INTERNATIONAL WORKING GROUP ON SOILLESS CULTURE

SUPPLY OF NUTRIENT IONS TO THE ROOT SURFACE

IN ARTIFICIAL SUBSTRATES

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INTRODUCTION

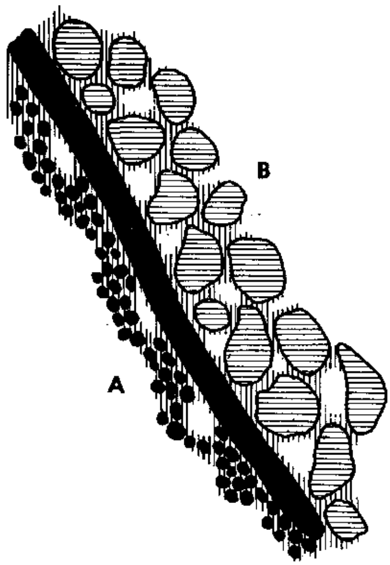
Plant growth is the result of the conversion of carbondioxide, water, ions - and maybe some soluble organic molecules as well - into plant material by means of light energy. All of these four factors may be growth limiting, but for the purpose of this discussion attention will be mainly directed to the adequate supply of ions and the relation of this supply to water movements.
Under general conditions - also in hydroponics - the entrance into the plant of water and minerals is through the root system. It thus seems relevant to have a look at the requirements which have to be met in the substrate to enable a sufficient development of the root system. But even more stress will be laid on the characteristics of the supply to the root surface of sufficient water, ions and oxygen. An understanding of the phenomena and processes involved can contribute to the evaluation of experiences with different substrates and the methods of application of nutrients.

ROOT DEVELOPMENT

To be able to grow roots require space, a supply of water, air and ions, a certain pH and absence of deleterious agents.
As far as soilless culture is performed directly in solution the problem is easy. Any reasonable, balanced nutrient solution is completely adequate and one of the main practical problems is the supply of sufficient oxygen. But forced aeration of the solution - even better when combined with a circulation of the solution at a high speed - meets all requirements (4). A steady replenishment of the water at the root surface removes the exhausted volume and minimizes the thickness of the stagnant water film and thus the resistance to oxygen diffusion.
As soon as an inert substrate is utilized the situation becomes more complex.
In general the coarseness of the material will be such that the diameter of the pores is quite adequate for root growth. And even in very fine substrates - such as sand - the rigidity will be small enough to allow penetration by the roots (8).
The behaviour of and the amount of water in the medium now assumes importance. For continuous growth a regular supply of water at the root surface is needed - if possible at a low or medium pF. This is best achieved by a combination of a system containing a sufficient amount of fine interconnected capillaries and the capacity for reasonable storage (Fig. 1). Only if continuous percolation is used the requirements become less stringent.
Water repellent surfaces or even poor wettability of the material impose severe restrictions on usefullness. Unless continuous waterfilms can exist the mobility of water in the capillaries will be inadequate.
But one of the main factors of importance in regard to root development is the aeration. Oxygen diffusion in water is a very slow process, so that either a continuous refreshment at the root surface by streaming is needed or only a thin film of water between air and root surface.

Unless continuous percolation of a well aerated solution is used, the requirements for oxygen supply can only be met in a system with a well dispersed and interlocked system of coarser capillaries, which will drain at a very low pF (Fig. 1, part B)

Fig. 1 Schematic representation of a root in moist sand or in a substrate of coarse porous particles



A. Moist sand, only in a few places air-filled capillaries near the root surface, most fine capillaries are filled with water.

B. Coarse porous particles, much more larger air-filled voids near the root sursurface; the water contained in the porous particles is also available for the greater part.

THE SUPPLY OF WATER AND IONS

The plant needs a more or less continuous supply of water and minerals for its growth. As this supply passes through the root surface we must consider whether the substrate allows a sufficient rate of replenishment.

The rate of water supply depends on the amount available in the immediate vicinity of the root and on a high mobility of the water in the pore system. The mobility of the water increases in importance as the storage in the immediate vicinity of the root is less. A high available amount is easily achieved by flooding the substrate or by regular percolation. But aeration may impose difficulties. In case of sub-irrigation or longer stagnant periods between flushing the mobility of water in the pores assumes importance. As the pF of the substrate will be kept at a low value - mostly not above 1,5 (ca 31 cm drainage height) - the pores with a diameter less than 100 µm will remain filled with water. As larger pores allow easier movement, and continuity of the water mass is of importance, a high percentage of interlocking pore channels of a diameter between 50 and 100 µm should be favourable.

In considering the supply of ions to the root surface the following processes have to be considered (1, 2). By growing roots come into contact with an amount of ions (interception) but this amount is negligible as far as the major nutrients are concerned. The other two replenishment systems in the water phase are diffusion and convection. If the water phase is immobile the diffusion process must cope with the plant-requirement. Mostly, however, there is a water movement towards the root - activated by transpiration - or an induced flow of solution - flushing or percolating - along the root. This latter process can transport large amounts of ions to the root surface, depending on rate of flow and concentration.

As we are only taking inert substrates into consideration we do not have to take into account an absorbed reserve, which can give additional supply through the process of release and diffusion. The other important consequence is the total absence of buffering.

In many systems of soilless culture the main driving force for water movement is the gradient of water potential towards the roots. In other words: a certain amount of the applied nutrient solution is transported to the root surface.

Now we have to consider a very important problem. Is the supply of nutriant along with the attracted water equivalent to the needs of the plant ? If this were the case the situation at the root surface would be constant: the supply automatically compensating for the absorption by the root. In case this equivalent uptake does not occur we must accept that other nutrient equilibria develop at the root surface than those established in the applied nutrient solution.

To examine certain aspects of the above-mentioned problem experiments were carried out in which a comparison was made of the uptake of plants from nutrient solution in water culture and the uptake by plants from sand, to which the same solution was applied by sub-irrigation. In these experiments differences in transpiration were artificially induced in order to alter the amount of water passing through the root surface (9).

The first phenomenon that can be observed in the culture in aerated and stirred nutrient solution is, that ions and water are not absorbed in the same relative amounts as in the supply. This is illustrated in Table 1.

Table 1 The relative influx rate in relation to concentration in the water culture experiments

Exp.	Concentration, mg/l N	P	K	Ca	Fresh weight in g	Transpiration in ml/plant	N flux	%	P flux	%	K flux	%	Ca flux	%
B2	48	15	140	40	112	3699	252	4.4	87	0.5	63	3.2	134	1.0
A1	83	15	140	90	204	5455	174	5.0	73	0.4	70	3.4	94	3.0
C1	103	15	197	90	211	4924	151	5.0	85	0.4	57	3.5	95	2.7

(Relative influx rate and mineral content: N, P, K, Ca flux and %.)

N is absorbed at a relative high rate (252, 174, 151) and K at relative low rates (63, 70, 57). If the plant contains the same amount of mineral as a volume of nutrient solution, just as large as the transpired amount of water, the relative rate of entry is 100. As the concentration of an ion in the nutrient solution is lowered its relative rate of entry appears to increase. Within this range of variation in concentration plant growth is hardly influenced as long as the supply is superfluous as the result of frequent replenishment (Table 1, Exp. A1 and C1).

A second important phenomenon is the fact that if transpiration varies the relative rates of entrance of the ions also change. Increase in humidity did not impair the growth of the tomato plants; also their intake of ions was practically the same. But transpiration was reduced, resulting in a rise in relative rate of entry. This is illustrated in Table 2. Both types of behaviour observed point to the fact that within this range of concentrations - such as occur in nutrient solutions - uptake of ions and intake of water are largely independent processes (7).

Table 2 The relative influx rate in relation to transpiration in the water culture experiments

Exp.	Concentration mg/l N	P	K	Ca	Air	Transpiration in ml	dry weight g	Relative influx rate N	P	K	Ca
VI	91	12	92	123	dry	1143	1.65	60	90	108	33
					normal	791	1.49	89	145	154	39
					moist	604	1.46	107	157	202	51

The consequences of the two phenomena mentioned above become important as soon as the same nutrient solutions are used for culture by means of sub-irrigation of an inert substrate - pure coarse sand in our experiments.

In a well stirred of circulating nutrient solution in which a worthwhile depletion is prevented, the concentration of an ion at the root surface remains reasonably constant. The potential amount available is far greater than plant demand. But in a system relying on sub-irrigation the only movement of water is that induced by transpiration. The result is that replenishment of ions at the root surface is determined by the amount of transpired water and its ionic content.

The consequence is that when on the nutrient solution the relative uptake is higher than 100 the replenishment in the sand culture will be insufficient. This insufficient supply results in a depletion of the solution in the sand as is evident for N and P contents in Table 3.

Table 3 Mineral content of the nutrient solution in the sand substrate at the end of the experiment

		Contents in mg/l N	P	K	Ca
Original solution		80	48	140	90
Solution in the sand:	in the rooted zone	6	6	270	245
	in the zone devoid of roots	29	-	-	220

Reducing transpiration will aggravate the condition. If the relative rate of entry is smaller than 100 the amount of transpired water will bring more ions to the root surface than the plant is able to absorb. In this case we may expect a rise in concentration around the root, which condition could be experimentally detected for K and Ca (Table 3). Besides the supply by convection in the sub-irrigated inert substrate an additional supply by means of diffusion will be induced if the concentration of ions at the root surface is lowered. But this mode of supply is only restricted and can never be more than the original volume of solution in the inert substrate its concentration. With large plants being cultured it may become more or less negligible. In sub-irrigated culture uptake by the plants should thus be less or at the best equal to the amount of ion occurring in the volume of transpired water + the volume in the substrate. The volume of solution in the substrate is permeated by the roots and can thus be fully utilized, while the transpired amount of water carries its nutrients to the root surface. The results given in Table 4 demonstrate this fact for N and K.

Table 4 Relative influx rates (I) and utilization of total supply [x)] (II) in sand and solution cultures

Exp.		Concentration mg/l			Weight	Transp. in ml	N		P		K	
		N	P	K			I	II	I	II	I	II
B2	sol.	48	15	140	112 g fresh	3699	252	61	87	21	63	15
	sand	48	15	140	8 g fresh	547	173	104	36	22	46	27
IV	sol.	91	12	92	2.62 g dry	1260	95	11	157	18	208	24
	sand	91	12	92	2.89 g dry	1244	97	76	114	89	135	105

x) Total supply = amount of ion contained in the volume of water transpired + the volume of water contained in the sand (rooted zone).

With this knowledge in mind we may have a look at the formulations for the nutrient solutions in use in hydroponics (3, 5, 6) and compare them with uptake by the plant. Nitrogen in solutions is apt to range between 100 and 400 ppm, phosphorus usually between 40 and 100 ppm, potassium between 100 and 300 ppm and calcium from 100 to 500 ppm. If the relative rates of entry were always to be 100 the solutions should contain something like N 150 - 330 ppm, P about 100 ppm, K 100 - 220 ppm and Ca 80 - 150 ppm. These figures can be calculated from data published in the IWOSC Proceedings (3). It is interesting to note that the requirements in general fall within the range used. On account of its poor solubility phosphorus is mostly applied in too low a concentration, while calcium is usually apt to be in excess.
The constitution of a nutrient solution is, however, also dictated by the requirements of certain ionic equilibria, such as K : Ca ratio, etc. Also one must realize that for every plant - with its specific requirements - and for every variation in transpiration an adapted formulation would be needed. This latter adaptation is already being practiced: using more diluted solutions in summer, when transpiration is much higher (3).

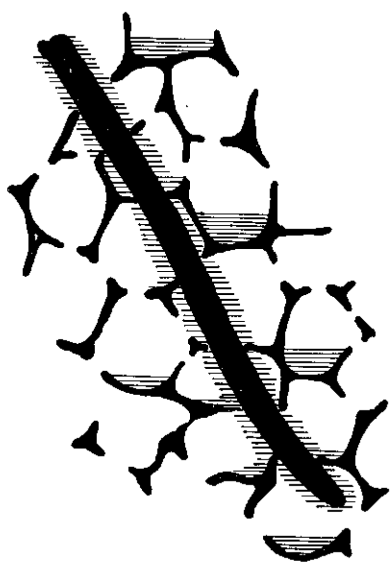
The conclusion from these considerations is that as calcium is apt to be in excess and could concentrate in the root zone the often already marginal supply of phosphate could be further endangered by formation of insoluble phosphates. To some extent these kinds of troubles have been encountered in practice.

EVALUATION OF SUBSTRATES

In case we have to do with solid substrates particle size will be the most important factor. Larger particles will make root penetration easy on account of the big pores, but water retention will be small and capillary rise is also apt to be restricted. If the particles become too fine (smaller than about 0.3 mm) the water retaining capacity will be high, but air content will mostly be too low for sufficient aeration. Experience in practice has already shown that intermediate particle size is to be preferred. Although in this case the substrate may contain a fair amount of air, Steiner has demonstrated that aeration in the smaller waterfilled capillaries is insufficient (Fig. 1). Thus regular flushing of the substrate with well aerated solution may be advisable. Quite often porous particles are used. Usually mineral particles have been used, mostly with sizes of 2 mm or larger. As far as rooting is concerned the larger pores in between the particles allow for easy penetration by roots. In many cases the porous particles themselves have pores too small for the growth of many roots. The advantage of these substrates is their generally large water-retaining capacity along with good aeration. But, depending on the amount of surface in contact from one particle to another the ease of water movement - such as necessary for fast capillary rise - may be small. Thus too large particles are apt to be less satisfactory (Fig. 1).
In supplying the nutrient solution to the substrate essentially two distinct methods are in use.
In one method there is a more or less continuous supply of solution at the bottom and the flow of water + minerals into the substrate is by capillary rise. Except for the occurrence of salt accumulation of the freely evaporating surface of the substrate the method has other drawbacks. As already discussed it is impossible to formulate a nutrient solution in which all constituents are absorbed in rates equivalent to their concentration. Thus in course of time the conditions at the root surface will change and ionic balance will alter. Other ions may be insufficiently supplied. No wonder that experience has shown that regular flushing of the substrate or supply by regular percolation is to be preferred. The more the necessity exists to achieve a standardized and well-defined ionic concentration and balance at the root surface, the more frequent or intense flushing and percolation should be. If this is indeed considered to be necessary then the water-retaining capacity of the porous substrates becomes of lesser value.
Nowadays the foam plastics have provided us with a new type of substrate: light in weight, free from disease and easy to handle. It can be used in large pieces or in shredded form.
In using large blocs of foam plastics the penetrability by the roots will first have to be considered. Some experience with poly-ester foams with open pores has taught us that root growth in this medium encounters no difficulties. Both pore size is large enough to allow the young root to grow and elasticity of the material adds to ease of penetration. In general there is not much indication that these foam substrates contain materials toxic to root growth.

The next thing to look at will be the water-retaining capacity of these foam plastics. Although in many cases 95 % of their volume can be filled with water the material will easily lose most of its water even at suctions below pF 1 (-10 cm). In these drained substrates a certain amount of water remains, usually a few percent. This remaining water, however, can be considered as nearly completely immobile. The pore system of these foams consists of single small isolated droplets and does not form a continuum (Fig. 2). So it is of no use to the plant unless the roots happen to touch these droplets.

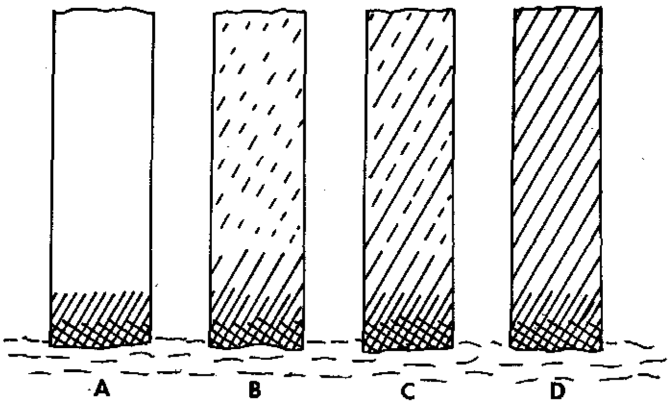
<u>Fig. 2 Schematic drawing of the root in foam plastic in a well drained situation</u>



The greater part of the retained water occurs in isolated droplets and is highly immobile; root aeration is very good.

The situation is that in these poly-ester foam plastics we get a moist layer of substrate with some immobile water in a highly dispersed state and then suddenly we have a layer a few cm high above the water table which is nearly completely water saturated (Fig. 3). Roots are then apt to concentrate in the boundary region between dry and moist.
The general large immobility of the water above the saturated zone makes these substrates rather unsuitable for the practice of sub-irrigation. They should do much better under a system of percolation, applying the nutrient solution from above at frequent intervals. It is only then that the required conditions can be maintained at the root surfaces. But even then in some cases a homogeneously dispersed percolation may be difficult to achieve.

Fig. 3 The mode of occurrence of capillary water in different substrates



A. Large pores and complete drainage till near the water table, only a small saturated fringe and little capillary rise.

B. A scattering of isolated droplets in the drained substrate without contact with the water table and a small saturated zone + mixed air-water layers.

C. Improved conditions, capillary rise still restricted.

D. A continuous system of water-filled pores interspersed with air above the water saturated capillary fringe.

Used in shredded form the material will behave in the same manner, and probably worse.
Last of all we may consider the continuous substrates made of mineral fibre felts. Their basic structure has more resemblance to that of soil or sand. But again their range in pore diameter is apt to be less than in soil or sand. This again has the effect that in general above a certain - usually rather low pF - they will only retain small amounts of water. But the advantage is that within the moist substrate at a low pF the water phase is highly mobile.
Used in sub-irrigation, however, the boundary between the aerated layers and the more or less water-saturated layers may be rather distinct. As in the water-saturated layer sufficient aeration is difficult to achieve this may be a drawback. In applying the nutrient solution by means of sub-irrigation over long periods of time the problem of maintaining the required equilibria and concentrations at the root surface again arises. So we may conclude that percolating these substrates with nutrient solution from above is apt to achieve the best control of supply of nutrient and water.
As regards rooting these fibre-wool materials do not impose worth-while restrictions, although as a result of anisotropy rooting in one direction may be easier than rooting perpendicular to the main fibre direction.

SUMMARY

As it is impossible to achieve a nutrient solution from which water and ions are absorbed in the same ratio as they are administered, the solution at the root surface will gradually change in time. As inert substrates do not have buffering capacity the maintenance of required conditions will often necessitate flushing or regular percolation.
The dispersal of water in the well-aerated layers may be such that its mobility is restricted. This may again be a factor implying the advantage of using a percolation technique to achieve regular supply. Pore space, and in some cases plasticity in general allows easy root penetration.

LITERATURE

1. Barber, S.A. (1962)
A diffusion and mass-flow concept of soil nutrient availability.
Soil Sci. 93, 39-49.

2. Barley, K.P. (1970)
The configuration of the root system in relation to nutrient uptake.
Advan. Agron. 22, 159-201.

3. IWOSC (1971)
Proceedings World Congress on Hydroponics, Las Palmas de Gran Canaria, 1969.
IWOSC, Wageningen.

4. Steiner, A.A. (1965)
A new method of growing plants in water culture.
Acta Bot. Neerl. 14, 400-402.

5. Steiner, A.A. (1968)
Recipe for a universal nutrient solution.
Gestencild Versl. 35, Centr. Plantenfysiol. Onderz., Wageningen.

6. Steiner, A.A. (1971)
The preparation of nutrient solutions, free from a precipitation of $CaSO_4$ and $CaHPO_4$.
Gestencild Versl. 52, Centr. Plantenfysiol. Onderz., Wageningen.

7. Tinker, P.B. (1969)
The transport of ions in the soil around plant roots.
In: Rorison, I.H. (Ed.), Ecological aspects of the mineral nutrition of plants. Oxford/Edinburgh, pp. 135-147.

8. Wiersum, L.K. (1957)
The relationship of the size and structural rigidity of pores to their penetration by roots.
Plant and Soil 9, 75-85.

9. Wiersum, L.K. (in press)
Some experiments on the supply of ions to the absorbing root surface.

QUESTIONS AND REMARKS

Question from Mr S. Attar, Kuwait

What is the effect and function of active absorption and mass flow on the uptake of ions ?

Answer

Active absorption occurs in the stage of transport where the ions are moved from the root surface into the interior of cell or tissue. It is a process requiring metabolic energy and demonstrates selectivity.
The concept of mass flow is most often used in relation to the movement of ions in the soil to reach the root surface.
As nutrients in the substrate may be a limiting factor the replenishment at the root surface can be a more important factor than the potential for active intake.
Mass flow is the process of transport of ions along with the water in which they are solved.
The two processes act in succession.
The influence of water transport on ion transport inside the plant is left out of this discussion.