Scientia Horticulturae, 19 (1983) 213—220
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

ROOT AERATION IN A DEEP HYDROPONIC SYSTEM AND ITS EFFECT ON GROWTH AND YIELD OF TOMATO

MOSHE ZERONI, JOSEPH GALE and JIFTAH BEN-ASHER

The Jacob Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sde Boqer 84990 (Israel)

(Accepted for publication 16 June 1982)

ABSTRACT

Zeroni, M., Gale, J. and Ben-Asher, J., 1983. Root aeration in a deep hydroponic system and its effect on growth and yield of tomato. *Scientia Hortic.*, 19: 213—220.

Tomato plants (*Solanum lycopersicum* L. 'Grandia') were grown in a deep-water culture system, with varying oxygen (O_2) concentrations in the nutrient solution. Oxygen depletion of the nutrient solution by the plants as a function of distance from an aeration point could be best described by a concave exponential curve. Increase of branch length, number of side branches and number of flowers per plant were plotted against time and found to produce different types of curves (exponential, logarithmic and linear, respectively). The slopes of the best-fit functions of these curves were linearly correlated to the O_2 concentration in the hydroponic medium. The effect of O_2 concentration in the nutrient solution on the fresh and dry weights of roots and shoots was positive and exponential.

There were no significant changes in response to O_2 in the ratios of root to shoot fresh and dry weights, or of the ratios of dry to fresh weights of roots or shoots. Fruit production increased linearly with O_2 concentration around the roots.

It was concluded that tomato plants in deep-water culture do not reach the theoretical maximum rate of O_2 uptake into the roots.

INTRODUCTION

Deep hydroponic systems may have several potential advantages over the nutrient film technique (NFT). These include low cost of construction, higher buffering capacity of the large volume of nutrient solution and the possibility of using the nutrient solution for heat storage in solar greenhouses (Gale, 1980). Aeration, or O_2 supply to the plant roots, is one of the main problems of deep hydroponic systems. Inadequate aeration may cause waterlogging in the roots of many plants, while sufficient forced aeration may be very expensive.

Nutritional requirements of plants in different soil-less culture systems have been summarised in recent reviews (I.W.O.S.C., 1977; I.S.O.S.C., 1980), but very little has been published on root aeration problems in deep hydroponic systems. Ben-Asher et al. (1980) presented a mathematical simulation

0304-4238/83/$03.00

model of mineral and O_2 uptake by plants from such a system. However, they pointed out that further experimental verification of the model is required.

The objective of this work was to study the effects of different O_2 concentrations in a deep hydroponic nutrient solution on the growth and yield of tomato plants. A further purpose was to test the model presented by Ben-Asher et al. (1980) with respect to the pattern of O_2 uptake.

MATERIALS AND METHODS

The hydroponic system. — An inexpensive, deep hydroponic system was constructed by digging a continuous channel in loops inside a greenhouse (see Fig. 1). The channel was lined with a double layer of polyethylene sheeting. The overall length of the channel was 96 m, its depth was 0.25 m and it contained approximately 6 m^3 of a nutrient solution (see below). A pump moved the solution through a flowmeter and the channel at a controlled rate of 4.5 l min^{-1} except for short experimental periods. Water lost by evapotranspiration was replaced automatically.

Plant material. — Tomato seedlings (*Solanum lycopersicum* L. 'Grandia') were inserted into holes in polystyrene foam sheets floating on the nutrient solution. Planting was on 6 November 1980 (Rows 1—4) and 26 January 1981 (Rows 5—8). There were 296 plants in the experiment, divided into 8 rows of 37 plants each.

Nutrical III (Nutrients and Chemicals Co., Israel), containing 7.5 N : 3 P : 6.5 K + 3% micronutrients, was added to water to form the nutrient solution. Sequestrene solution (Fe-EDDHA, Ciba-Geigy, Switzerland) was added every 10—14 days. The electrical conductivity of the solution was held at 2.18 ± 0.16 mmho cm^{-1} and the pH at 6.80 ± 0.26.

Aeration system. — Different O_2 concentrations in the hydroponic nutrient solution ($[O_2]$) were achieved by using various rates and methods of aeration, depicted in Fig. 1. They included heavy aeration at the beginning of a row (Rows 1 and 6), light aeration at the beginning of a row (Row 5), aeration through a 12-mm trickle-irrigation pipe fitted with 2 l h^{-1} drippers (Plason Co., Israel) under the roots of each plant (Row 7), and a porous plastic tube (LDPE 0610, Mizpe Industries, Israel) (Row 8).

Measurements. — The O_2 concentration was measured with a membrane-covered voltametric sensor (Ben-Yaakov, 1979). Measurements were taken at 3 fixed points in each row at 5-cm depth, every few days, together with air and water temperatures. Water temperature ranged from 16 to 26°C. Due to the varying temperature, all results are expressed as a percentage of the maximum (saturation) concentration of O_2 in water under air, at the existing temperature ($\%[O_2]$).

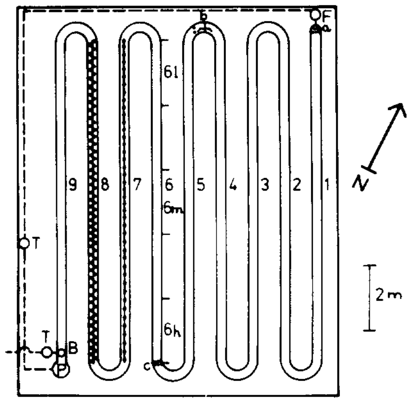


Fig. 1. Schematic diagram of a deep, circulating, water-culture system. 1—9 = number of channel sections (rows); a, b, c = aeration points; 6h, 6m, 6l = sections of Row 6 with high, medium and low O_2 concentrations, respectively; B = float; F = flowmeter; P = pump; T = tap; broken line = water tube; dotted line = aeration by an air tube with in-line drippers; heavily dotted line = aeration by porous air tube.

The total length of all the branches of each of the plants in Rows 5—8 was measured weekly between 27 January and 23 March. The number of side branches and flowers developed on each plant in Rows 5—8 was counted weekly between 24 February and 12 April. The plants in these rows were harvested on 13 May and the fresh weights of roots and shoots were taken. Dry weight was measured after 48 h drying in a ventilated oven at 80°C. Fruit from each plant in Rows 1—4 was harvested and weighed every 2—3 days throughout April. The yield of every 10 neighbouring plants was averaged.

Calculations. — Data were tested for best fit to linear, exponential, power, logarithmic and square functions. All curves presented are of those functions which gave the best fit (highest r^2).

RESULTS

O_2 gradient. — The changes in $[O_2]$ with distance from aeration point, at 2 rates of water flow along 40 m of channel, with 5-month-old, fruit-bearing tomato plants, take the form of exponential curves with negative slopes (Fig. 2). The $[O_2]$ percentages found in the nutrient solution of different rows and sections are summarized in Table I.

Plant growth and development. — Three parameters of growth and development were plotted against time for different $[O_2]$: accumulative growth per plant (Fig. 3), number of side branches per plant (Fig. 4) and number of flowers per plant (Fig. 5).

The results show exponential, logarithmic and linear curves, respectively,

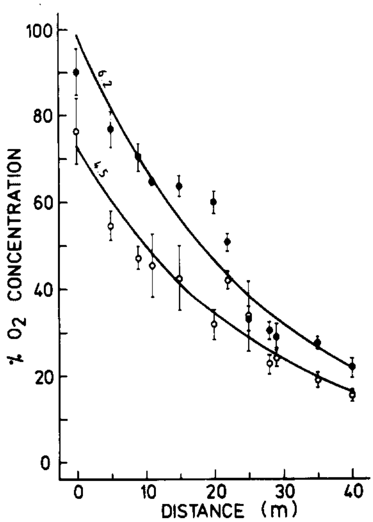


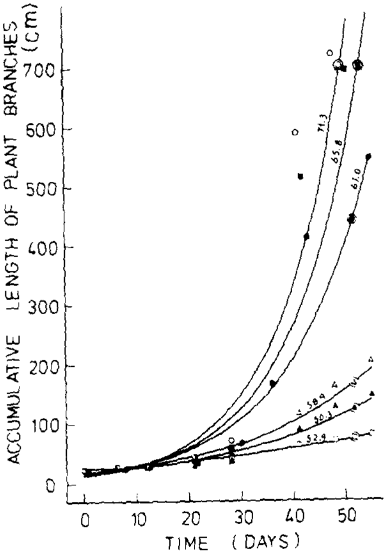
Fig. 2. Change of $[O_2]$ with distance from aeration point in a deep circulating hydroponic system. Rates of water flow were 4.5 l min^{-1} (○) and 6.2 l min^{-1} (●). Vertical lines are standard deviations.

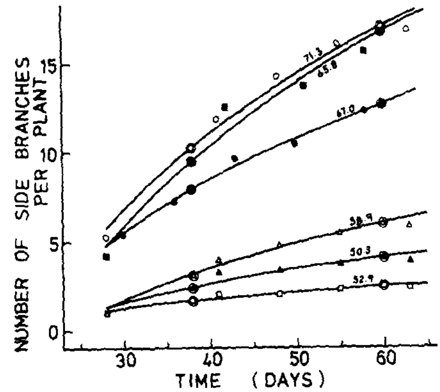
TABLE I

The % $[O_2]$ found in the nutrient solution of different rows and sections of the experiment

Row/section	% $[O_2]$ ± S.D.
Row 5	50.3 ± 3.04
Section 6h	65.8 ± 5.09
Section 6m	58.9 ± 4.57
Section 6l	52.9 ± 4.32
Row 7	71.3 ± 2.45
Row 8	67.0 ± 1.96

with relatively high correlation coefficients (r^2 between 0.940 and 0.993). All parameters showed a close relationship to $[O_2]$; the ascending order of the lines was not in complete accord with the increase in $[O_2]$ in the nutrient solution, but was consistent in all parameters measured. Apparently, 2 groups of curves could be observed in each of the graphs (Figs. 3—5) related to the higher and lower O_2 concentrations. Linear relationships were found to exist between the 6 slopes of each parameter of growth and development with time and the % $[O_2]$ (Fig. 6), with relatively high correlation coefficients (r^2 between 0.930 and 0.951).





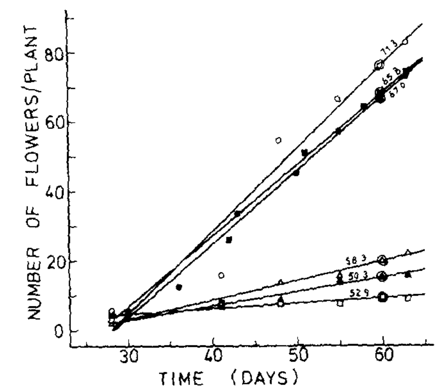


Fig. 3. Branch growth of tomato plants, growing in a deep circulating hydroponic system, as related to dissolved O_2 concentration. Best-fit curves are marked by the respective encircled symbols and by %[O_2]. 50.3% [O_2] = (▲); 52.9% = (□); 58.9% = (△); 65.8% = (■); 67.0% = (●); 71.3% [O_2] = (○). M.S.E. (mean standard error) = 6.15% of point value.

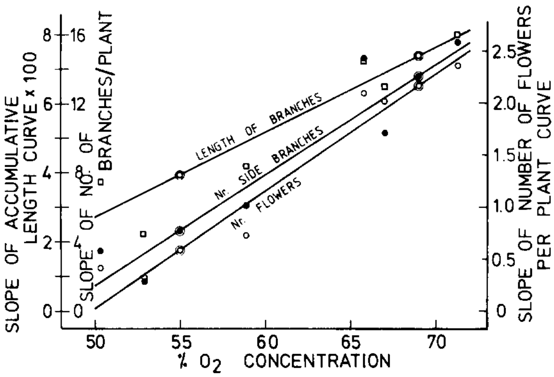
Fig. 4. Number of side branches of tomato plants growing in a deep, circulating, hydroponic system as related to dissolved O_2 concentration. Symbols as in Fig. 3. M.S.E. = 9.16%.

Fig. 5. Number of flowers per plant of tomato plants, growing in a deep, circulating, hydroponic system, as related to dissolved O_2 concentration. Symbols as in Fig. 3. M.S.E. = 14.53%.

Fresh and dry weights of roots and shoots were exponentially related to O_2 concentration around the roots (Fig. 7), but there was no significant effect of this concentration on either the ratios of root to shoot fresh and dry weights or on the ratios of dry weight to fresh weight of roots and shoots.

Fruit production. — Fruit production decreased exponentially with distance from the aeration point and increased linearly with O_2 concentration in the nutrient solution (Fig. 8).

It should be noted that the variability of fruit production among plants was quite large, especially between 15 and 25 m from the aeration point (35—45% [O_2]).



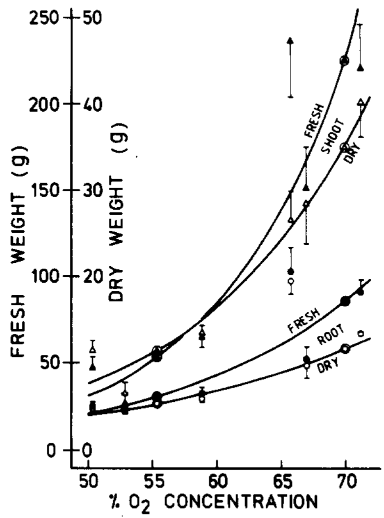


Fig. 6. The effect of % $[O_2]$ on the growth and development rates of tomato plants in a deep, circulating hydroponic system as expressed by the slopes of the curves of accumulative length of branches per plant (▫), number of side branches per plant (•) and number of flowers per plant (○) when plotted against time. Best-fit curves are marked by the respective encircled symbols.

Fig. 7. Final weights of roots and shoots of tomato plants, growing in a deep, circulating, hydroponic system, as related to dissolved O_2 concentration. Average root dry weight (○), root fresh weight (•), shoot dry weight (△) and shoot fresh weight (▲). Vertical bars are half standard errors. Best-fit curves are marked by the respective encircled symbols.

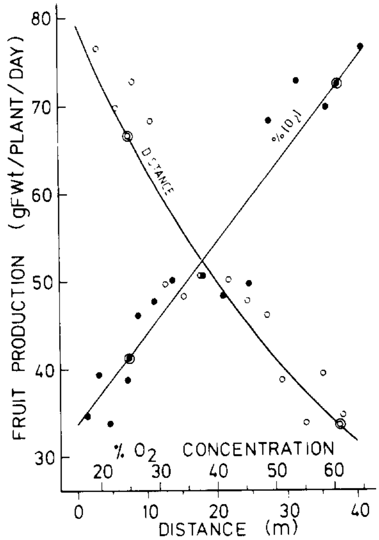


Fig. 8. Fruit production in tomato plants, growing in a deep, circulating hydroponic system, as related to distance from aeration point and dissolved O_2 concentration. Distance from aeration point (○), % $[O_2]$ (•). Best-fit curves are marked by the respective encircled symbols.

DISCUSSION

The decrease of O_2 concentration in the nutrient solution with increasing distance from the aeration point took the form of a concave curve (Fig. 2). This indicates that roots of upstream plants, exposed to higher O_2 concentrations, consume more O_2. O_2 consumption by the roots (F) was related to O_2 concentrations by

$$F = -V \frac{\delta C}{\delta x} \tag{1}$$

where V is the nutrient solution flow rate, C is the concentration of dissolved O_2 and x is the distance from the aeration point for which C is calculated. As shown in Fig. 2, $[O_2]$ changed with distance according to

$$C\,(x) = A_1 e^{-A_2 x} \tag{2}$$

Solving eqn. 1 accordingly gives

$$F\,(x) = VA_1A_2e^{-A_2x} = VA_2C(x) \tag{3}$$

Equation 3 shows a linear relationship between O_2 uptake rate (F) and $[O_2]$ around the roots at a given distance ($C(x)$) when flow rate is unchanged.

As noted above, each of the 3 parameters representing growth and development showed, apparently, 2 groups of curves, one for the higher $[O_2]$ and one for the lower $[O_2]$ (Figs. 3—5). On the other hand, Fig. 6 shows linear relationships between the 6 slopes of each parameter of growth and development with time against % $[O_2]$. This indicates that the gap between the high and the low O_2 concentration curves (Figs. 3—5) is temporary and, given time, all plants will achieve their maximum length, number of side branches and number of flowers.

It is concluded that O_2 concentration in the nutrient solution of deep-water culture is a limiting factor for tomato plants. The plant, under these circumstances, will not reach the maximum possible rate of O_2 uptake. The following evidence supports this conclusion:

(a) the concave curve for O_2 depletion as a function of channel length (Fig. 2);
(b) the linear correlation between O_2 concentration in the medium and O_2 uptake by plant roots (eqn. 3);
(c) the linear correlation between O_2 concentration and the slopes of the functions of growth and development (Fig. 6);
(d) the linear correlation between O_2 concentration and fruit production (Fig. 8).

These conclusions differ from those of Ben-Asher et al. (1980) which were based on "maximum O_2 uptake".

The above argument does not mean that plants cannot survive and even thrive in a deep circulating hydroponic system, but that the uptake of O_2 by the plant roots is highly dependent upon the O_2 concentration of the immediate root environment. Thus, decreasing the size of the boundary layer around the roots may be of importance.

Waterlogging and O_2 deficiency may cause anatomical and morphological changes in plants (Bryant, 1934; Vlamis and Davis, 1944). However, no significant changes in root to shoot and dry weight to fresh weight ratios (Fig. 7) were found here. This indicates that in our experiments, the plants were not stressed enough to develop any major structural changes.

Fruit production showed a pronounced (36%) increase of between 45 and 49% $[O_2]$ (Fig. 8). Plants growing in 35—45% $[O_2]$ showed large variability in fruit production. 50% $[O_2]$ appears to be the critical level for fruit production, while 65% of O_2 saturation appears to be the lowest desirable level, for both vegetative and reproductive growth.

ACKNOWLEDGEMENTS

The authors wish to thank O. Aboulafia, T. Savitzky, R. Kopel and Y. David for technical assistance and E. Zahavi for the drawings.

This work was supported by the "Bundesministerium für Forschung und Technologie" (BMFT, Federal Republic of Germany), The National Council for Research and Development (NCRD, Israel) and by the Vinik fund (Israel).

REFERENCES

Ben-Asher, J., Gordon, J.M., Gale, J. and Kopel, R., 1980. A computational approach for water culture. Agric. J., 72: 640—645.

Ben-Yaakov, S., 1979. A portable dissolved-oxygen analyser for fish farming industry. Bamidgeh, 31: 69—77.

Bryant, A.E., 1934. Comparison of anatomical and histological differences between roots of barley seedlings grown in aerated and in non-aerated solutions. Plant Physiol., 9: 389—391.

Gale, J., 1980. Controlled environment agriculture for hot desert regions. In: J. Grace, E. D. Ford and P.G. Jarvis (Editors), Plants and their Atmospheric Environment. Blackwell Scientific, Oxford, London, Edinburgh, Boston, Melbourne, pp. 391—402.

International Society for Soil-less Culture (I.S.O.S.C.), 1980. Proc. Fifth Int. Congr. Soil-less Culture. Int. Soc. Soil-less Culture, Wageningen, The Netherlands.

International Working Group on Soil-less Culture (I.W.O.S.C.), 1977. Proc. Fourth Int. Congr. Soil-less Culture. Int. Working Group Soil-less Culture, Wageningen, The Netherlands.

Vlamis, J. and Davis, A.R., 1944. Effects of oxygen tension on certain physiological responses of rice, barley and tomato. Plant Physiol., 19: 33—51.