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A COMPARISON OF OXYGEN DIFFUSION RATES IN SAND MOISTENED WITH WATER OR PEG 20000 SOLUTION

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A b s t r a c t. Oxygen diffusion rates (ODR) were measured in water/sand/air and PEG solution/sand/air mixtures, spanning a range of liquid/solid/air volume ratios. Replacement of water with PEG solution as the liquid phase was found to reduce the ODR within a given mixture by a factor of approximately two. ODR values were compared with limiting values for plant emergence quoted in another study. It was concluded that PEG solutions could be used to control the osmotic potential of a sandy growth medium without adversely affecting seed germination due to oxygen starvation, providing that the pore volume was less than 70% occupied with liquid.

K e y w o r d s: ODR, PEG solutions, water/sand/air mixtures

INTRODUCTION

High molecular weight polyethylene glycol (PEG) is commonly used in aqueous solution as an experimental means of applying water stress to plants. Polymer molecules are unable to penetrate plant cell membranes, and such solutions thus behave as an inert osmoticum [4]. Commercially, PEG finds use in horticulture as a seed primer, capable of increasing the germination rate of dormant seeds, over and above levels achieved through priming in water alone [3,7]. Recent experiments have utilised PEG 20000 solutions mixed with sand as a medium in which to germinate and grow seedlings under controlled levels of water stress [8].

Despite its apparent inertness to plant cells, PEG has been associated with adverse effects on growing plants, not attributable to osmosis alone, and these have variously been ascribed to the presence of trace contaminants arising in PEG manufacture [5], to the high viscosity of PEG solutions inhibiting rates of water flow through roots [1], or to a possible incidental reduction in the rate at which oxygen reaches plants by diffusion through the growth medium when water is replaced by a PEG solution [9]. This last possibility formed the basis of our study.

Experiments were carried out in PEG solution, in PEG solution/sand/air mixtures and comparable water/sand/air mixtures, with the aim of assessing the oxygen diffusion rates (ODR) in such mixtures. The intention was to measure the ODR in a simple, well defined and reproducible soil analogue over a wide range of liquid saturation with either water or a specified PEG solution. Results were compared with limiting ODR values for successful plant emergence, taken from the literature [2]. It was found that the compromised aeration of PEG solutions used as hydroponic growth media could be ameliorated by distribution of the PEG solution in an aerated sand matrix.

MATERIALS AND METHODS

ODR was measured in all tests by means of a Pt wire cathode, 5 mm long x 0.5 mm diameter, mounted to project from the end of an

epoxy-resin-filled thin-walled steel tube, inserted into the medium under test and biased negatively with respect to a calomel electrode in contact with the surface of the medium. A suitable bias voltage was determined in each case by prior voltage/current scan, and in near-saturated media, the bias voltage was selected to lie on the characteristic current plateau at a value of -650 mV. In unsaturated media, voltage/current scans revealed the absence of a current plateau in the range 0 to -1100 mV, and the bias voltage was arbitrarily standardised at -650 mV. ODR was measured using the technique of Lemon and Erickson [6] as refined by Rankin and Sumner [10]. The very small current flow, reflecting the ODR, was measured by passing the current through a 200 Ω series resistor, and monitoring the resultant voltage drop with a DL3000 data logger (Delta-T Devices Ltd., Burwell, Cambridge, England) operating in differential voltage mode.

Prior to each measurement of ODR, the Pt cathode was lightly abraded with grade 00 emery paper and rinsed in distilled water in order to remove surface contaminants which are known to influence ODR measurements in soils [2]. Measured ODR values typically vary with elapsed time after voltage switch-on. According to boundary conditions, a quasi-steady state may be reached, in which the rate of oxygen removal at the cathode surface is matched by the rate of oxygen diffusion to it [6]. It is common practice to allow a short time to elapse after voltage switch-on prior to ODR measurement, typically 3-4 min. In the majority of our tests, ODR was measured for at least 20 min after switch-on, and the rate of change of ODR with time was often seen to be still appreciable at 3-4 min. For this reason, it was decided to compare ODR values 12 min after application of the voltage, at which point readings were more stable.

Tests on liquids

The ODR of unstirred PEG stock solution (0.190 kg PEG 20000 per kg aqueous solution) was compared with that of unstirred distilled water. The liquids were held in 100 ml beakers at 18°C during testing, and the Pt cathode was positioned 25 mm below the liquid surface in each case.

Tests on sand/liquid mixes

A number of liquid/sand/air mixes were prepared, in which the liquid was either PEG stock solution or distilled water. The pore volume of the dry sand was calculated by comparing the bulk density (obtained by weighing a known volume) with the known density of the constituent silica. Liquid was added to the sand in such quantities as to produce mixes with notional pore volume liquid saturations in the range 10% to 90%. For each mix prepared, approximately 600 g of dry sand (Grade 65 dried silica sand from Hepworth Minerals and Chemicals, Stoke-on-Trent, England, particle size distribution (wt% retained): 710 μm, 0.1%; 500 μm, 0.7 %; 355 μm, 7.3 %; 250 μm, 28.3%; 180 μm, 41.5 %; 125 μm, 19.2 %; 90 μm, 2.4 %; 63 μm, 0.4 %; <63 μm, 0.1 %) was stirred for 5 min in a polythene beaker, together with the requisite volume of liquid, using an aluminium rod, followed by kneading for a further 3 min using gloved hands. Samples for ODR testing were tamped gently into a glass beaker (capacity 310 ml) in 20 mm layers until the beaker was filled. The surface of the moist sand was then levelled flush with the top of the beaker. The density was measured in each case by weighing the known volume of moist sand contained in the beaker.

ODR measurements were made on each beaker of moist sand in turn by insertion of the Pt cathode to a depth of 75 mm at the centre of the beaker, and by placement of the tip of the calomel electrode in contact with the surface of the moist sand. The biasing voltage was then applied and the current flow monitored. The temperature of the moist sand during ODR measurement was recorded using a thermistor probe.

In order to assess the characteristic repeatability of the ODR tests, a series of measurements was carried out on six replicate beakers of identical water/sand/air mixture, which facilitated calculation of a standard error for the measurement technique, as shown on the ODR data-points in Fig. 1.

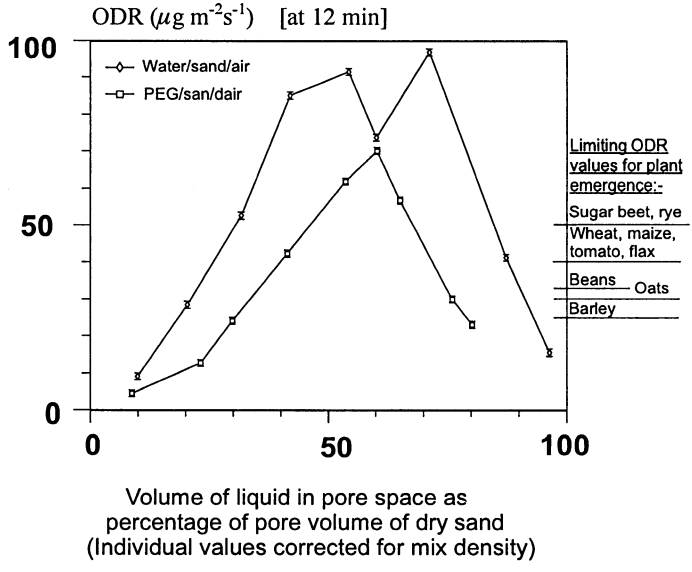

Fig. 1. Graph showing the variation of oxygen diffusion rate with degree of liquid saturation for water/sand/air and PEG/sand/air mixes. The limiting values of ODR for plant emergence are taken from Gliński and Stępniewski [2].

RESULTS

Table 1 shows the results of ODR measurements in unstirred PEG stock solution and distilled water, which demonstrate that the oxygen diffusion rate was virtually halved by the presence of the PEG in solution. Fig. 1 shows ODR plotted against the percentage of pore volume occupied by liquid (as calculated from density measurement of each mixture), for water/sand/air and PEG/sand/air mixtures.

Table 1. Oxygen diffusion rates measured in unstirred liquids at 18°C

	ODR ($\mu g m^{-2} s^{-1}$)
Distilled water	35.0
PEG 20000 Solution	18.1

It can be seen that for most of the mixtures, the ODR of water/sand/air exceeded that of similar PEG/sand/air mixtures by a factor of at least two. Exceptions were those mixtures close to the discontinuities in each set of results, for which the differences in ODR were somewhat smaller.

Also shown in Fig. 1 are specific values of ODR which have been found to limit the successful emergence of a range of cultivated plants [2].

DISCUSSION

The shapes of the traces in Fig. 1 cannot be explained solely in terms of increasing liquid saturation blocking aeration pathways, since at low pore saturations, an apparent increase in ODR was measured with increasing liquid saturation. It is generally acknowledged that this method of measuring ODR in soils is critically dependent on the presence of a continuous liquid film at the active surface of the cathode [6]. Such a film is generally maintained over a wide range of water tensions in heavy soils containing a wide distribution of particle sizes. However, the large size and narrow size distribution of the sand particles used in these tests is unlikely to favour maintenance of a continuous liquid film at the cathode at low moisture contents, and it is thought likely that a variation in the area of cathode in contact with the liquid film is responsible for the effect observed at low saturations in Fig. 1,

invalidating the ODR measurements in this region. In this respect, the choice of sand alone as a growth medium may be ill-advised, carrying with it the possibility of sudden pore drainage over a very narrow range of liquid content. Aeration within such a medium may thus vary greatly and unpredictably for small changes in ambient conditions.

Comparison of valid ODR values (i.e., those to the right of the peaks in Fig. 1) with the reported limiting ODR values for plant emergence shows that, for example, sugar beet or rye emergence would be unaffected in PEG/sand/air mixes with <68% liquid saturation, whereas the emergence in water/sand/air would not be adversely affected up to liquid saturations approaching 84%. Thus although water appears preferable to PEG in promoting adequate root aeration in the liquid phase, [9], we have demonstrated that the reduced diffusivity of oxygen in PEG solution may not be limiting if the PEG is distributed in a well-aerated sand matrix.

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