SAND AND WATER CULTURE METHODS used in the study of PLANT NUTRITION

by

E. J. Hewitt

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FOREWORD

By SIR EDWARD SALISBURY, C.B.E.,
Vice-President and Secretary of the Royal Society,
Director of the Royal Botanic Gardens, Kew.

The methods of sand and water culture originated in pure scientific enquiry more than a century ago and they have proved of the greatest value in the hands of the plant physiologist in assessing nutritional requirements and the role of various ions. These methods have enabled us to establish the fact that plants can be grown successfully, generation after generation, in solutions of pure chemicals and thus dispose of the claim that organic constituents are essential to the nutrition of the green plant, however beneficial these may be for practical culture. The technique has enabled us to study the nutritive requirements of the plant in an effective manner that would have been frankly impossible had the complex medium that we term soil proved essential to efficient culture. This technique that has proved so valuable a tool in the pursuit of fundamental knowledge has also provided a practical means of culture that avoids the sources of infection that a soil may and often does provide.

The discovery of the significance of the micronutrients, however, at once gave added importance to these methods and called for a great improvement of techniques alike with respect to the receptacles employed, the chemicals from which the culture solutions were made and the sand when such is employed.

Dr. Hewitt in this survey has given us a valuable summary of the techniques involved, of their difficulties and how they can be met or avoided. Dr. Hewitt brings to his task the result of his own investigations at Long Ashton in the refinement of methods for the study of deficiencies. He calls attention to his experience that the purest chemicals available commercially are normally contaminated with minute traces of the micronutrients that render them unsuited, without further purification, to the needs of critical experiments where such micronutrients are the object of study. The results of the author's experience in providing remedial methods should be of great value to all who carry out investigations of this character.

Dr. Hewitt has, in fact, provided us here with a compendium of information on this subject. Just because there is much more to be learnt on these topics and a wide field of experimentation yet to be explored this compilation of the state of present-day knowledge is the more valuable and it should find a wide welcome amongst pure scientists, agriculturists and practical horticulturists and indeed all who are concerned in the culture of plants or theoretical aspects concerned therewith.

CONTENTS

PART ONE

GENERAL REVIEW

	Page
Objects, scope and definitions	1
Historical	2
Plant containers	4
Drainage	4
Undrained containers	4
Drained containers	5
Capacity	5
Sand culture	6
Water culture	14
Relation to solation renewal and aeration	14
Shape of containers	14
Covers for containers	15
Exclusion of light and heat	15
Exclusion of dust	15
Support of culture plants	16
Composition of covers	17
Composition of containers	17
Metal	17
Cement	18
Wood and paper	19
Plastic	19
Unglazed clay	19
Glazed clay	20
Glass	22
Cleaning containers	23
Multiple compartment containers and "Split root" methods	24
Solid rooting media	26
Particle size of sand	26
Mechanical analysis	26
Choice of particle size	27
Chemical analysis and purity of sand	29
Macronutrients	29
Micronutrients	29
Relation to grading	30
Toxic constituents	30
Sand purification	30
Use of unpurified sand	30
Methods and results using purified sand	30
Mixed solid media	32
Base exchange materials	34
Zeolites and synthetic resins	36
Colloidal clays	38
Other materials	40
Solid nutrient compounds	40
Water	42
Sources of water	42
Rain water	42
Composition	42
Storage	46
Consumption	48
Use	48
Tap water	48
Distilled water	50
Metal stills	50
Non-metal stills	52
Demineralised water	57
Activated carbon	62
Nutrient impurities and purification methods	64
Impurities in nutrient salts and raw materials	64
Phosphates	64
Potassium salts	65
Nitrates	65
Other salts	65
Iron and heavy metal salts	66
Experiments using unpurified salts	66
Tests of nutrient purity	68
Conclusions	69
Methods of purifying nutrient reagents	69
Recrystallisation	70
Distillation methods and extraction of solid reagents	71
Carbon adsorption techniques	72
Phosphate, alkaline earth and related adsorption methods	73
Co-precipitation with organic reagents or sulphides	78
Extraction with immiscible solvents	80
After chelation	80
With ether-hydrochloric acid	81
Other methods of purification	81
Summary of recommended methods	82
Composition of the nutrient solution	83
Terminology	83
Specimen solutions	84
Osmotic pressure, salt concentration and sodium content of nutrient solutions	89

	Page
Osmotic pressure	89
Salt tolerance	91
Sodium content	92
Source of nitrogen in nutrient solutions	93
Nitrate and ammonium nitrate	93
Relation to pH	93
Solution renewal	94
Season	94
Aeration and micronutrient supply	94
Nutrient uptake	95
Iron requirements	95
Relative tolerance and effect on growth	95
Other sources of nitrogen in culture solutions	97
Influence and control of pH of the nutrient solution	98
Influence of pH	98
Production of specified pH values	99
pH stability	100
Control of nutrient pH	101
Supply and utilization of iron in nutrient solutions	102
Solid iron compounds	102
Inorganic salts	103
Organic compounds	105
Other sources	108
Micronutrients supplied in nutrient solutions	108
Micronutrient supplements	108
Micronutrient requirements	110
Threshold and toxicity levels for micronutrients	111
Sources of micronutrients	114
Organic supplements for inorganic nutrient solutions	115
Use of radioactive isotopes in culture experiments	116
Methods for the renewal and application of culture solutions	117
Intermittently renewed solutions	117
Leaching	118
Re-use of nutrient solutions	119
Alternating solutions	119
Continuous renewal of solution	119
Methods	120
Mariotte's bottle	120
Constant level cultures	122
Wick cultures	122
Atomised culture solutions	122
Tensiometers and methods based on water loss	122
Distribution of solution	124
Metering pumps and other equipment	127
Solution renewal in relation to aeration	127
Irrigation techniques specially adapted for sand cultures	129
Aeration of culture solutions and study of root atmosphere	131
Importance of aeration	131
Methods of aeration	133
Sealed cultures for study of root atmosphere	137
Absorption of nutrients from culture media	138
Tree cultures and large-scale techniques	141
Tree cultures	141
Large-scale installations	143
Seed sterilisation, sterile cultures, pest control and the raising of culture plants	147
Seed sterilisation	147
Sterile cultures for whole plants	149
Associated growth cultures	150
Pest control measures	150
Methods of germination of seeds and raising of culture plants	151
Comparative aspects of sand and water cultures and choice of technique	154
Comparative aspects of sand and water cultures	154
Choice of plants for culture experiments	156
Choice and limitations of technique	157
Influence of environment and biological factors on the behaviour of culture plants	159
Influence of environment	159
Light	159
Temperature	160
Humidity	160
Season	161
Controlled environment equipment	161
Large-scale installations	162
Supplementary light	163
Light integrators	163
Influence of biological factors	163
Influence of the seed on growth	163
Legumes	165
Variability of culture plants	165
Design of experiments	165
Arrangement	166
Design	167
Measurement of responses of culture plants	168
Interpretation of data obtained in culture experiments	169

Part Two

THE LONG ASHTON TECHNIQUE FOR LARGE-SCALE POT SAND CULTURES

	Page
Objects and requirements of technique ...	171
Basic materials used	172
Containers	172
The clay pot	172
Glass containers	173
Plastic containers	173
Glazed containers	174
Sand	174
Source and grade	174
Treatment before use	174
Routine use of sand purification equipment	178
Effectiveness of purification	180
Water	180
Collection and storage of rain water ...	180
Consumption in relation to storage capacity	181
Suitability and purification	181
Operation of demineralisation apparatus	182
Reagents for testing water supplies ...	185
Distilled water	186
Metal stills	186
Glass stills	186
Tap water	187
Nutrient reagents	187
Composition and preparation of nutrient solutions	187
Preparation of nutrient solutions for micronutrient deficiency work	191
Purification of stock solutions from iron, manganese, copper and zinc	191
Removal of copper and zinc	191
Purification of stock solutions from boron	191
Purification of stock solutions from molybdenum	192
Co-precipitation with 8-hydroxyquinoline	193
Co-precipitation with copper sulphide	193
Purification of compounds used to supply iron	194
Removal of manganese, copper and zinc	194
Removal of molybdenum...	194
Tentative method for preparation of iron compounds free from manganese, copper, zinc, molybdenum and gallium	194
Purification of manganese compounds ...	195
Removal of iron	195
Removal of molybdenum...	195
Cleaning of glassware	196
Testing nutrient solutions	196
For iron	196
For manganese	196
For copper, zinc, etc.	196
For boron	196
General technique	197
Lay out and treatment code	197
Raising experimental plants	197
Method of planting	198
Treatment of sand at planting time ...	198
Change of treatment	199
Frequency of watering	199
Pest control	199
Choice of crop	200

	Page
Acknowledgments	201
Bibliography and author index	202
Subject index	233

ILLUSTRATIONS

Fig			*Page*
1		Large-scale still for production of copper and zinc-free water	53
2		Constant level pyrex glass stills	56
3	A, B and C	Pyrex glass constant-level stills used at Long Ashton	58-59
4		Demineralisation of tap water	63
5	A—I	Methods for constant rate delivery of nutrient solution	
	A	(i) Early solution renewal apparatus and (ii) multiple distributor	121
	B	Simple constant level device for water culture	121
	C	Constant-renewal, aeration and constant level devices in water culture	123
	D	Constant rate of renewal device in sand culture	133
	E	Control of solution renewal with automatic change of reservoirs	125
	F	Regulating the flow of liquid into a culture vessel by capillary tube	125
	G	Regulating the flow of liquid into a culture vessel by annular valve	125
	H	Control of solution at high rate of delivery	126
	I	Controlled solution renewal for several water cultures	126
5	J	Multiple aerator and devices for circulation of nutrient solution in water cultures ...	128
5	K	Apparatus for absorption tests from nutrient solutions	130
6	A—D	Automatically irrigated sand cultures	
	A	Automatically operated sand culture using air lift	132
	B	Irrigated sand cultures and aerated water cultures	134
	C	Cross section view of irrigated sand cultures using air pressure	136
	D	Automatic flooding of multiple pot aggregate cultures	138
6	E—G	Tree water cultures and large-scale sand cultures	
	E	Growing apple trees in water cultures	142
	F	Shallow beds for use with automatically operated sand cultures	146
	G	Automatically operated deep sand cultures	148
7	A	Original automatic sand washing equipment	176
7	B	Improved " Keebush " sand digester	177
8		Lay-out and flow sheet for use of ion-exchange water purification equipment ...	181

Plates		*Facing*
A	Biological breakdown of waxed lining in clay pot	20
B	Effect of container on production of iron and manganese deficiencies in oat ...	21
C	Boron deficiency in lucerne and effect of container	22
D	Sand purification equipment at Long Ashton	31
E	Constant-level glass stills at Long Ashton	56
F	Effect of water supply on the production of copper deficiency in tomato in sand culture	57
G	Zinc and copper deficiencies in tomato	179
H	Molybdenum deficiency in lettuce	193
I	Molybdenum deficiency in kale	199

TABLES

		Page
Table 1.	Examples of capacities of containers used in sand culture experiments	7
Table 2.	Examples of capacities of containers used in water culture experiments in relation to provision of aeration, storing and change of solution	10
Table 3.	Relation between size of container, yield of cauliflower, depth of sand and moisture content	14
Table 4.	Comparative data for mechanical analysis of sands used in culture experiments ... ...facing	24
Table 5.	Approximate correspondence between particle size and standard sieve apertures	26
Table 6.	Yields of crops grown in two grades of silica sand	28
Table 7.	Mineral impurities in silica sands ... ... 33 and facing	33
Table 8.	Types and exchange capacity of some base-exchange materials	35
Table 9.	Miscellaneous data on mineral content of rain water, excluding chlorine, nitrogen and sulphur	44
Table 10.	Analyses of rain water obtained at Long Ashton...	45
Table 11.	Summary of concentrations of nutrient elements found in rain water at Long Ashton ...	46
Table 12.	Concentrations of zinc causing injury to culture plants	46
Table 13.	Analytical data for tap water samples used in culture experiments	49
Table 14.	Effect of demineralisation on removal of ions from rain water and tap water at Long Ashton	60
Table 15.	Examples of relative efficiency of removal of certain ions from water by demineralisation ...	61
Table 16.	Steinberg's data on effect of nutrient purification on yields of *A. niger* or *Lemna* after omission of various micronutrients	77
Table 17.	Residual concentrations of manganese after treatment by various modifications of the phosphate adsorption technique	78
Table 18.	Examples of molybdenum content in culture materials as determined by microbiological assay with *A. niger* ... ... facing	80
Table 19A.	Composition of nutrient solutions selected to show historical development and typical modern examples ... ... facing	96
Table 19B.	Other typical nutrient solutions classified according to macronutrient salt composition facing	96
Table 20.	Use of magnetite in sand cultures	102
Table 21.	Levels of zinc and manganese in some culture solutions	113
Table 22.	Composition of permanent artificial standards for manganese test	154
Table 23.	Concentration of standard stock solutions	

Part I

OBJECTS, SCOPE AND DEFINITIONS

The preparation of this Technical Communication was undertaken at the request of the Commonwealth Bureau of Horticulture and Plantation Crops on the suggestion of Professor T. Wallace, C.B.E.

The objects of writing it were : firstly to review and assess the numerous sand and water culture methods used in the study of plant nutrition, and secondly to give a detailed description of the method in use to date at Long Ashton for growing plants in large-scale pot sand cultures, together with all necessary information on the materials used, their source and manipulation.

The scope of the first part has been restricted to aspects of the subject connected with research methods ; hydroponic methods and problems mainly concerned with commercial horticultural applications are not considered unless they have a special bearing on the subject of this review.

Certain other points are excluded from this communication, namely : detailed historical treatment beyond that necessary to give some perspective to the development of the methods under review ; soil pot cultures unless having a special bearing on some point ; tissue culture methods except when used for growth (or regeneration) of whole plants ; nutrition of micro-organisms except where the methods are of importance in relation to their application, as, for example, to micronutrient deficiency techniques ; description of results of experiments, except to illustrate the efficiency, applicability or interpretation of a method.

Special attention has been given to methods for study of micronutrient deficiency problems, including the selection of appropriate materials, preparation of pure solutions of nutrient reagents, and sources of contamination.

No special need for definitions arises in this work except as regards the use of the terms major or macronutrient element and micronutrient element. These are convenient for the description of essential or beneficial elements in terms of the amounts normally supplied to, or found in apparently healthy plants. The term macronutrient element is applied here to nitrogen, sulphur, phosphorus, calcium, magnesium, potassium and, where relevant, to sodium, since these elements are usually supplied in amounts exceeding one part per million in solution and often at a hundred times this concentration or more. The corresponding term for nutrients normally required in very small amounts has been the subject of some discussion. The question has been given special consideration by Arnon (1948) (1950 b), who proposed the term ***micronutrient element***. This is explicit and quantitative, and avoids the possible wrong emphasis on importance given by the use of the word " minor," or under estimation of the effects of toxic concentrations due to use of the words " trace," " rare," *spuren* or *oligo*-element. The term micronutrient element, briefly referred to as micronutrient, is adopted throughout this work and is applied to the elements manganese, copper, zinc, boron and molybdenum normally required in amounts less than one part per million in solution and often less than one-tenth of this concentration and also to iron, which behaves as a micronutrient and is conveniently treated in this group as regards problems of technique. Elements of indeterminate status in plant nutrition, e.g. aluminium, gallium, silicon, chlorine, cobalt, vanadium and others, are sometimes described by the term potential micronutrient.

HISTORICAL

This historical review is not intended as a reference work on the historical aspects of plant nutrition investigation, but merely as an introduction to the subject as a whole, particularly with regard to the use of culture methods. Further detailed accounts of this aspect may be obtained from the works of Tottingham (1914), Pfeffer (1918), Shive (1940a), Reed (1942). Stiles (1946), and Woodman (1946).

Plant physiology is a relatively recent subject in relation to such other aspects of botany as ecology, taxonomy and anatomy, and dates from the seventeenth century (Reed 1942). Plant nutrition, however, is probably one of the earliest of the many aspects of plant physiology to be studied quantitatively. Van Helmont (1577-1644) made what appears to have been the first quantitative attempt to gain some idea of the origin of the increase of fresh weight of a plant. He grew a weighed willow branch in a weighed amount of soil, the surface of which was protected from dust and supplied only with water, for five years, at the end of which the tree and soil were again weighed. Woodward (1699) made the earliest recorded use of a water culture method without any solid substrate, and grew vetch, potato and mint in water obtained from springs, rivers, conduits, rain and distillation. He concluded that water is merely a carrier of " terrestrial matter." This work was followed 60 years later by experiments by Duhamel du Monceau (1758) who grew oak, almond, chestnut, walnut and beans in cultures with filtered water from the Seine. De Saussure (1804) made the first attempt to use controlled water culture experiments. He grew *Polygonum persicaria* and *Bidens cannabina* in distilled water, and in dilute solutions of various salts. He found that nitrates were necessary in addition to other mineral salts ; that the uptake of solution was not selective against toxic substances ; that the relative amounts of different solutions absorbed varied and that the required amounts of mineral salts can be taken up from a very dilute solution. This work was only extended after an interval of nearly 40 years by Wiegman and Polstorf (see Reed 1942) who concluded that except for the mineral constituents present in the seed, the plant obtained the whole of the rest of its requirements by absorption through the roots. They thus realised that plants can make some development by using the mineral reserves of the seed and were the first to draw attention to the significance of this source of supply. The first elucidation of the essential nature of the macronutrients was attributed by Shive (1940 a) to Sprengel. The importance of iron was recognized by Gris (1844).

Boussingault (*c.* 1851-1856) (cited by Shive 1940 a) was one of the first to use sand culture as a means of study and his work was extended by that of Salm-Horstmar (1849) (1851). The detailed references elsewhere to the latter's experiments are a testimony to his remarkable insight into the problems and scope of culture methods. He grew oats in waxed glass or pure wax containers with sand, quartz or charcoal that had been acid-extracted to remove mineral impurities. He then omitted different elements and produced evidence for the need of nitrogen, phosphorus, sulphur, calcium, potassium, magnesium, silicon, iron and manganese and described visual symptoms of deficiency effects including those of " grey speck " due to lack of manganese. The modern approach to the study of plant nutrition through sand culture methods was thus established at this time. The basis of modern water culture technique rests on the later work of Sachs (1860) carried out at the School of Forestry in Tharandt. Sachs realised that water cultures were in many ways simpler than sand cultures as they avoided the solid phase, and possible associated impurities when search was being made for mineral elements necessary for plant growth. Sachs was the first to use a standardised and relatively simple type of nutrient solution which contained all those elements considered at that time to be essential, namely nitrogen, phosphorus, sulphur, potassium, calcium, magnesium and iron. The solution was prepared from two stock mixtures, one of which contained no phosphates. Manganese sulphate was also included. Sachs also introduced the procedures of changing the solution at intervals, of limiting the plant density according to size and he tried the effects of using ammonium compounds.

The work of Sachs was actually published simultaneously with that of Knop (1860) who paid attention to standardising the methods of producing seedling material by the now widely used method of germination on muslin. Knop (1861) (1865) made further experiments

on variation in composition and introduced further improvements in the nutrient solution, which was simpler than that used by Sachs and based on molar ratios. Knop (1865) published a nutrient solution which was widely used until recently. The importance of changing the nutrient solution was further emphasised by Knop and by Wolf (1866). Mazé (1900) examined the use of ammonium compounds as a source of nitrogen for maize and showed the value of adding calcium carbonate to the cultures.

A systematic, quantitative study with wheat of the effects of nutrient composition, osmotic pressure and concentration was made in classical experiments by Tottingham (1914). In this work a solution which comprised only four principal salts and an iron compound was developed from the study of fresh weight production in eighty-four nutrient combinations and in Knop's standard solution. Tottingham based the nutrient variations on the molar fractions of the four salts that contributed one-tenth increments in total osmotic pressure for three values of osmotic pressure corresponding to 0·05, 2·50, and 8·15 atmospheres. The results were represented with the aid of triangular diagrams introduced to plant physiology by Schreiner and Skinner (1910). The use of molar fractions was not entirely new but was emphasised more than hitherto. Great attention was also paid to the avoidance of precipitation in the culture solution and to establishing the optimum total concentration of salts at about 0·6% or less. This work was extended by Shive (1915 a, b) who further simplified the basal nutrient solution to three principal salts, and this type of " three salt " nutrient solution has been widely used up to the present. The salts used were calcium nitrate, potassium dihydrogen phosphate and magnesium sulphate. Sodium compounds were thus eliminated and an important limitation not explicitly realised then was that the ions—calcium and nitrate, or potassium and phosphate—could not be varied independently. The technique used was similar to that of Tottingham (1914), but the " best " solution, which was superior to Tottingham's " best," had a lower concentration and an osmotic pressure of 1·75 atmospheres. Shive paid considerable attention to methods for raising uniform seedlings and used rotating tables to reduce unevenness in the environmental factors. The development of three-salt type nutrients was completed by Livingstone and Tottingham (1918) who drew attention to the fact that six combinations of the pairs of ions present in the Shive three-salt nutrient were possible.

The development of nutrient solution types was based, as outlined here, on the supply of essential elements in suitable concentrations and ratios, and the use of the simplest formula consistent with satisfactory results. In addition to the classical formula evolved by Shive, other early types of importance and still in general use include those of van der Crone (1904), Hoagland (1919) and the Rothamsted solution. In Crone's solution solid nutrients including ferrous phosphate were added and it is frequently a satisfactory nutrient for avoiding the accidental development of iron deficiency chlorosis prevalent in water culture experiments. Hoagland's (1919) solution was designed to reflect as closely as possible the proportions of nutrient elements in soil solution. The nutrient solution developed more recently by Arnon and Hoagland (1940) was intended to present the nutrient elements in the approximate proportions in which they were found to be absorbed by the (tomato) plant.

The importance of allowing access of air to roots was recognised by Hall *et al.* (1914 a, b) and methods for the continuous renewal of the culture solution probably date from the work of Nobbe (1868) and Schloessing (1899).

The indication that the early type standard nutrient solutions devised by Sachs and others were able to maintain normal growth and development did not prevent the search for other possible nutrient elements required in smaller quantities, and from that time historical events of importance were mainly in connection with developments of this nature and the improvements in technique that were needed for such work. The first micronutrients in addition to iron, for which evidence of essentiality was obtained for fungi or higher plants, were manganese, studied by Salm Horstmar (1851), Raulin (1863), Bertrand and Javillier (1911), (1912 a, b), McHargue (1922) ; zinc shown by Javillier (1907), Mazé (1914), Steinberg (1919), Sommer and Lipman (1926) ; and boron shown by Aghulon (1910), Mazé (1915) (1919), and Warington (1923), who produced convincing proof of the essential nature of this element.

Although Bertrand and Javillier developed special procedures for the purification of nutrient salts and recognised the importance of using appropriate glassware, the most important advance was that made by Steinberg (1919) *et seq.* who introduced an efficient routine procedure for the elimination of certain heavy metals, especially zinc, from culture solutions.

The more difficult proof of the essential nature of copper was achieved independently (and with different degrees of success) by Sommer (1931) and by Lipman and MacKinney (1931). Molybdenum was added to the list for bacteria by Bortels (1930) and for higher plants by Arnon (1938), and Arnon and Stout (1939 b).

Claims have also been made for the essential or beneficial nature of silicon for cereals by Sommer (1926) and beet by Raleigh (1939) and Wagner (1940); of aluminium by Stoklasa (1922) and by Sommer (1926); of chlorine by Lipman (1938) and of gallium by Steinberg (1938 b) (1941) for *Aspergillus* and *Lemna*. These claims need further substantiation and have not greatly stimulated research up to the present. Steinberg (1945 a) reported inability to repeat earlier results after using up a particular batch of sugar in spite of the application of specific methods to remove gallium. Liebig *et al.* (1943 b) also failed to produce a response to gallium with citrus. Evans (1950) noted a beneficial response to cobalt injected into cacao plants. Trelease and Trelease (1938) showed that selenium stimulated growth in *Astragalus racemosus*.

There may, however, yet be other micronutrients essential for plant growth. Arnon and Stout (1939 a) and Arnon (1948) (1950 a) have specified certain criteria of essentiality, to be applied when seeking proof of the essential nature of a given element. Failure to produce a response after attempts to eliminate a particular element from the nutrient solution must be interpreted in terms of those criteria, not to mean that the element is not essential but in a strictly quantitative sense to mean that the element in question, if essential, is required in amounts less than the limit set by the technique employed.

Arnon's criteria are as follows :

1. The plant must be unable to grow normally or complete its life cycle in the absence of the element.
2. The element must be specific and not replaceable by any other.
3. The element must have a direct influence on the plant and be involved in its metabolism.

Potassium satisfies these criteria, as its function cannot be wholly replaced by sodium. Molybdenum satisfies the criteria for higher plants when nitrate nitrogen is given but possibly may not be required by certain organisms in the presence of ammonium nitrogen and its status needs further evaluation in this respect. The ability of vanadium to replace molybdenum in *Azotobacter* but not so far in other plants introduces the concept that one is essential in the absence of the other and that neither is entirely essential if both are present. Other instances of partial exception to the criteria of essentiality may perhaps be anticipated as techniques improve.

PLANT CONTAINERS

The main points to be discussed here are those of size and shape, composition and inertness, and applicability of containers to sand or water culture, and multiple compartment containers adapted for split root experiments. Details of tanks and beds used in large-scale experiments are also given in the section devoted to these methods.

Drainage

Undrained containers for sand cultures. Sand cultures provide natural aeration of the roots more efficiently than water cultures, mainly because drainage of the solution out of the containers assists air to penetrate the pore space vacated by the liquid. Free drainage is now always implied in the operation of sand cultures and stagnation of the culture solution in sand usually leads to unsatisfactory growth unless handled with considerable care and skill. Most containers used are designed to allow the excess fluid to drain from a basal outlet.

Some work, however, has been published where containers were used without free drainage and excess solution was removed by suction. Thus McCall (1916 a, b), McCall and Richards (1918), Shive (1918 a), Wolkoff (1918) used small undrained vessels holding about 1·5 kg. of sand to grow wheat, buckwheat and soya beans. Their cultures were maintained at 15% moisture by removing excess solution (added through a funnel on the surface) through a tube by suction and by weighing the cultures. Johnston (1920) grew potatoes in undrained sand cultures holding 4·5 kg. sand. The solution was added through a central tube leading to the bottom and excess was removed by suction through another tube to produce a constant weight. Hoagland (1919) grew barley in sand cultures in undrained 5-gallon glazed jars. The solution was introduced through a central 1-litre percolator and excess solution was removed by siphoning under reduced pressure. Reed and Haas (1923 a) grew citrus in large tanks or cylindrical cans. In the first experiment excess solution was removed by suction through a tube leading out of the top of the containers, but in the later experiments natural drainage by gravity was substituted. De Haan and Schoorel (1940) and de Haan (1941) grew tea in pots with a constant water table maintained near the bottom of the pot by the level of solution in a reservoir connected to them. Solution was drained off and replaced at intervals.

Drained containers : *retention of sand.* The great majority of sand culture containers are drained by gravity from a basal outlet. The importance of free drainage has been emphasised by Shive and Robbins (1942). It is necessary to arrange that the sand is retained whilst fluid can escape. A gauze of copper wire was used to retain the sand in clay pots, by Wallace (1921), (1924), (1930), and Davis (1930), for fruit trees, by Beard (1932) for hops, by Hewitt (1944), (1945), (1946 a, b), for several farm and market garden crops, and by Eaton (1931) for large-scale irrigated sand beds. Mitchell (1939) used a monel metal gauze in work with *Pinus strobus*. The use of metal gauze to retain the sand is apparently free from any obvious toxic effects, but is only suitable for experiments with macronutrients and sand not treated with any acid.

Sand is effectively retained by glass wool. This method was used by Blake *et al.* (1937) for apple tree cultures, by Woodman (1939 b) where glass wool was secured by piano wire around a glass tube inserted in the side tubulure and by Meyer (1946). When the drainage exit is a central basal aperture, a watch glass serves to take the weight of the sand off the glass wool. This method was used by Davidson and Shive (1934) for peach tree cultures, by Shive (1938), Hewitt (1947 a, b), (1948 a), Hewitt and Jones (1947), (1949) for vegetables, and by Chapman and Liebig (1938) and by Gauch and Wadleigh (1943) for automatically-operated cultures.

The use of glass wool and a watch glass is particularly useful when acid-treated sand is to be used. For micronutrient deficiency experiments the glass wool and watch glasses can be thoroughly cleaned as described in Part Two. For the most exacting work the watch glass should be placed convex side upwards, but the weight of the sand tends to force the rim of the watch glass against the glass wool and the base of the container and an almost complete seal may occur, especially if the sand is shaken during leaching prior to use. A watch glass only was used by Spencer and Shive (1933), Shive and Robbins (1942), and Robbins (1946).

Eaton (1936) (1941 a) used a porous aluminium silicate tile and gravel to provide free drainage in large sand cultures. Evans (private communication) found that cacao in sand culture was especially sensitive to impeded drainage. It was necessary to accelerate drainage during early growth by a wick leading out of the drainage hole.

Capacity

The capacity of the containers used in sand and water culture experiments varies over a wide range. The choice of size of container is determined partly by cost and ease of manufacture and partly by the fact that changes in nutrient composition occur during growth. These changes are greater for small containers and the degree of precision required in this respect and the problem of eliminating traces of a micronutrient, which become more significant in

a large volume, also influence the size of container most suited to the work. Some plants, e.g. Brassicas and potato, appear to need greater root space. Hoagland and Martin (1923) pointed out that sand and water cultures of the same volume are not comparable. This is because the effective solution capacity of a sand culture may be only 20-30% by volume of the sand. Comparison of equal capacity sand and water cultures is also invalidated because of the difference in freedom of diffusion of nutrient ions and the relative number of collisions between them and root absorbing surfaces; the critical levels of nutrient ions were found by Chapman and Liebig (1940) to differ widely between sand and water cultures.

A summary of examples of container sizes selected in sand and water culture experiments is presented in Tables 1 and 2, where details of crop density, frequency of renewal and inclusion of aeration or stirring are given.

Sand culture. Probably the smallest sand culture vessels on record were those used by Salm-Horstmar (1851). They were made of paraffin wax and measured 6 cm. by 3 cm. and held only 60 g. of sand. Colwell (1943) used 1 lb. cannery tins for standardising the sunflower biological boron test. The capacity of pots used in early work was probably insufficient. The containers used by McCall (1916 a, b), Shive (1918 a) and Wolkoff (1918) for cereals and buckwheat held only 1·5-2·5 kilo and Johnston (1920) attempted to grow potatoes in only 4·5 kilo sand. Wallace (1922) used 6-inch pots holding 2·5 kilo for strawberry plants and 10-inch pots for apple trees. Later 18-20 inch diameter pots were recommended for tree fruits by Wallace (1924) (1930). This size of container is satisfactory for the study of deficiency effects in trees on dwarfing or semi-dwarfing stocks such as Malling IX or II and several experiments have been made on tree fruits grown in 2-3 gallon containers holding 14-20 kilo sand, both with intermittent application and continuous flow of nutrient solution as shown in Table 1. Extensive experiments with vegetables have been carried out by the writer with 10-inch pots. Recent experiments at Long Ashton by E. J. Winter (1949 unpublished)* have shown that the " economic " pot size for a plant such as cauliflower grown with a complete nutrient solution is probably the 12-14 inch size when the nutrient is applied intermittently. Pots smaller than the 10-inch size caused considerable reduction in growth and delayed flowering, whilst the largest (20-inch pots) resulted in wilting during early growth owing to the inadequate moisture in the upper regions of the sand. This is due to the fact that the moisture content of the freely drained sand depends on the depth of sand and its particle size. The data given in Table 3 show that the upper regions of the sand in a large container may be near the wilting point (note especially the values marked (S)) and confirm the observations of Lebedeff (1927). Davidson (1946) drew attention to the importance of this relationship in selection of the size of container and particle size of sand (discussed in the Section on rooting media) and emphasised that deep containers need a finer grade of sand than shallow ones. It was found by Winter,* when the largest pots were emptied that a " pan " or concretion had formed at about the depth (6 inches down) where capillary moisture began to increase. This feature appears to be novel in sand cultures.

It would appear that for sand cultures with intermittent application of nutrients, containers holding not less than 10-14 kilo sand are suitable for many vegetables and those holding 40-100 kilo are satisfactory for single tree and bush fruit cultures. Larger containers (Table 1) were used for holding several plants by Arnon and Hoagland (1940), and in a few experiments on fruit trees containers holding up to 22½ tons of sand were used by Lagasse (1929). It must, however, be remembered always that, where purified sand is to be used to eliminate minute traces of micronutrients, large containers may be a disadvantage. Small cultures holding as little as 0·7 kilo may find special application in short-term experiments involving numerous replications, as for example in the work of Ferres and Trumble (1943), on the availability of nutrients in soils as determined by pot tests with small plants. Cook and Millar (1946) showed that growth of beet in soil cultures was directly related to pot size, but not appreciably affected by plant density.

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* These experiments were made by Mr. E. J. Winter of the National Vegetable Research Station whilst at Long Ashton and use of the data is gratefully acknowledged.

TABLE 1

Examples of Capacities of Containers Used in Sand Culture Experiments.

Reference	Size of Container	Approx. wt. of sand	Plants grown	Remarks
I. *Intermittent Application with Undrained Containers.* (Rate of application daily or less frequently)				
Salm-Horstmar (1851)	6 × 3 cms.	60 g.	Oat 1 per pot	Probably smallest sand cultures on record.
McCall (1916 a, b)	—	1·5 kilo	Wheat 5 per pot	Careful control of watering essential.
Wolkoff (1918)	—	1·5 kilo	Soya bean 3 per pot	,, ,, ,, ,, ,,
Shive (1918 a) (1920 b)	1400 ml.	2·5 kilo	Buckwheat and wheat	,, ,, ,, ,, ,,
Johnston (1920)	—	4·5 kilo	Potato 3 per pot	Probably inadequate rooting space.
Hoagland (1919)	5-gallon	30 kilo	Barley 5 per pot	Adequate root space.
De Haan and Schoorel (1940), de Haan (1941)	27L (6-gal.) cubic glazed pot	42 kilo	Tea 5 per pot	Potassium and other deficiencies.
II. *Freely Drained Containers. Intermittent Application*				
Colwell (1943)	1 lb. cannery tins	0·5 kilo	Sunflower 1 per pot	Biological assay of available boron.
Wallace (1922)	6″ clay pot	2·5 kilo	Strawberry 1 per pot	Deficiency treatments.
Davis *et al.* (1934)	,,	2·5 kilo	,, ,,	,, ,,
Woodman (1940 a, b)	,,	6 kilo	Onion or lettuce 1 per pot	Optimum nutrient levels.
Hewitt and Jones (1947) (1949) (1950) (1951)	5L pyrex beaker or 1-gallon pyrex urn liner	7·5 kilo	*Brassicas* 1 per pot Clovers 5 per pot Cereals 10 per pot	Molybdenum, copper and zinc deficiencies.
Wallace (1922)	10″ clay pot	9·5 kilo	Apple trees (Cox's orange pippin) on broad-leaved Paradise stock	Deficiency treatments.
Hewitt (1944 onwards)	10″ clay pot	9·5 kilo	Wide range of crops: e.g., 10-15 cereal; 3-5 legume; 1-4 beet; 1 tomato; 1 potato or 1 *Brassica* per pot	Deficiency and toxicity treatments and nutrient interrelationships.
Tyner (1935)	2-gallon glazed pot	10 kilo	Maize 3, clovers 20, other cereals, pea, soya bean 10 per pot	Availability of felspar.
Gregory and Crowther (1928)	2-gallon glazed pot	14 kilo	Barley 3 per pot	Solid nutrient reagents used in deficiency experiments.
Gregory and Richards (1929)	2 ,, ,, ,,	14 kilo	,, ,,	,, ,,

[*continued overleaf*

TABLE 1 (*contd.*)

Reference	Size of Container	Approx. wt. of sand	Plants grown	Remarks.
Lineberry and Burkhart (1943)	2-gallon glazed pot	14 kilo	Strawberry 2 per pot	Deficiency experiments.
Davis (1930)	12″ clay pot	14 kilo	Fruit trees 1 per pot	,, ,,
Wallace (1930)	12″ ,, ,,	14 kilo	,, ,, ,,	,, ,,
Hill and Johnston (1940)	12″ ,, ,,	14 kilo	,, ,, ,,	,, ,,
Blake *et al.* (1937)	3-gallon glazed pot	21 kilo	Apple or peach trees 1 per pot	,, ,,
Cullinan *et al.* (1938)	3 ,, ,, ,,	21 kilo	,, ,, ,,	,, ,,
Waltman (1940)	3 ,, ,, ,,	21 kilo	,, ,, ,,	,, ,,
Batjer and Degman (1940)	3 ,, ,, ,,	21 kilo	,, ,, ,,	,, ,,
Woodman (1939 a, b) (1941 b)	3-gallon glazed pot	22 kilo	Lettuce or cabbage 1 per pot	Optimum nutrient levels.
Brown (1945)	4-gallon bins	28 kilo (approx.)	Peach trees 1 per bin	Absorption experiments.
Loustalot *et al.* (1950)	4-gallon jars	,, ,,	Tung seedlings 1-3 per jar	Relation of nutrition to growth, etc.
Roy and Gardner (1946)	8-gallon glazed pot	55 kilo (approx.)	Orange tree 1 per pot	Absorption experiments.
Davis (1930)	18″ clay pot	70 kilo (approx.)	Apple tree 1 per pot	Deficiency treatments.
Wallace (1930)	18″ clay pot	70 kilo (approx.)	Apple tree 1 per pot	,, ,,
Beard (1932)	18″ clay pot	70 kilo (approx.)	Hop 1 per pot	,, ,,
Reed and Haas (1923 a)	Bins 20″ diam. × 26″ deep	200 kilo (approx.)	Citrus tree 1 per pot	Absorption experiments.
Haas (1949)	,, ,, ,, ,,	200 kilo (approx.)	Citrus trees 3 per pot	Potassium nutrition.
Alben *et al.* (1942)	Cylindrical drums, 55 gal.	350 kilo (approx.)	Pecan tree 1 per pot	Deficiency treatments.
Arnon and Grossenbacher (1947)	460 L. (105-gal.) tanks	630 kilo	Tomato 20 per tank	Use of ion exchange materials.
Arnon and Hoagland (1940)	50 cu. feet tanks (312·5 gal.)	2,000 kilo (approx.)	Tomato 20 per tank	Absorption experiments.
Hayward *et al.* (1946)	300 cu. ft. concrete tanks	12 tons (13,000 kilo approx.)	Peach tree 1 per tank	Salt tolerance.
Lagasse (1929)	12 ft. diam. concrete pits	22·5 tons (24,000 kilo)	Peach tree 1 per tank	Nutrient treatments.