	16.6	-	0.0202	-	0.0179
No. 6313	1032	-	353	-	18.5	-	0.0214	-	0.0163
Sawagrow	883	647	351	-	17.9	-	0.0260	0.0215	0.0135
UC-mix Control	2515	1892	522	11.2	15.6	18.5	0.0212	0.0212	0.0150

(-) no measurement depends on method (Table 5)

Table 7. Average results of dissolved oxygen balance in hydroponic systems.

Substrate	Oxygen input (nutrient solution) mg O_2/plant*d	Oxygen output (consumption) mg O_2/ plant*d	Oxygen output (drain solution) mg O_2/ plant *d	Oxygen balance (excess) mg O_2/d*plant
UC-mix	0.6108	0.4762**	0.1473**	- 0.0127
No. 6313	0.6014	0.4034	0.2171	- 0.0191
Sawagrow	0.5947	0.3975	0.2057	- 0.0085
UC-mix Control	0.7265**	0.5290**	0.2036	- 0.0061

** significant at p = 0.05

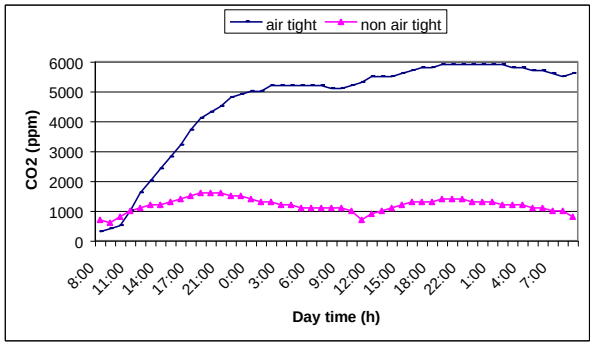

Figure 1: CO_2 -concentrations of UC-mix measured with the 'bell method'.

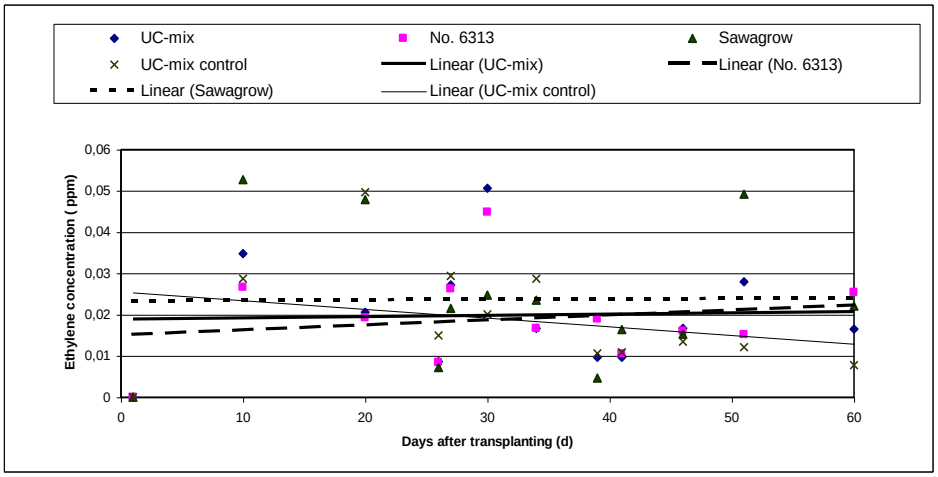

Figure 2: Time course of ethylene concentration in substrates at the bottom.

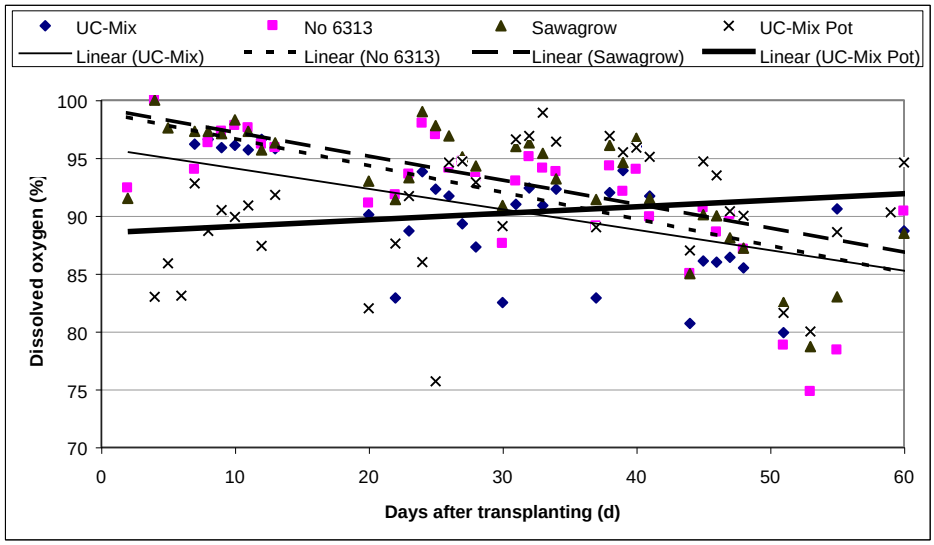

Figure 3: Dissolved oxygen concentration in drain solution.

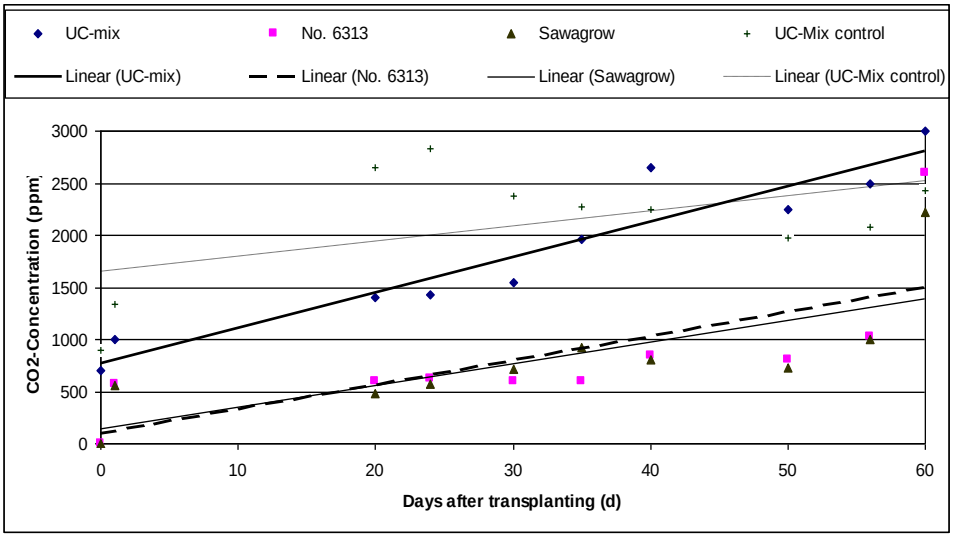

Figure 4: Time course of CO2- concentrations in substrates at the bottom.