Optimization of Oxygen Levels in Root Systems as Effective Cultivation Tool

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Abstract

To investigate the influence of oxygen concentrations in the root system on plant development, young cucumber plants were grown during three weeks on stone wool blocks. A continuous flow of nutrient solution (0.75 L h⁻¹), containing 0.5, 3.5 or 10 mg L⁻¹ dissolved oxygen, was led through the substrates. Already after 3 days, the impact of the various oxygen levels in the root systems became evident. Plant development was reduced when plants were subjected to the lowest oxygen concentration. In time, increasing differences in leaf area were observed when plants were grown under different oxygen levels, showing largest leaf area at 10 mg L⁻¹ oxygen. Also, root mass was significantly reduced when plants were grown under low oxygen conditions. Bacteria and other micro-organisms that consume oxygen can reduce oxygen levels. Oxygen consumption was detected in samples that were taken at different places in greenhouses, e.g. irrigation water storage tanks, irrigation supply system and substrates. During the winter period, the contribution of micro-organisms in oxygen consumption was low. However, in April oxygen consumption in the samples was significantly higher. Sometimes, oxygen in nutrient solution, present in the substrates, was fully consumed within 30 minutes, indicating that roots would suffer anoxia. Frequent refreshment of nutrient solution in the irrigation supply system had a major impact on oxygen levels. Continuous measurements showed that during the day oxygen levels in the irrigation system were high just after refreshment of the nutrient solution, but between two refreshments oxygen levels in the system dropped towards very low oxygen values. If technically feasible, in future the control of oxygen levels in root systems may become a new tool for growers to manage cultivation in horticulture, in addition to light, temperature, carbon dioxide, nutrition and water.

INTRODUCTION

In horticulture, many parameters, such as PAR light, air humidity, air temperature, carbon dioxide, water content in the slab, and the drain of nutrient water, are measured. Most parameters, which are used to feed back process computers, are derived from environmental conditions in the green house, while besides water content, EC and temperature, conditions in the root environment inside substrates are poorly taken into account. This may be surprising since the root system is used for uptake of nutrients and water, and is essential for growth. Many processes inside the roots require energy, which is generated by oxygen dependent dissimilation. Hence, depletion of oxygen in the root system could result in reduced root activity and development and thereby growth retardation, and eventually reduced yield. Additionally, hypoxia may result in enhanced susceptibility to diseases (Zheng et al.).

Measurements of oxygen in the root system has been focused mainly on monocots (Armstrong and Gaynard, 1976; Saglio et al., 1984). Research on oxygen supply in substrates in horticulture is scarce, and was hampered for long time due to the lack of a reliable sensor, which could measure oxygen in the root environment. Electrochemical oxygen sensors may be useful in those locations of the green house where water is constantly moving, but these sensors are not useful in a non-stirred environment such as substrates. First of all, electrochemical sensors do consume oxygen, and therefore affect the oxygen levels in its direct environment. Secondly, these sensors need frequent calibration, and are fragile due to the membrane present. The introduction of an optical oxygen sensor, a few years ago, could
overcome most of the limitations of the electrochemical sensors. The optical oxygen sensor is robust, it does not consume oxygen, and needs little maintenance, which makes it useful for measurements in substrates. Figure 1 shows an optical sensor, which we developed for the use of measurements non-stirred liquid environment, such as substrates.

The availability of the optical oxygen sensor gave us the opportunity to investigate the relevance of oxygen in the root environment for plant quality. So, primarily the aim of the research presented here was to carry out an experiment, in which could be determined whether oxygen supply in the root environment is essential for plant development (proof of principle). In addition, we have investigated oxygen profiles at different locations in the green house, e.g. irrigation water storage tanks, irrigation supply system and substrates. Finally, the contribution of micro-organisms in oxygen consumption was determined on different locations, and during different periods during the growing season. It will be discussed, which management actions can be taken by growers to control oxygen levels in substrates.

MATERIALS AND METHODS

Growing Conditions for Proof of Principle (Experiment 1)

To investigate the role of oxygen levels in the root environment for plant development and plant quality (proof of principle), young cucumber plants (Cucumber sativis L. cv. Aviance) were grown in a green house on stone wool blocks. Therefore, cucumber seeds were germinated on vermiculite, and after 10 days seedlings were transferred to stone wool blocks, attached in special Perspex boxes, for further growing. An experimental set-up was used that allowed us to keep all root environment parameters equal, except for the oxygen concentration. The stone wool block was placed in a first box that had an inlet on top of the stone wool block, and an outlet at the bottom (solution flow through the system). The first box was placed inside a second box with an outlet at the level of the nutrient solution of the first box. This made it possible to subject the growing plant to a continuous flow (0.75 L h⁻¹) of standard nutrient solution for cucumber (Fig. 2). Plants were grown on nutrient solution, which contained either 0.5 mg L⁻¹ dissolved oxygen, 3.5 mg L⁻¹ per, or 10 mg L⁻¹. An oxygen concentration of 0.5 mg L⁻¹ oxygen represents a situation of anoxia, while 10 mg L⁻¹ represents a situation of saturation with oxygen. Previous work (data not shown) has shown that 3.5 mg L⁻¹ dissolved oxygen represent a critical level, meaning that below these concentrations reduction of metabolic processes inside root cells may occur, resulting in reduced activity. Nutrient solution was pumped to the plants from storage tanks of about 300 liter. For each condition 5 plants were cultivated, which were randomly located in the green house to avoid differences in plant growth due to local climate differences. Using the optical oxygen sensor (Fig. 1), oxygen levels inside the substrates were controlled continuously. In Figure 2 the set up is depicted.

Plant Measurements for the Proof of Principle (Experiment 1)

After 3 weeks, the 15 cucumber plants (5 for each oxygen condition) were harvested, and the total leaf area was determined for each plant.

Detection of Oxygen Levels for the Proof of Principle (Experiment 1)

Oxygen levels inside the substrates were detected using the optical oxygen sensor (Fig. 1). The principle of the optical sensor is based on an oxygen sensitive dye, which fluorescence changes depend on oxygen pressure.

Consumption of Oxygen by Micro Organisms (Experiment 2)

To determine the contribution of micro organisms to oxygen consumption in the water system of a green house, samples were taken at different locations, e.g. irrigation water storage tanks, irrigation supply system. In the green house where the samples were taken, productive cucumber plants (Cucumber sativis L. cv. Aviance) were cultivated. Samples were taken both in February, and in April. Samples (1 mL) were taken with a syringe, and concentrated 10 fold on a 0.2 µm filter. The filter, containing concentrated nutrient solution, was used for oxygen measurements. For oxygen measurements, a measurement device was
used based on the same principle as described above for the sensor. The device enabled us to
measure oxygen consumption of 6 samples simultaneously during time.

Oxygen Profiles in Substrates in the Greenhouse during Growing of Roses (Experiment 3)

The optical oxygen sensor (Fig. 1) was used to carry out an investigation of oxygen
levels at different location in a professional greenhouse, where cut roses (*Rosa hybrida* L. cv.
Rolex) were cultivated. Oxygen measurements were performed both in substrates (stone wool),
tubings, and irrigation storage tanks. Oxygen levels were determined continuously for
a few weeks.

RESULTS AND DISCUSSION

Proof of Principle

To determine the role of oxygen supply to the roots for plant development, young
cucumber plants were cultivated at different levels of oxygen in the supply of nutrient
solution, i.e. 0.5 mg L⁻¹ dissolved oxygen, 3.5 mg L⁻¹ and 10 mg L⁻¹. Oxygen measurements
using the optical sensor showed that inside the substrate blocks the indicated concentrations
were realized, expect for a supply of 10 mg L⁻¹ in the nutrient solution that resulted in a
concentration of 6 mg L⁻¹ dissolved oxygen in the substrates. The decrease is probably due to
oxygen consumption by the roots. So, the oxygen levels inside the substrates were 0.5, 3.5
and 6 mg L⁻¹ dissolved oxygen, where 0.5 mg L⁻¹ represents a situation of anoxia, 3.5 mg L⁻¹
represents about critical oxygen levels, and 6 mg L⁻¹ probably is a situation with sufficient
oxygen to supply activity of root systems.

In Figure 3, the total leaf area is depicted of cucumber plants with different oxygen
levels after 3 weeks of growing. It can be seen that the total leaf area of plants, which are
grown under low oxygen conditions, is significant lower, than the leaf area of plants, which
are grown under medium (3.5 mg L⁻¹), or oxygen rich (6 mg L⁻¹) conditions. So, a situation of
anoxia in the substrates leads to impaired plant development. Surprisingly, plants which are
grown using nutrient solution, which is oxygen saturated, have a higher leaf area then border
plants, which were not subjected to continuous refreshment of nutrient solution. A
comparison between plants grown using oxygen saturated nutrient solution, and border
plants, showed that an increase of leaf area is achieved of about 20%. We conclude that the
gas factor oxygen is of significant importance for plant development. In practical situations
the gradual decline in plant production caused by sub-optimal oxygen supply may remain
unnoticed as there is no specific indicative symptom.

Consumption of Oxygen by Micro Organisms

Bacteria and other micro-organisms that consume oxygen can reduce oxygen levels in
the water system of the greenhouse. Oxygen consumption was detected in samples that were
taken at different places in greenhouses, e.g. irrigation water storage tanks, irrigation supply
system and substrates. During the winter period, the contribution of micro organisms in
oxygen consumption was low. However, in April oxygen consumption in the samples was
significantly higher. Sometimes, oxygen in nutrient solution, present in the substrates, was
fully consumed within 30 minutes, indicating that roots would suffer anoxia. Next, oxygen
profiles were measured for several days in a greenhouse where cut roses were cultivated.
Figure 4 shows that oxygen levels in tubings of the irrigation system display significant
fluctuations, probably as a result of subsequent water supply during a day. During the night
very low oxygen levels occur in the tubings. Figure 4 shows that the use of hydrogen
peroxide, an agent which is known to reduce levels of micro-organisms, results in significant
higher oxygen levels. Also, at the end of the day, when water gifts are stopped, the decrease
in oxygen levels is delayed as a result of hydrogen peroxide. Further measurements show that
use of hydrogen peroxide did not result in higher oxygen levels inside substrates.

Oxygen Profiles in the Root Zone of Cucumber and Roses during Growing of
Cucumber and Roses in the Greenhouse

Continuous measurements of oxygen levels in substrates during growing of cucumber
and roses in the greenhouse, showed that oxygen levels in stone wool slabs are also
dependent from the position inside the slab. Figure 5 shows for cucumber that in higher parts of the stone wool slab, oxygen levels are high, and show little fluctuation during the day. However, at positions in the slab just under the stone wool blocks that are located on top of the slab, significant fluctuation in oxygen levels were detected. These fluctuations were measured simultaneously with water supply during the day, indicating that oxygen is supplied to the stone wool slab by water gifts. Figure 5 also shows that between water gifts supplied by the drippers to the stone wool slab, oxygen levels may be very low, probably due to oxygen consumption by plants. At the bottom of the slab, very low levels were detected continuously. Figure 6 shows oxygen profiles in stone wool slabs during growing of roses. In agreement with data from Figure 5, one can see that oxygen levels inside the stone wool slab depend on the position in the slab. Lowest levels were detected at the bottom of the slab.

From our data it can be concluded that the gas factor oxygen is of significant importance for plant development. Furthermore, it can be concluded that unless water is refreshed regularly in the slab, roots may often suffer from hypoxia, in particular in the lower parts of the slab. As a result of micro organisms, oxygen levels in tubings of the irrigation system may fall dramatically. Hydrogen peroxide has a positive effect on oxygen levels in nutrient solution in tubings, but benefits for oxygen levels inside substrates could not be detected. Oxygen supply for the root system inside substrates may be improved by optimization of water management, where water supply from drippers, and draining of the slab should be adjusted according to the needs of the plant.

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Literature Cited

Fig. 1. Optical oxygen sensor for use in substrates.
Fig. 2. Schematic drawing showing the experimental set-up to grow cucumber plants with continuous flow of nutrient solution. The oxygen sensor is placed at root level in the stone wool block.

Fig. 3. Leaf area of cucumber plants after growth on 6 mg L$^{-1}$ (oxygen rich), 3.5 mg L$^{-1}$ (medium oxygen) or 0.5 mg. L$^{-1}$ (low oxygen) oxygen in the root environment. The standard deviation is indicated on top of the bars.
Fig. 4. Oxygen levels in nutrient solution in tubings of the irrigation system. Nutrient solution in storage tanks was treated with or without hydrogen peroxide.

Fig. 5. Profiles of oxygen levels during growing of cucumber in a stone wool slab. Sensors were place at 3 positions, indicated in the figure, and oxygen was measured continuously during 3 subsequent days. The spikes in the oxygen profiles just under the block coincide with the water supply during the day.
Fig. 6. Profiles of oxygen during growing of roses in a stone wool slab. Sensors were placed at three different heights in a stone wool slab, i.e. at 4 cm deep, 5 cm deep and at 6 cm deep, which is nearly at the bottom of the slab. For each height 3 sensors were used, which are depicted in the graph underneath each other.