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THE WATER-CULTURE METHOD FOR GROWING PLANTS WITHOUT SOIL

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FOREWORD

FOR APPROXIMATELY a quarter of a century, the California Agricultural Experiment Station has conducted investigations of problems of plant nutrition with the use of water-culture technique for growing plants, as one important method of experimentation. The objective has been to gain a better understanding of fundamental factors which govern plant growth, in order to deal more effectively with the many complex questions of soil and plant interrelations arising in the field. Many workers have participated in these investigations. One of them, Dr. W. F. Gericke, conceived the idea some time ago that the water-culture method, hitherto employed only for scientific studies, might be adapted to commercial use, and proceeded to devise special technique for this purpose.

This development was soon given widespread publicity in newspapers, Sunday supplements, and popular journals. The possibility of growing plants in a medium other than soil intrigued many persons, and soon extravagant claims were being made by many of the most ardent proponents of the commercial use of the water-culture method. Furthermore, amateur gardeners sought to make this method a new hobby. Thousands of inquiries came to the University of California for detailed information for general application of the water-culture method to commercial as well as to amateur gardening.

Because of doubts expressed concerning many claims made for the use of the water-culture method as a means of crop production, it became evident that an independent appraisal of this method of growing crops was highly desirable. I therefore requested Professor D. R. Hoagland

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and Dr. D. I. Arnon to conduct certain additional investigations and to prepare a manuscript for a popular circular on the general subject of the growth of plants in water culture.

In view of the complexity of the whole problem of the use of the water-culture method commercially or by amateurs, the Station can make no general recommendations at the present time. Those who wish to experiment with the water-culture method on their own responsibility, however, are entitled to the benefit of such information as is now available from the researches of the Station.

The purpose of this circular is to present that information.

C. B. HUTCHISON, *Director*
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INTRODUCTION

During the past few years, the popular press has given an immense amount of publicity to the subject of commercial or amateur growing of crops in "water culture", that is, growing plants with their roots in a solution containing the mineral nutrients essential for plant growth. The solution takes the place of soil in supplying water and mineral nutrients to the plant. This method of growing plants is also described under such names as "tray agriculture," "tank farming," and the recently coined term, "hydroponics." Frequently, popular accounts of recent experiments on growing plants by the water-culture method leave the reader with the impression that a new discovery has been made which bids fair to revolutionize present methods of crop production, and indeed promises to produce in the future far-reaching social dislocations by dispensing with the soil as a medium for growing many crops.

Wholly unfounded claims have been made by promoters that a new "profession of soilless farming" has been developed, which affords extraordinary opportunities for investment of time and funds. Attempts have been made to convince the public that a short course of training will give preparation for entering this new "profession." The impression has been given also that the water-culture method offers an easy means of raising food for household use.

Some of the popular articles on the water-culture method of crop production are grossly inaccurate in fact and misleading in implication. Widely circulated rumors, claims, and predictions about the water-culture production of crops often have little more to commend them than the author's unrestrained imagination. Erroneous and even fantastic ideas have been conceived that betray a lack of knowledge of elementary principles of plant physiology. For example, there have been statements that in the future most of the food needed by the occupants of a great apartment building may be grown on the roof, and that in large cities "skyscraper" farms may supply huge quantities of fresh fruit and vegetables. One Sunday-supplement article contained an illustration showing a housewife opening a small closet off the kitchen and picking tomatoes from vines growing in water culture with the aid of electric lights. There has even arisen a rumor that the restaurants of a large chain in New York City are growing their vegetables in basements.

Stories of this kind have gained wide currency and have captured the imagination of many persons. Many factors have doubtless contributed to arousing the surprisingly wide interest in the water-culture method of crop production. The psychological effect of current discussion of the wastage of soil resources through soil erosion and depletion has made the public especially receptive to new ideas relating to crop production. Some people have been impressed by the assumed social and economic significance of the water-culture method. Others, moved by the common delight of mankind in growing plants, even though the garden space is reduced to a window sill, have sought directions to enable them to try a novel technique of plant culture. The consequence of the discussion of this method has been the creation of a great public demand for more specific information. Should this newly aroused interest in plant growth lead to a greater diffusion of knowledge of certain general principles of plant physiology, the publicity regarding the water-culture method of crop production might in the long run have a beneficial effect. Growing plants in water culture has been considered by some popular writers as a "marvel of science." The growth of plants is indeed marvelous, but not more so when plants are grown in water culture than when they are grown in soil.

Sometimes two entirely distinct lines of investigation at the California Agricultural Experiment Station, in which the water-culture technique is used, have been confused in popular discussions. One of these concerns methods of growing plants in water culture under natural light, the other the study of special scientific problems of plant growth in controlled chambers artificially illuminated. It is economically impossible at the present time to grow crops commercially solely under artificial illumination, even if there were any reason for doing so. At several other institutions, considerable attention has been devoted to study of the effect of supplementing daylight with artificial light during some seasons of the year, to control the flowering period or to accelerate growth of certain kinds of plants (particularly floral plants) in greenhouses, but this practice has mainly been applied so far to plants developed in soil and has no essential relation to the water-culture method of growing plants.

HISTORICAL SKETCH OF THE DEVELOPMENT OF THE WATER-CULTURE METHOD

Curiously enough, the earliest recorded experiment with water cultures was carried out in search of a so-called "principle of vegetation" in a day when so little was known about the principles of plant nutrition that there was little chance of profitable results from such an experiment. Woodward in 1699 grew spearmint in several kinds of water: rain, river, and conduit water to which he in one case added garden mold. He found that the greatest increase in the weight of the plant took place in the water containing the greatest admixture of soil. His conclusion was

"That earth, and not water, is the matter that constitutes vegetables."

The real development of the technique of water culture took place about three-quarters of a century ago. It came as a logical result of the modern concepts of plant nutrition. By the middle of the nineteenth century, enough of the fundamental facts of plant physiology had been accumulated and properly evaluated to enable the botanists and chemists of that period to correctly assign to the soil the part which it plays in the nutrition of plants. They realized that plants are made of chemical elements obtained from three sources: air, water, and soil; and that the plants grow and increase in size and weight by combining these elements into various plant substances.

Water is, of course, always the main component of growing plants. But the major portion, usually about 90 per cent, of the *dry matter* of most plants is made up of three chemical elements: carbon, oxygen, and hydrogen. Carbon comes from the air, oxygen from the air and from water, and hydrogen from water. In addition to the three elements named above, plants contain other elements, such as nitrogen, phosphorous, potassium, and calcium, which they obtain from the soil. The soil, then, supplies to the plant a large number of chemical elements, but they constitute only a very small portion of the plant. Yet various elements which occur in plants in comparatively small amounts are just as essential to growth as those which compose the bulk of plant tissues.

The publication, in 1840, of Liebig's book on the application of organic chemistry to agriculture and physiology,[3] in which the above views were ably and effectively brought to the attention of plant physiologists and chemists of that period, served as a great stimulus for the undertaking of experimental work in plant nutrition. (Liebig, however, failed to understand the role of soil as a source of nitrogen for plants, and the fixation of atmospheric nitrogen by nodule organisms was not then known.)

Once it was recognized that the function of the soil in the economy of the plant is to furnish certain chemical elements, as well as water, it was but natural to attempt to supply these elements and water independently of soil. The credit for initiating exact experimentation in this field belongs to the French chemist, Jean Boussignault, who is regarded as the founder of modern methods of conducting experiments in vegetation.

Boussignault, who had begun his experiments on plants even before 1840, grew them in insoluble artificial soils: sand, quartz, and sugar charcoal, which he watered with solutions of known composition. His results provided experimental verification for the mineral theory of

[3] Liebig, Justus von. Chemistry in its applications to agriculture and physiology. [English translation.] 401 p. John Wiley and Sons, New York, N. Y. 1861.

plant nutrition as put forward by Liebig, and were at once a demonstration of the feasibility of growing plants in a medium other than a "natural soil." This method of growing plants in artificial insoluble soils was later improved by Salm-Horstmar (1856–1860) and has been used since, with various technical improvements, by numerous investigators throughout the world. In recent years, large-scale techniques have been devised for growing plants for experimental or commercial purposes in beds of sand or other inert solid material.

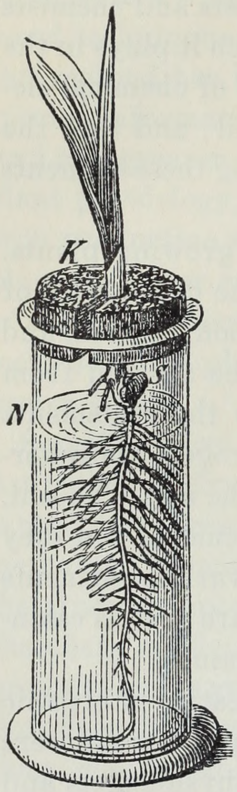

Fig. 1. — Water-culture installation employed by the plant physiologist Sachs in the middle of the last century. (Reproduced from Sachs, *Lectures on the Physiology of Plants*, Clarendon Press, 1887.)

After plants were successfully grown in artificial culture media, it was but one more step to dispense with any solid medium and attempt to grow plants in water to which the chemical elements required by plants were added. This was successfully accomplished in 1860 by Sachs and about the same time by Knop. To quote Sachs directly:

> In the year 1860, I published the results of experiments which demonstrated that land plants are capable of absorbing their nutritive matters out of watery solutions, without the aid of soil, and that it is possible in this way not only to maintain plants alive and growing for a long time, as had long been known, but also to bring about a vigorous increase of their organic substance, and even the production of seed capable of germination.[4]

The original technique developed by Sachs for growing plants in nutrient solutions is still widely used, essentially unaltered. He germinated the seed in well-washed sawdust, until the plants reached a size convenient for transplanting. After carefully removing and washing the seedling, he fastened it into a perforated cork, with the roots dipping into the solution. The complete assembly is shown in figure 1, which is a reproduction of Sachs's illustration.

Since the publication of Sachs's standard solution formula (table 1) for growing plants in water culture, many other formulas have been suggested and widely used with success by many investigators in different countries. Knop, who undertook water-culture experiments at the same time as Sachs, proposed in 1865 a nutrient solution, which became one of the most widely employed in studies of plant nutrition. Other formulas for nutrient solutions have

[4] Sachs, Julius von. Lectures on the physiology of plants. 836 p. Clarendon Press, Oxford. 1887.

been proposed by Tollens in 1882, by Schimper in 1890, by Pfeffer in 1900, by Crone in 1902, by Tottingham in 1914, by Shive in 1915, by Hoagland in 1920, and many others.

At the very inception of the water-culture work, investigators clearly recognized that there can be no one composition of a nutrient solution which is always superior to every other composition, but that within certain ranges of composition and total concentration, fairly wide latitude exists in the nutrient solutions suitable for plant growth. Thus Sachs wrote:

TABLE 1

COMPOSITION OF NUTRIENT SOLUTIONS EMPLOYED BY EARLY INVESTIGATORS*†

Sachs's solution (1860)		Knop's solution (1865)		Pfeffer's solution (1900)		Crone's solution (1902)	
Ingredient	Grams per 1,000 cc H_2O	Ingredient	Grams per 1,000 cc H_2O	Ingredient	Grams per 1,000 cc H_2O	Ingredient	Grams per 1,000 cc H_2O
KNO_3	1.00	$Ca(NO_3)_2$	0.8	$Ca(NO_3)_2$	0.8	KNO_3	1.00
$Ca_3(PO_4)_2$	0.50	KNO_3	0.2	KNO_3	0.2	$Ca_3(PO_4)_2$	0.25
$MgSO_4$	0.50	KH_2PO_4	0.2	$MgSO_4$	0.2	$MgSO_4$	0.25
$CaSO_4$	0.50	$MgSO_4$	0.2	KH_2PO_4	0.2	$CaSO_4$	0.25
NaCl	0.25	$FePO_4$	Trace	KCl	0.2	$FePO_4$	0.25
$FeSO_4$	Trace			$FeCl_3$	Small amount		

* These and other formulas are given in: Miller, E. C. Plant physiology. p. 195-97. McGraw-Hill Book Co., New York, N. Y. 1931.

† For best results, these solutions should be supplemented with boron, manganese, zinc, copper, and molybdenum; see discussion in the text, pp. 35-37.

I mention the quantities (of chemicals) I am accustomed to use generally in water cultures, with the remark, however, that a somewhat wide margin may be permitted with respect to the quantities of the individual salts and the concentration of the whole solution—it does not matter if a little more or less of the one or the other salt is taken—if only the nutritive mixture is kept within certain limits as to quality and quantity, which are established by experience.

Until recently, the water-culture technique was employed exclusively in small-scale, controlled laboratory experiments intended to solve fundamental problems of plant nutrition and physiology. These experiments have led to the determination of the list of chemical elements essential for plant life. They have thus profoundly influenced the practice of soil management and fertilization for purposes of crop production.[5] In recent years, great refinements in water-culture technique have made pos-

[5] However, nutrient solutions such as are employed in water-culture experiments are not applied directly to soils. For discussion of fertilizer problems consult: Hoagland, D. R. Fertilizer problems and analysis of soils in California. California Agr. Exp. Sta. Cir. 317:1–15. Revised 1938.

sible the discovery of several new essential elements. These, although required by plants in exceedingly small amounts, often are of definite practical importance in agricultural practice. The elements derived from the nutrient medium that are now considered to be indispensable for the growth of higher green plants are nitrogen, phosphorous, potassium, sulfur, calcium, magnesium, iron, boron, manganese, copper, and zinc. New evidence suggests that molybdenum may have to be added to the list.[6] Present indications are that further refinments of technique may lead to the discovery of still other elements, essential in minute quantity for growth.

In addition to the list of essential elements, which is obviously of first importance in making artificial culture media for growing plants, a large amount of information has been amassed on the desirable proportions and concentrations of the essential elements, and on such physical and chemical properties of various culture solutions as acidity, alkalinity, and osmotic characteristics. A most important recent development in water-culture technique has been the recognition of the importance for many plants of special aeration of the nutrient solution, to supplement the oxygen supply normally entering the solution when in free contact with the surrounding atmosphere.

The recently publicized use of the water-culture technique for commercial crop production does not rest on any newly discovered principles of plant nutrition other than those discussed above. It involves rather, the application of a large-scale technique, developed on the basis of an understanding of plant nutrition gained in previous investigations conducted on a laboratory scale. The latter have provided knowledge of the composition of suitable culture solutions. Furthermore, methods of controlling the concentration of nutrients and the degree of acidity are, except for modifications imposed by the large scale of operations, similar to those employed in small-scale laboratory experiments.

The selection of a particular type of covering for the tanks adapted to large-scale water-culture operations and of methods for supporting the plants depends on the kind of plant. For example, in growing potatoes by the water-culture method, provision must be made for a suitable bed above the level of the solution, in which tubers can develop. On the other hand, in growing tomatoes, it is only necessary to provide adequate support for the aerial portion of the stem, assuming that the roots are in a favorable culture-solution medium, adequately aerated, and with light excluded; a porous bed may be convenient as a means of facilitating aeration of the solution, as a heat insulator, or as a support for the plant,

[6] Unpublished data of D. I. Arnon and P. R. Stout.

but plays no indispensable role. Aside from such considerations, the choice of a covering is determined largely by expense and convenience, provided the materials used are not toxic to plants.

With any kind of covering for the tanks, an adequate supply of air to the roots must be provided. While the use of a porous bed instead of a perforated cover facilitates aeration of roots, the bed can be dispensed with if provision is made to bubble air through the nutrient solutions

Fig. 2.—The use of the water-culture technique for studying the nutritional responses of lettuce plants under controlled conditions. The individual plants are supported in corks which are placed in holes drilled in the metal covers. The glass and rubber tubes carry air under pressure, which is bubbled through the nutrient solution in the tanks.

(fig. 2). Recent experiments have shown that even with the use of a porous bed, bubbling air through the solution may be advantageous or, under some conditions, indispensable.

As illustrations of some scientific problems of plant nutrition which have been elucidated by the aid of the water-culture method of experimentation, the effects of aeration of the roots on plant growth are shown in plate 1, *A* and the foliage symptoms of deficiencies of mineral elements required in large or minute quantity in plate 1,*B* and plates 2 to 4.

The method of water culture is, as previously indicated, not the only one for growing plants without soil. Several other experiment stations have developed large-scale techniques of sand or gravel culture. These involve the periodic flooding or subirrigation of a solid medium with nutrient solutions similar to those employed in the water-culture method. Some investigators hold the opinion that the sand- or gravel-culture methods have certain advantages in practical use over the water-culture method, particularly in respect to conditions for aeration of the root system.[7]

PRINCIPLES AND APPLICATION OF THE WATER-CULTURE METHOD

The purpose of this circular is to give an account of the water-culture method as a means of supplying mineral nutrients and water to plants. The absorption of nutrient salts and water are only two of the physiological processes of the plant. In order to evaluate the possibilities and limitations of any special technique for growing plants, one has to understand the significance of other interrelated processes, especially photosynthesis, respiration, transpiration, and reproduction.

IMPORTANCE OF CLIMATIC REQUIREMENTS

Many inquiries have been received on the possibility of growing plants in water culture in dimly lighted places, or at low temperatures, under conditions which would prevent growth of plants in soil. Obviously, no nutrient solution can act as a substitute for light and suitable temperature. If there is doubt of the suitability of a particular location or season for the growth of any kind of plant, a preliminary experiment should be made by growing the plant in good garden soil. If the plant fails to make satisfactory development in the soil medium because of unfavorable light or temperature, failure may also be expected under water-culture conditions.

Sunlight and suitable temperatures are essential for green plants, in order that they may carry on one of the fundamental processes of plant growth, known as "photosynthesis." In this process, the element carbon, which forms so large a part of all organic matter, is fixed by plants from the carbon dioxide of the atmosphere. This reaction requires a large amount of energy, which is obtained from sunlight.

[7] Further information on the sand- and gravel-culture methods may be obtained from the following publications:

Withrow, R. B., and J. P. Biebel. Nutrient solution methods of greenhouse crop production. Indiana (Purdue Univ.) Agr. Exp. Sta. Cir. 232:1–16. 1937.

Biekart, H. M., and C. H. Connors. The greenhouse culture of carnations in sand. New Jersey Agr. Exp. Sta. Bul. 588:1–24. 1935.

Shive, J. W., and W. R. Robbins. Methods of growing plants in solution and sand cultures. New Jersey Agr. Exp. Sta. Bul. 636:1–24. 1938.

Eaton, Frank M. Automatically operated sand-culture equipment. Journal of Agricultural Research 53:433–44. 1936.

Chapman, H. D., and George F. Liebig, Jr. Adaptation and use of automatically operated sand-culture equipment. Journal of Agricultural Research 56:73–80. 1938.

Plants depend on photosynthesis for their food, that is, organic substances, such as carbohydrates, fats, and proteins, which provide them with energy and enter into the composition of plant substance. The mineral nutrients absorbed by roots are indispensable for plant growth, but they do not supply energy, and in that sense, cannot be regarded as "plant food." Animal life is also absolutely dependent on the ability of the green plant to fix the energy of sunlight.

TEMPERATURE RELATIONS

An earlier report of a preliminary experiment by other investigators suggested that under greenhouse conditions heating the nutrient solution would produce large increases in the yield of tomatoes.[8] Experiments that we have carried on with tomatoes in a Berkeley greenhouse (unheated except on a few occasions to prevent temperatures from falling below 50–55° Fahrenheit) have now given evidence that under the climatic conditions studied, the beneficial effects of heating the nutrient solution (to 70° F in the fall-winter and to 75° F in the spring-summer period) are not of significance. If favorable air temperatures are maintained, there seems to be no need to heat the solution. Attempts should not be made to guard against frost injury or unfavorable low air temperatures merely by heating the nutrient solution. Proper provision should be made for direct heating of the greenhouse. This may be found desirable even when danger from low temperatures is absent, in order to control humidity and certain plant diseases.

These experiments on tomatoes suggest that if greenhouse temperatures are properly controlled, the solution temperature will take care of itself. Certainly no expense, either in a greenhouse or outdoors, should be incurred for equipment for heating solutions until experimentation has shown that such heating is profitable. There is no one best solution temperature. The physiological effects of the temperature of the solution are interrelated with those of air temperature and of light conditions.

Most amateurs who try the water-culture method will grow plants in warm seasons and probably will not wish to complicate their installation by the addition of heating devices. Anyone who desires to test the influence of heating the culture solution should make comparisons of plants grown under exactly similar conditions, except for the difference of temperature in the solutions.

COMPARISON OF YIELDS BY SOIL AND WATER CULTURE

The impression conveyed by most of the popular discussions of the water-culture method is that much more can be produced on a given

[8] Gericke, W. F., and J. R. Tavernetti. Heating of liquid culture media for tomato production. Agricultural Engineering **17**:141–42, 184. 1936.

surface of nutrient solution than on an equivalent surface of soil, even under the best soil conditions feasible to maintain. Often quoted is the yield of tomato plants grown for a twelve months' period in a greenhouse water-culture experiment in Berkeley.[9] This yield is compared with average yields of tomatoes under ordinary field conditions, and the yield from the water-culture plants is computed to be many times greater. But closer analysis shows that mistaken inferences may be drawn from this comparison. Predictions concerning yields in large-scale production are of doubtful validity when based on yields obtained in small-scale experiments under laboratory control. In any event, there is little profit in comparing an average yield from unstaked tomato plants grown during a limited season under all types of soil and climatic conditions in the field, with yields from staked plants grown in the protection of a greenhouse for a full year. Evidence has long been available that yields of tomatoes grown in a greenhouse, in soil, can far exceed yields obtained in the field. It is true that in one series of outdoor experiments, the yields of tomatoes under water-culture conditions were reported to be much higher than under ordinary field conditions, on a unit-surface basis; but again, the general cultural treatment of the plants (especially with regard to spacing and staking) was so different that comparisons of yield do not mean very much. Furthermore, the equipment for an acre of water-culture plants would be very costly, and technical supervision of the cultures and the labor of staking vines would necessitate large and as yet unpredictable expenditures.

A real test of the relative capacities of soil and water-culture media for crop production requires that the two types of culture be carried on side by side, with similar spacing of plants and with the same cultural treatment otherwise. The soil should be of suitable depth and have its nutrient supplying power and physical condition as favorable for plant growth as possible. We initiated an experiment of this kind in Berkeley late last summer, with the tomato as the test plant. The experiment has now been carried on over a full year, and several of the conclusions derived from it warrant emphasis. The yield of tomatoes grown by the usual tank-culture technique was larger than any heretofore reported as obtained by this method. The yield from the soil-grown plants, however, was not markedly different from that of the plants grown by the tank method (fig. 3). When the greenhouse yields of tomatoes from *either* soil- or solution-grown plants were computed on an acre basis and compared with average yields of field-grown tomatoes, the greenhouse plants

[9] Gericke, W. F., Crop production without soil. Nature 141:536–40. 1938. See also the article cited in footnote 8, p. 11.

gave far greater yields. But as already suggested, such comparisons have no direct practical significance because of the differences of climatic factors, cultural practice, and length of season in the greenhouse and in the open field.

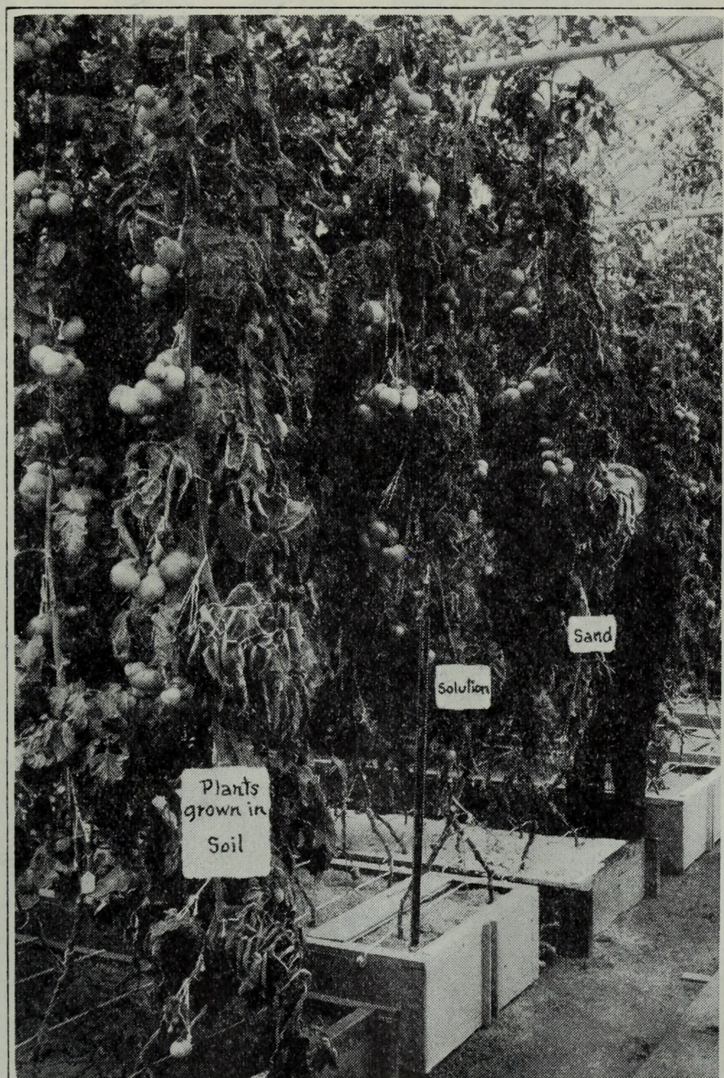

Fig. 3.—Growth of tomato plants in fertile soil, in nutrient solution, and in pure silica sand irrigated each day with nutrient solution. Fruit had been harvested for 7 weeks prior to taking the photograph. All plants have made excellent growth and set large amounts of fruit in all three media. The general cultural conditions—spacing, staking, etc.—were the same.

In one California commercial greenhouse, the yields of tomatoes grown in soil were of the same magnitude as those obtained in a successful commercial greenhouse employing the water-culture procedure, and in another greenhouse using soil the yields were larger.

Recently, data have become available on yield of potatoes grown in a bed of peat soil in Berkeley. This yield was as large as any heretofore reported as produced by the water-culture method.

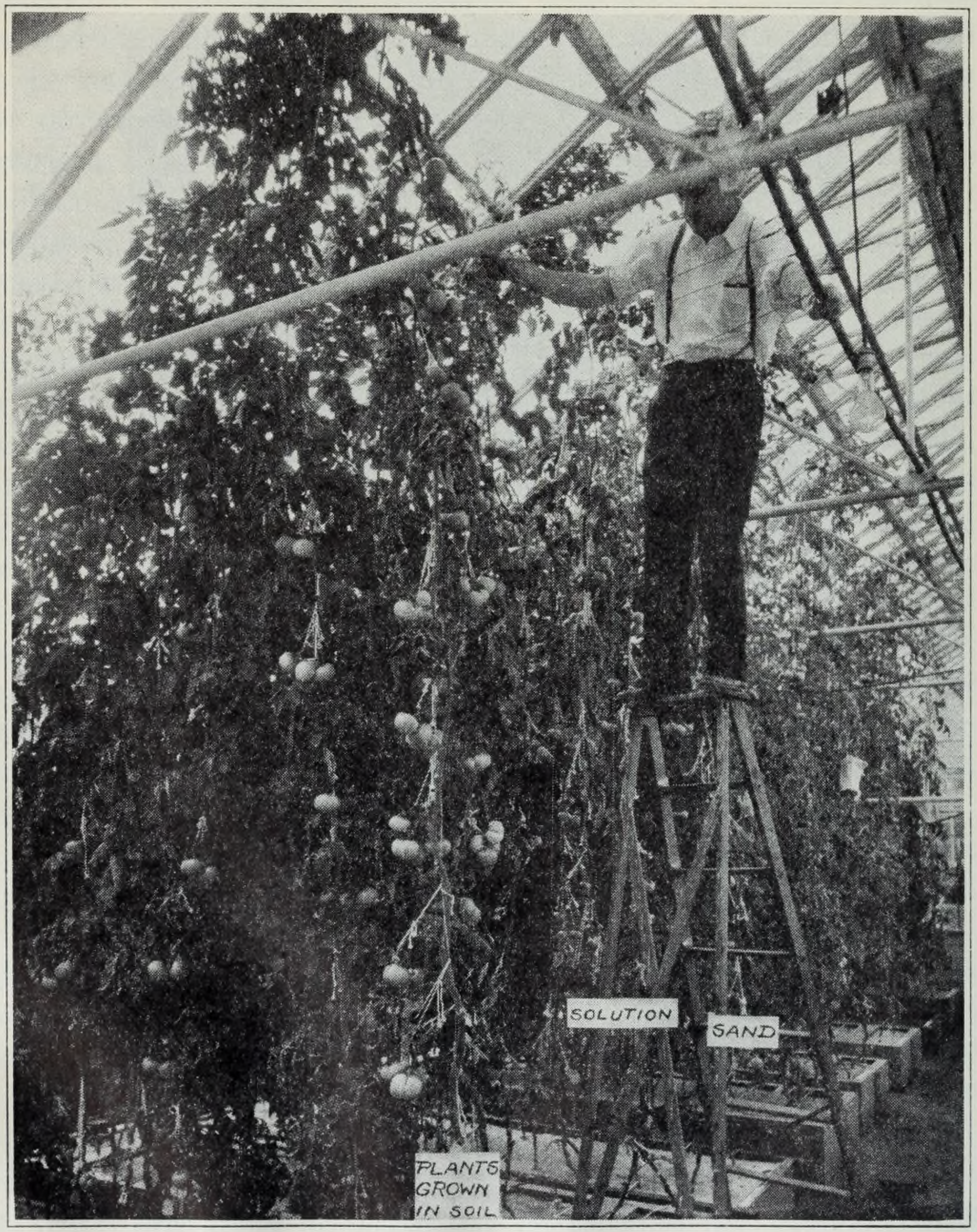

Fig. 4.—Under favorable conditions, tomato plants can grow to a great height and bear fruit over an extended period of time. This is equally possible in soil, sand, and water-culture media. The plants in the foreground were grown in a bed of fertile soil. At the time of taking this photograph, several days before the termination of the experiment, most of the fruit had already been harvested.

The suggestion has sometimes been advanced that plants can be grown more closely spaced in nutrient solutions than in soil, but no convincing evidence of this has been given. In our experiments, we were able to grow tomato plants as close together in the soil as in the solution (fig. 3). The density of stand giving the highest yields would be determined by the adequacy of the light received by the plants when growth is not limited by the supply of nutrients or water derived from either soil or nutrient solution. Closeness of spacing under field conditions is of course limited by practical considerations involving cost of crop production. This consideration of economic factors and of the adequacy of light for plant growth does not justify the view that the water-culture medium is better adapted than soil to growing several different crops simultaneously in the same bed.

Published pictures of tomato plants grown in water culture show impressive height, and this growth in length of vines is frequently the subject of popular comment. As a matter of fact, the ability of tomato vines to extend is characteristic of the plant and not peculiar to the water-culture method. Staked plants grown for a sufficiently long period in a fertile soil, under favorable light and temperature conditions, can also reach a great height and bear fruit at the upper levels (fig. 4). In commercial greenhouse practice, growers usually "top" the vines. Fruit developed at higher levels is likely to be of inferior quality, and relatively expensive to produce because of labor required to attach supports to the vines and the inconvenience of harvesting. Furthermore, it may become profitable to discontinue the tomato harvest when prices become low in the summer and use the greenhouse space to plant another crop for the winter harvest.

There is no magic in the growth of plants in water culture. This is only another way of supplying water and essential mineral elements to the plant. Land plants have become adapted to growing in soils during their evolutionary history, and it is not reasonable to expect some extraordinary increase in their potentialities for growth when an artificial medium is substituted for soil. If no toxic conditions are present and a fully adequate supply of water, mineral salts, and oxygen is provided to the root system, either through an artificial nutrient solution or a soil, then in the absence of plant diseases and pests, the growth of a plant is limited by its inherited constitution and by climatic conditions.

NUTRITIONAL QUALITY OF PLANT PRODUCT

Modern research on vitamins and on the role of mineral elements in animal nutrition has justly aroused great public interest. But unfortunately one of the results is much popular discussion of diets and their influence on health which is without scientific basis. It is, therefore, not unexpected that claims have been advanced that food produced by the water-culture method is superior to that produced by soil.

As part of our investigation, careful studies of chemical composition and general quality have been made on tomatoes of several varieties grown in a fertile soil, and in sand- and water-culture media, side by side in the same greenhouse, and with the same general cultural treatment. No significant difference has been discovered in the mineral content of the fruit developed on plants grown in the several media. (There is no scientific basis for referring to tomatoes grown in water culture as "mineralized.")

Neither could any significant difference be found in content of vitamins (carotene, or provitamin A, and vitamin C). Tomatoes harvested from the soil and water cultures could not be consistently distinguished in a test of flavor and general quality.[10]

Concerning the mineral content of tomatoes, it may further be added, as a point of general interest, that all tomatoes contain but small amounts of calcium and are not an important source of this mineral element in the diet.

The similarity in composition and general quality of the tomatoes grown in soil and water culture in the present experiments, is explained by the fact that the climate and time of harvest were comparable and the supply of mineral nutrients adequate in both cases. Whether plants are grown in soil or water culture, climate and time of harvest are, of course, of greatest importance in influencing quality and composition of plant product.

Claims of unusual nutritional value for food products from certain sources should not be accepted unless supported by results obtained in research institutes of high standing.

PRESENT STATUS OF THE COMMERCIAL WATER-CULTURE METHOD

What is the justification for considering the water-culture method as a means of commercial crop production? The answer to this question is that the method has certain possibilities in the growing of special high-priced crops, particularly out of season in greenhouses in localities where good soil is not available, or when maintenance of highly favorable soil conditions is found too expensive. Soil beds in greenhouses often become infected with disease-producing organisms, or toxic substances may accumulate. Installation of adequate equipment for sterilizing soils and operation of the equipment may require considerable expense. Also, in

[10] The quality tests were conducted by Dr. Margaret Lee Maxwell of the Division of Home Economics, and the carotene determinations were made by Dr. Gordon Mackinney of the Division of Fruit Products, College of Agriculture.

theory at least, a water-culture medium, when expertly supervised, should be subject to more exact control than a soil medium.

Present information does not warrant a prediction as to how widely the water-culture method will find practical application in greenhouses. One firm in California has reported success with this method in the production of tomatoes; another California firm, which invested a large sum in equipment, met such serious difficulties that the equipment was not being utilized at last report. We suggest that those who plan to use the water-culture method for commercial purposes, make a preliminary test with a few tanks of solution to compare the yields from soil and water-culture media, and to learn some of the requirements for control of the process. However, without some expert supervision, commercial success is unlikely.

Indispensable to profitable crop production by the water-culture method is a general knowledge of plant varieties, habits of growth, and climatic adaptations of the plant to be produced, pollination, and control of disease and insects; in other words, the same experience now needed for successful crop production in soils.

The above discussion is primarily based on experiments with greenhouse crops. Conceivably, in regions highly favored climatically, and with a good water supply available, but where soil conditions are adverse, some interest may arise in the possibilities of growing crops outdoors, commercially, by the water-culture method. What crops, if any, could be profitably grown by this method would depend on the value of the crop in the market served, in relation to cost of production, which would include a large outlay for tanks and other equipment and materials, as well as special costs of supervision and operation. Thus far, no evidence is available on which to base any prediction as to future development of the water-culture method of crop production under outdoor conditions. Before planning any investment in this field, the most careful consideration should be devoted to the economic and technical factors concerned. It seems improbable, in view of the present cost of a commercial water-culture installation, that crops grown by this method could compete with cheap field-grown crops.

Recently, popular journals have discussed a project for growing vegetables in tanks of nutrient solution on Wake Island, in mid-Pacific, to supply fresh vegetables (which constitute only a small proportion of the total food requirements) for the inhabitants of the island and for passengers of the clipper airships. This, however, is a special case, and there is no reason to assume that it has any general agricultural significance.

GROWING OF PLANTS IN WATER CULTURE BY AMATEURS

Most numerous among the inquiries for information about the water-culture method are those from persons who wish to grow plants in this way as a hobby. These persons usually seek exact directions as to how to proceed to carry on water cultures. For reasons which, we hope, will be made clear through reading this circular, it is not possible to describe a general procedure that will insure success. Many technical difficulties may be met: character of water, adjustment of acidity of the solution, toxic substances from tanks or beds, uncertainty as to time for replenishing salts in the nutrient solution, or for changing the solution, and the like.

Why, it may be asked, do not most of these technical difficulties of the water-culture method arise when plants are grown in soil? Because in a naturally fertile soil, or one which can be made fertile by simple treatment, there occurs an automatic adjustment of many of the factors determining the nutrition of the plant.

Some amateurs have recently reported results satisfactory to themselves, with certain kinds of plants grown in water culture, and similar success can presumably be achieved by others through a fortunate combination of nutritional and climatic conditions. Yet without knowledge and control of the factors involved, no assurance can be given that success with one kind of plant at one season can be consistently repeated with other kinds of plants, or at other seasons. True, not every successful gardener has a thorough training in plant and soil science. Nor can such training, by itself, always insure success in gardening. However, since the growing of plants in soil is one of the oldest occupations of mankind, the gardener can often obtain guidance based on a rich store of accumulated experience. Such experience is lacking for the growth of plants by the water-culture method.

In any case, growing of plants as a hobby, in either soil or culture solution, without regard to cost of labor and materials, is of course a very different matter from producing crops for profit. The experience of the amateur gardener, whether he uses soil or the water-culture method, is not adequate preparation for commercial crop production.

USE OF PREPARED SALT MIXTURES

Many amateurs have become interested in the purchase of mixtures of nutrient salts ready for use, and various individuals and firms have offered for sale small packages of salt mixtures. Clearly a prepared salt mixture does not obviate the difficulties which may be met in growing plants in water culture. Recently, some firms have made highly mislead-

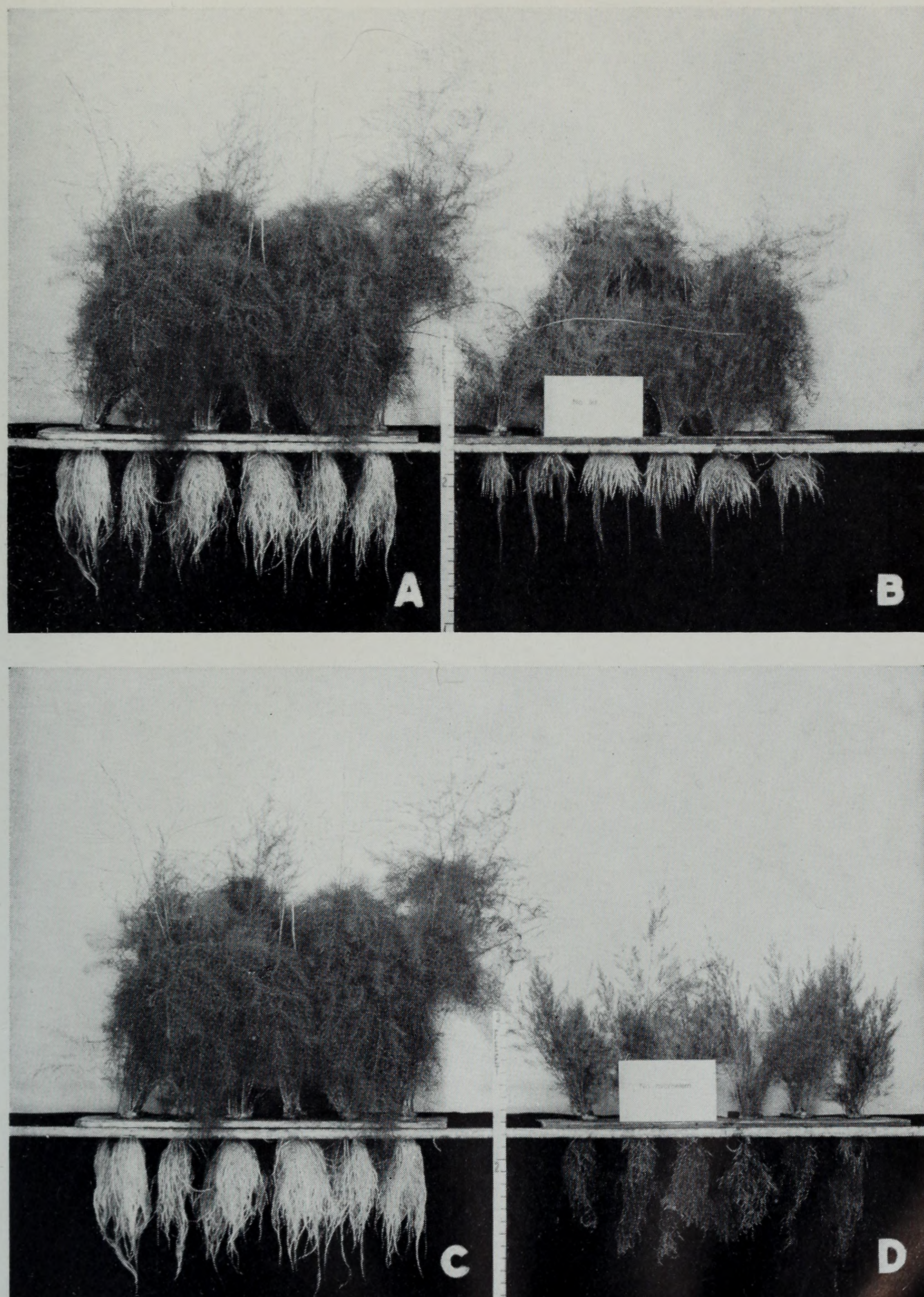

Plate 1.—*A*, *B*, Effect of forced aeration on asparagus plants grown in culture solutions: *A*, plants grown in solution through which air was bubbled continuously; *B*, plants without forced aeration.

C, Asparagus plants grown in a nutrient solution in which boron, manganese, zinc, and copper were present in such small amounts as one part in several million parts of solution; *D*, plants grown in solutions to which these elements were not added.

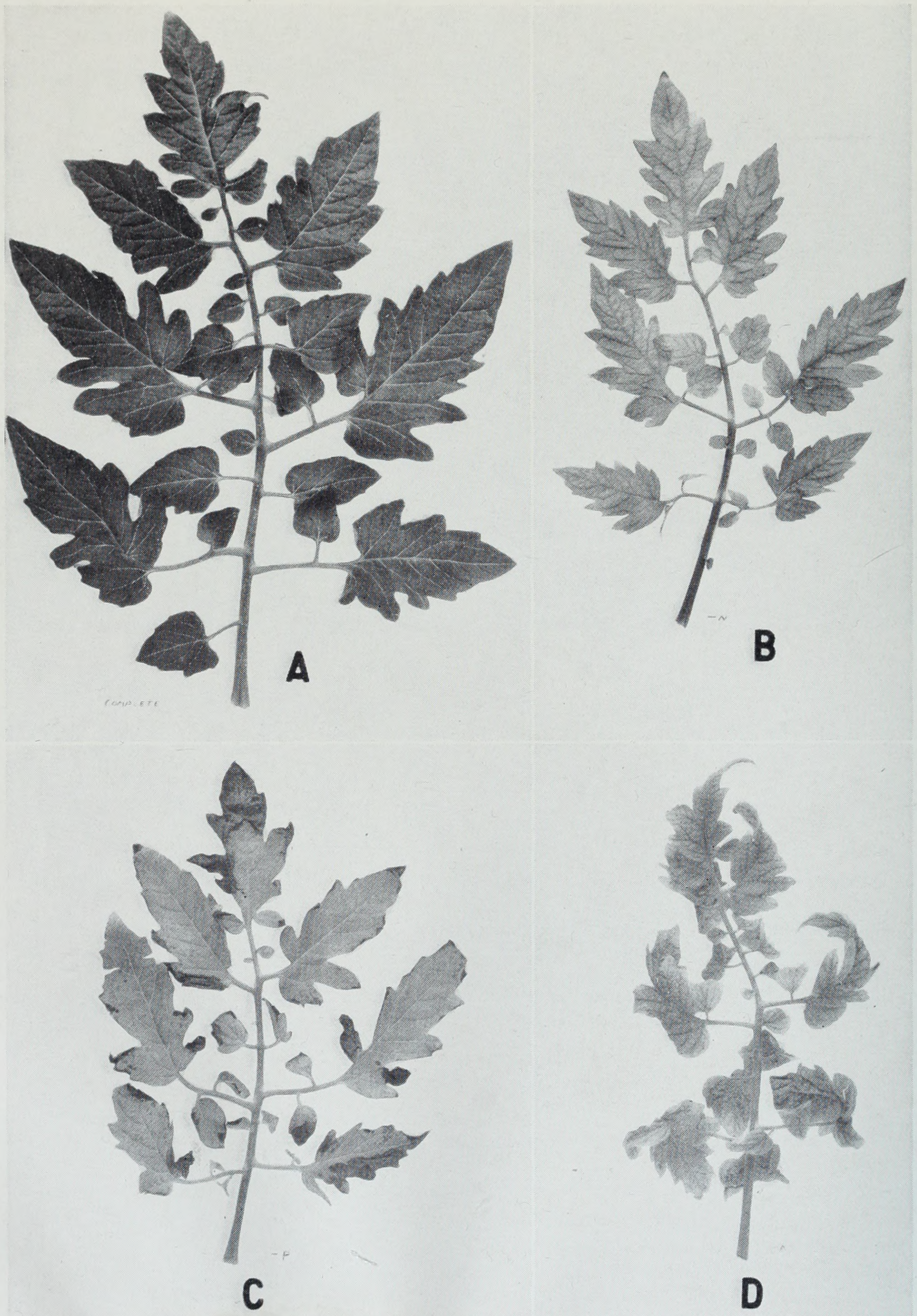

Plate 2.—Symptoms of mineral deficiencies shown by tomato plants: *A*, complets nutrient solution; *B*, solution lacking nitrogen; *C*, solution lacking phosphorus; *D*, solution lacking potassium.

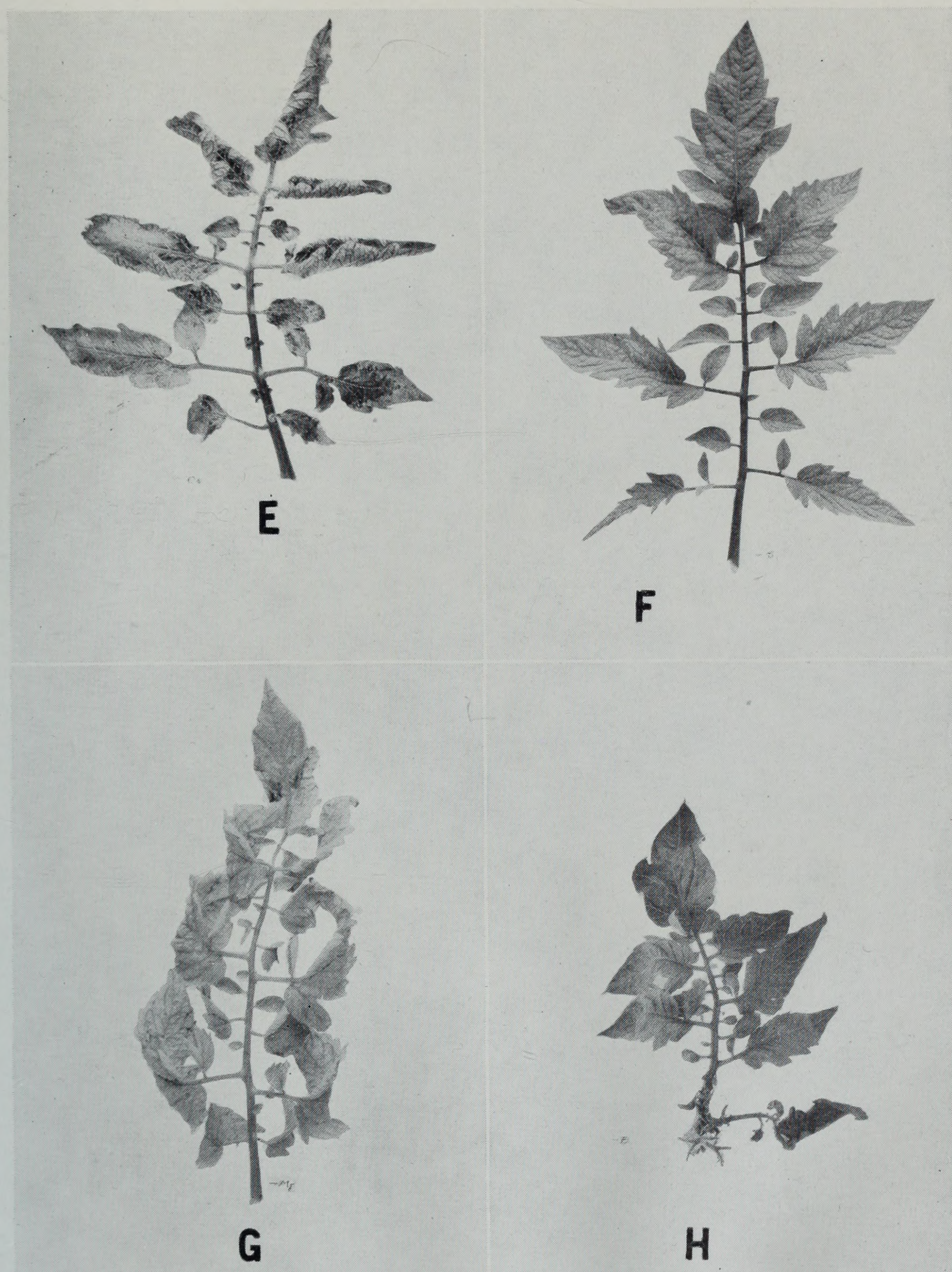

Plate 3.—Symptoms of mineral deficiencies shown by tomato plants: *E*, solution lacking calcium; *F*, solution lacking sulfur; *G*, solution lacking magnesium; *H*, solution lacking boron.

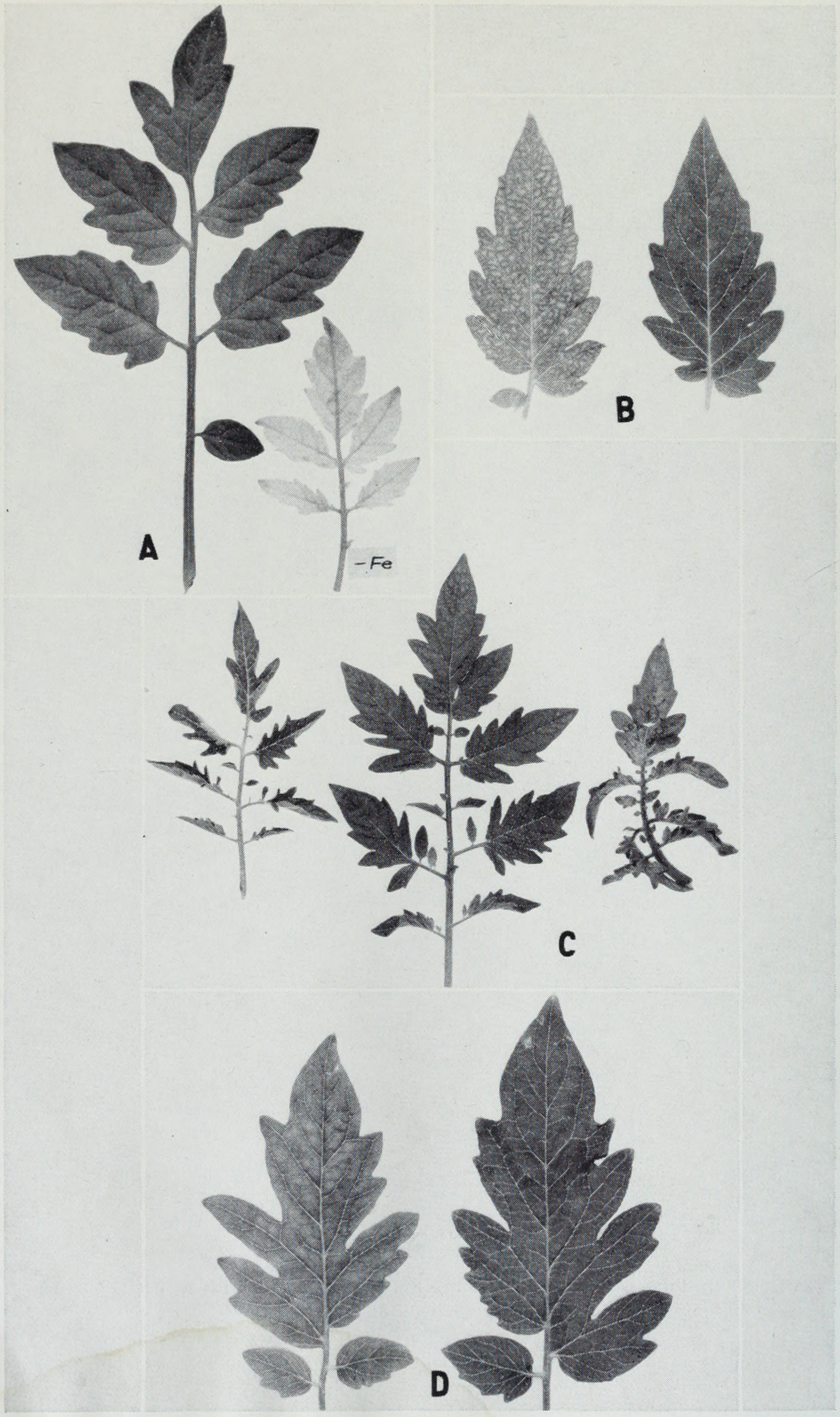

Plate 4.—Symptoms of mineral deficiencies shown by tomato plants: *A*, right, iron deficiency; left, complete nutrient solution; *B*, left, Manganese deficiency; right, complete nutrient solution; *C*, left, copper deficiency; middle, complete nutrient solution; right, zinc deficiency; *D*, left, molybdenum deficiency; right, complete nutrient solution. (Illustration from recent unpublished results of D. I. Arnon and P. R. Stout.)

ing claims for the salt mixtures they sell. The Station makes no recommendation with regard to any salt mixture, and the fact that a mixture is registered with the California State Department of Agriculture, as required by the law governing sale of fertilizers, implies no endorsement for use of the product. The directions given later will, we hope, help the amateur to prepare his own nutrient solutions.

COMPOSITION OF NUTRIENT SOLUTIONS

Thousands of requests have been received by the Station for formulas for nutrient salt solutions. It is often supposed that some remarkable new combination of salts has been devised and that the prime requisite for growing crops in solutions is to use this formula. The fact is that there is no one composition of a nutrient solution which is always superior to every other composition. Plants have marked powers of adaptation to different nutrient conditions. If this were not so, plants would not be growing in varied soils in nature. We have already emphasized in the historical sketch of the water-culture method that within certain ranges of composition and total concentration, fairly wide latitude exists in the preparation of nutrient solutions suitable for plant growth. Many varied solutions have been used successfully by different investigators. Even when two solutions differ significantly in their effects on the growth of a particular kind of plant under a given climatic condition, this does not necessarily mean that the same relation between the solutions will hold with another kind of plant, or with the same kind of plant under another climatic condition.

Another point concerning nutrient solutions needs to be stressed. After plants begin to grow, the composition of the nutrient solution changes because the constituents are absorbed by plant roots. How rapidly the change occurs depends on the rate of growth of the plants and the volume of solution available for each plant. Even when large volumes of solutions are provided, some constituents may become depleted in a comparatively short time by rapidly growing plants. This absorption of nutrient salts causes not only a decrease in the total amounts of salts available, but a qualitative alteration as well, since not all the nutrient elements are absorbed at the same rates. One secondary result is that the acid-base balance (pH) of the solution may undergo changes which in turn may lead to precipitation of certain essential chemical elements (particularly iron and manganese) so that they are no longer available to the plant. Also to be considered are the effects of salts added with the water (discussed later).

For these various reasons, the maintenance of the most favorable nutrient medium throughout the life of the plant involves not merely the selection of an appropriate solution at the time of planting, but also continued control, with either the addition of chemicals when needed or replacement of the whole solution from time to time. Proper control of culture solutions is best guided by chemical analyses of samples of the solution taken periodically and by observations of the crop. Further investigation will determine if successful standardized procedures requiring only limited control and adjustments can be developed for a given crop, locality, and season of the year.

The plant physiologist, in his experiments, prepares his solutions with distilled water, for the purpose of exact control. The commercial grower, or the amateur, is usually limited to the use of domestic or irrigation water which contains various salts, including sodium salts, such as sodium chloride, sodium sulfate, and sodium bicarbonate, as well as calcium and magnesium salts. Most waters suitable for irrigation or for drinking can be utilized in the water-culture method, but the adjustment of the reaction (pH) in the nutrient solution depends on the composition of the water. Some waters may contain so much sodium salt as to be unfit for making nutrient solutions. Even with a water only moderately high in salt content, the salt may concentrate in the nutrient solution with possibly unfavorable effects on the plant, if large amounts of water have to be added to the tanks and the solutions are not changed. Also we have had experience with a well water which was highly toxic because it contained too high a concentration of zinc, apparently derived largely from circulation through galvanized pipes. The water was, however, not injurious to tomato plants when used on a soil, because of the absorbing power of the soil for zinc.

As already indicated, the successful growth of a crop is dependent on sunlight and temperature and humidity conditions, as well as on the supply of mineral nutrients furnished by the culture medium. Complex interrelations exist between climatic conditions and the utilization of these nutrients. The relation of nitrogen nutrition and climatic conditions to fruitfulness has often been stressed. In some localities, deficient sunshine may prevent the production of profitable greenhouse crops of many species, in winter months, no matter what nutrient conditions are present in the culture solution.

NUTRIENT REQUIREMENTS OF DIFFERENT KINDS OF PLANTS

The question is frequently asked: Does each kind of plant require a different kind of nutrient solution? The answer is that if proper measures are taken to provide an adequate *supply* of nutrient elements, then many kinds of plants can be grown successfully in nutrient solutions of the same initial composition. (The same fertile soil can produce high yields of many kinds of plants.)

The composition of the nutrient solution should always be considered in relation to the total supply as well as the proportions of the various nutrient elements. To give a specific illustration: assume that several investigators prepare nutrient solutions of the same formula, but one uses 1 gallon of the solution for growing a certain number of plants, another 5 gallons of solution, and still another 50 gallons of solution. If plants were grown to large size, each investigator would reach a different conclusion as to the adequacy of the nutrient solution employed, although the initial composition was the same in all cases. The investigator using the small volume might find that his plants became starved for certain nutrients while the one using the larger volume experienced no such difficulty. In fact, the precise initial composition of a culture solution has very little significance, since the composition undergoes continuous change as the plant grows and absorbs nutrients. The rate and nature of this change depends on many factors, including total supply of nutrients. Adequacy of supply of nutrients involves volume of solution in relation to the number of plants grown, stage of growth of the plant and rate of absorption of nutrients, and frequency of changes of solution.

Apart from the question of adequate supply of nutrients, there are certain special responses of different species of plants which have to be taken into account in the management of nutrient solutions. Plants vary in their tolerance to acidity and alkalinity. They also differ in their susceptibility to injury from excessive concentrations of elements like boron, manganese, copper, and zinc. Some plants may be especially prone to yellowing because of difficulty in absorbing enough iron or manganese. Some may succeed best in more dilute nutrient solution than is employed for most kinds of plants. Unfavorable responses by certain plants to high nitrogen supply, in relation to fruiting, under certain climatic conditions, may require consideration.

Since the adaptation of a nutrient solution to the growth of any particular kind of plant depends on the supply of nutrients and on climatic conditions, there is no possibility of prescribing a list of nutrient solutions, each one best for a given species of plant.[11] Some general type of solution, such as those described in this circular, should be tried first. It may be modified later if found necessary by experiment.

[11] A number of inquiries have been received regarding the culture of mushrooms. The water-culture method under discussion is unsuited to the culture of mushrooms. These plants require organic matter for their nutrition, and differ in this way from green plants, which can grow in purely mineral nutrient solutions like those described in this circular.

NUTRIENT DEFICIENCIES, INSECT ATTACKS, AND DISEASES

Marked deficiencies of various nutrient elements are reflected in symptoms appearing in the leaves and other parts of the plants. A series of photographs (plates 2 to 4) shows the general character of foliage symptoms for deficiency of each essential element as developed by the tomato plant.

Contrary to some statements, it is not true that plants grown by the water-culture method are thereby protected against diseases (except strictly soil-borne diseases) or the attacks of insects. Recent observations suggest that diseases peculiar to water culture may sometimes attack plants grown in nutrient solutions.

WATER REQUIREMENTS OF PLANTS GROWN BY THE WATER-CULTURE METHOD

The use of water by plants is primarily determined by the physiological characteristics of each species of plant, extent of leaf surface, and atmospheric conditions, just as when plants are grown in soil. If a large crop is produced, either by the water-culture method or in soil, and if climatic conditions favor high evaporation of water from the plant, the amount of water used in producing the crop is necessarily large.

In a greenhouse experiment conducted in Berkeley for the purpose of comparing the growth of tomatoes in soil and water-culture media, according to actual measurement, somewhat more water was required to produce a unit weight of fruit under water-culture conditions than under soil conditions. The principal loss of water is by evaporation through the plant, and that is common to both soil and water culture; but possibly more water was evaporated from the water surface than from the soil surface. The fallacy of the idea that plants could be grown in a desert region with a fraction of the water needed to produce crops in irrigated soil is evident, if reasonably good management of irrigation practices is assumed.

RESUMÉ OF THE WATER-CULTURE TECHNIQUE

Many types of containers for nutrient solutions have been found useful. In investigational work, 1- or 2-quart Mason jars provided with cork stoppers often serve as culture vessels (fig. 5). Sometimes 5- or 10-gallon earthenware jars have been found suitable for experimental purposes. Small tanks of various dimensions have been extensively used. For certain special investigations, shallow trays or vessels of Pyrex glass are required. The selection of a container depends on the kind of plant to be grown, the length of the growing period, and the purpose for which the plants are grown. Figure 7 shows the varied types of containers for nutrient solutions as employed at the Station for research purposes. Some of the smaller containers illustrated would doubtless be convenient for amateur use, but the importance of the factor of aeration of the solution should be stressed. If small containers are employed and a large root

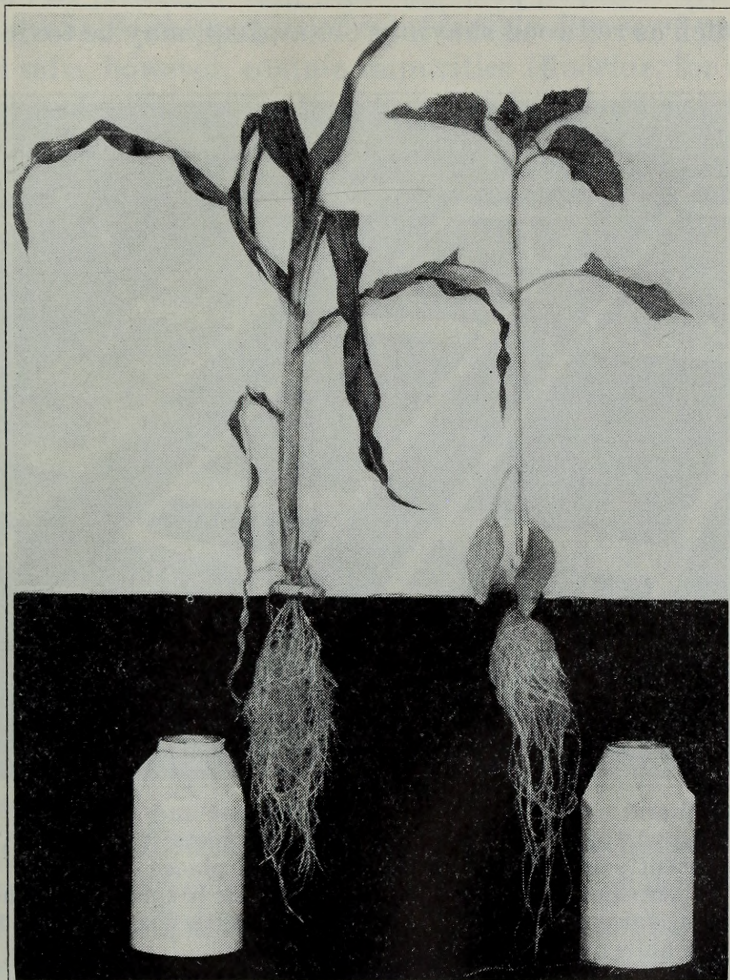

Fig. 5.—Corn and sunflower plants grown in nutrient solution contained in 2-quart Mason jars. Note method of placing plants in perforated corks. The jars are covered with thick paper to exclude light.

system is to be developed, special aeration of the culture solutions may be desirable or necessary. Plants differ greatly in regard to their requirements for aeration of the root system.

For commercial water culture, long, narrow, shallow tanks have been employed. They may be constructed of wood, cement, black iron coated with asphalt paint, or other sufficiently cheap materials which do not give off toxic substances. In these tanks is placed the nutrient solution in which roots of the plant are immersed. Wire screens are placed over the tops of the tanks, or inside, above the solution. The screens support a layer of bedding of varying thickness (often 3 or 4 inches), according to the kind of plant grown (fig. 6). This technique was first suggested by W. F. Gericke.[12] The bed may be prepared from a number of inexpensive materials—for example, pine shavings, pine excelsior, rice hulls. Some materials, such as redwood shavings or sawdust, may be toxic. Seeds are

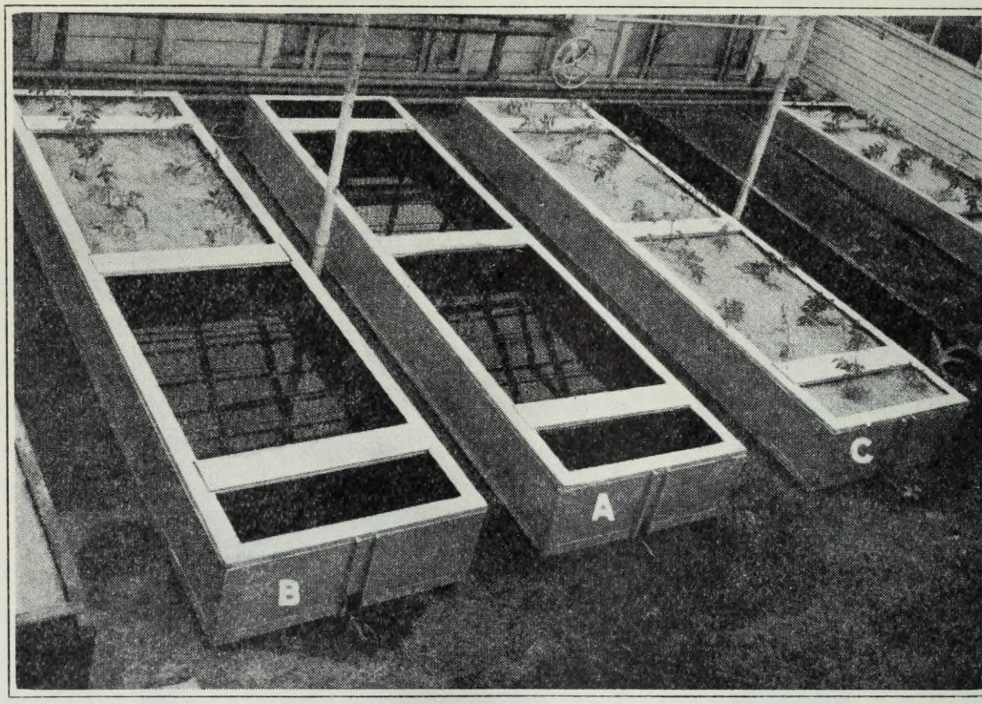

Fig. 6.—General arrangement of tank equipment and method of planting: *A*, a frame supporting a wire screen fits over the metal tank (fig. 7, *A*) filled with the nutrient solution; *B*, tomato plants are placed with their roots immersed in the nutrient solution; a layer of excelsior is spread over the netting, as shown in the far end of the tank; *C*, the planting is completed by spreading a layer of rice hulls over the excelsior.

planted in the moist beds, or young plants from flats are set in them with their roots in the nutrient solution. Roots may later develop not only in the solution in the tanks, but also in the beds.

The shallowness of the tanks and the porous nature of the beds facilitate aeration of the root system—an essential factor—but as already pointed out, such aeration unsupplemented by an additional oxygen supply, does not give the best growth of all kinds of plants. Recently evidence became available that significant improvement of growth and yield of tomato plants resulted from continuous bubbling of air through

[12] Gericke, W. F. Aquaculture: a means of crop production. American Journal of Botany 16:862. 1929.

the nutrient solution, although the yields from unaerated cultures were at least as large as any previously reported for water culture.

Chemically pure salts commonly employed in making nutrient solutions for scientific experiments would be too expensive for commercial practice, and a number of ordinary fertilizer salts can serve in large-scale production of crops. Recent developments in the fertilizer industry have made available cheap salts of considerable degree of purity. Some commercial salts, however, contain impurities (fluorine, for example, is commonly found in phosphate fertilizers) which may be toxic to plants under water-culture conditions.

DIRECTIONS FOR GROWING PLANTS BY THE WATER-CULTURE METHOD

TANKS AND OTHER CONTAINERS FOR NUTRIENT SOLUTIONS

Various kinds of tanks have been utilized for growing plants in water culture. Tanks of black iron, well painted with asphalt paint (most ordinary paints cannot be used because of toxic substances), have proved satisfactory for experimental work. Galvanized iron may give trouble, even when coated with asphalt paint, if the paint scales off.

Concrete tanks have been tried, but they may require thorough leaching before use. Painting the inside of the tank with asphalt paint is advisable. Wooden tanks will serve the purpose, if made watertight. Redwood may give off toxic substances and therefore may require preliminary leaching to remove these substances. Finally, coating with asphalt paint is desirable.

For small-scale cultures, 2- or 4-gallon earthenware crocks may be serviceable. A wire screen to hold the bedding material can be bent over the sides of the crock. But if a number of plants are to be grown to large size in such jars, the solution may require special aeration as by bubbling air through it (see p. 9).

For demonstrations in schools, Mason jars covered with brown paper, to exclude light, can be employed (fig. 5). The jars are provided with cork stoppers in which one or more holes have been bored (sometimes a slit is also made in the cork; see fig. 1). Plants are fixed in the holes with cotton. Wheat or barley plants are very suitable for these demonstrations, since they may be grown in the jars without any special arrangements for aeration.

Other types of culture vessels are shown in figure 7.

The dimensions of tanks must be selected in accordance with the objective. One kind of tank, of moderate size, adapted to many purposes, is

30 inches long, 30 inches wide, and 8 inches deep (fig. 2, p. 9, and fig. 7, *B*). A smaller tank, 30 inches long, 12 inches wide, and 8 inches deep, is convenient for use in many experiments (fig. 7, *C*). In general, shallow tanks will be found suitable. The length and width may be determined by consideration of convenience and economy. As an alternative to the porous bed, for many kinds of plants, tanks can be provided with metal or wooden covers perforated to hold corks in which plants are fixed with

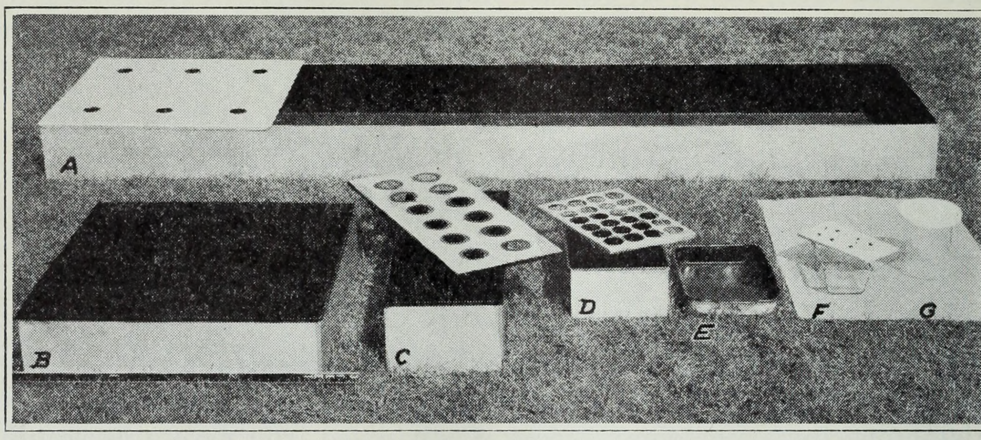

Fig. 7.—Various types of containers for carrying on water-culture experiments:

A, Large iron (not galvanized) tank painted inside with asphalt paint, outside with aluminum paint. Dimensions: 10 ft. × 2½ ft. × 8 in. Shows one section of metal cover. Perforated corks for supporting plants are fixed in the holes (fig. 2). Wooden frames containing bedding material may also be set over these tanks as shown in figure 6.

B, Iron tank of dimensions: 30 in. × 30 in. × 8 in.

C, Iron tank of dimensions: 30 in. × 12 in. × 8 in.

D, Iron tank of dimensions: 15½ in. × 10½ in. × 6 in.

E, Graniteware pan 16 in. × 11 in. × 2½ in. used for growing small plants. Perforated metal covers as shown in *A*, *C*, and *D* may be used on all metal tanks or trays. The number of holes in the cover can be varied according to the number and size of plants to be grown.

F and *G*, Pyrex dish and beaker used for special experiments designed to study the essentiality of certain chemical elements required by plants in minute quantity, such as zinc, copper, manganese, and molybdenum. The covers for these containers shown in the illustration, are molded from plaster of Paris and then coated with paraffin.

cotton, if adequate aeration is maintained (fig. 2.)[13] (See discussion of aeration, p. 9.

When large tanks are to be used with a porous bed, a heavy chicken-wire netting (1-inch mesh), coated with asphalt paint, is fastened to a frame and placed directly over the tank to provide support for the porous bed. In constructing a frame, it is advisable to leave several nar-

[13] A description of the construction of aerating devises for culture solutions is given by: Furnstal, A. F., and S. B. Johnson. Preparation of sintered Pyrex glass aerators for use in water-culture experiments with plants. Plant Physiology 11: 189–94. 1936.

row sections not covered with wire netting, but with wooden covers which can be conveniently removed for inspection of roots or for adding water or chemicals. The wire netting should be stretched immediately above the surface of the solution when the tank is full. Cross supports may be placed under the netting to prevent it from sagging (fig. 6). A carpenter or mechanic can design and build suitable tanks and frames, which may take many forms.

NATURE OF BED[14]

When a porous bed is to be employed, a wire screen is covered by a layer of the porous material 3 or 4 inches thick—thicker when tubers or fleshy roots develop in the bed. Various cheap bedding materials have been suggested: pine excelsior, peat moss, pine shavings or sawdust, rice hulls, etc. Some materials are toxic to plants. Redwood should usually be avoided. One type of bed which has produced no toxic effects in experiments carried on in Berkeley, with tomatoes, potatoes, and certain other plants, consists of a layer of pine excelsior 2 or 3 inches thick, with a superimposed layer of rice hulls about 1 or 2 inches thick. For plants producing tubers of fleshy roots, some finer material may possibly need to be mixed with the excelsior. This is also essential when small seeds are planted in the bed, to prevent the seeds from falling into the solution and to effect good contact of moist material with the seed. In all cases, the bed must be porous and not exclude free access of air.

If seeds are planted in the bed, it must, of course, be moistened at the start and maintained moist until roots grow into the solution below. For the development of tubers, bulbs, fleshy roots, etc., the bed should be maintained in a moist state, by occasional sprinkling. Great care should be observed to prevent waterlogging of the bed, resulting from immersion of the lower portion of the bed in the solution. This leads to exclusion of air and to undesirable bacterial decompositions.

PLANTING PROCEDURES

Seeds may be planted in the moist bed, but often it is better to set out young plants chosen for their vigor, which have been grown from seeds in flats of good loam. Some seeds (for example, cereal seeds) may also be conveniently germinated between layers of moist filter paper (or paper toweling), particularly if plants are to be fixed in corks and grown in jars or in tanks with perforated metal or wooden covers. The upper layers of moist paper are removed after seeds begin to germinate. The seed-

[14] The general arrangement of this type of bed was described by: Gericke, W. F., and J. R. Tavernetti. Heating of liquid culture media for tomato production. Agricultural Engineering 17:141–42, 184. 1936.

lings are allowed to grow on the moist bed until large enough to place in corks. An excess of water is then added to the moist paper and the young plants removed carefully so as not to damage the roots.

In transplanting from a flat of soil, the soil is thoroughly soaked with water so that the plants can be removed with the least possible injury to the roots. The roots are then rinsed free of soil with a light stream of water and immediately set out in the beds or corks, with the roots immersed in the solution. When young plants are set out in the beds, the roots are placed in the solution, and at the same time the layer of excelsior is built up over the screen. Then the layer of rice hulls is placed on top of the excelsior (fig. 6). If seeds are to be planted in the bed, the whole bed must be installed and moistened before the seed is planted.

SPACING OF PLANTS

In our experiments with tomato plants, they were set close together, in some instances 20 plants to 25 square feet of solution surface. No general advice can be offered as to the best spacing. This depends on the kind of plant and on light conditions. Individual experience must guide the grower.

ADDITION OF WATER TO TANKS

In starting the culture, the tank is filled with solution almost to the level the lower part of the bed. As the plants grow, water will be absorbed by plants or evaporated from the surface of the solution, and the level of the solution in the tank will fall. The recommendation has generally been made that after the root system is sufficiently developed, the level of the solution should remain from one to several inches below the lower part of the bed, to facilitate aeration. However, since the solution level should not be permitted to fall very far, regular additions of water are required.[15]

As pointed out earlier, when large amounts of water have to be added to a tank, excessive accumulations of certain salts contained in the water may occur, especially if the salt content of the water is high. To avoid this difficulty, the entire solution is changed whenever the salt concentration becomes high enough to influence the plant adversely. Should plants be injured, however, by the presence in the water of high concentrations of elements like zinc, changing solutions will not prevent injury. Because of the wide variation in the composition of water from different sources, no specific directions to cover all cases can be given.

[15] Certain methods of circulating culture solutions (such as those described by J. W. Shive and W. R. Robbins, in the citation given in footnote 7, p. 10) may be convenient for maintaining a supply of water and nutrients, as well as assisting in aeration of roots. One commercial greenhouse concern has utilized on a large scale a method of circulating nutrient solution from a central reservoir.

CHANGES OF NUTRIENT SOLUTION

As the plants begin to grow, nutrient salts will be absorbed and the acidity of the solution will change. More salts and acid may be added, but to know how much, chemical tests on the solution are required. When these cannot be made, an arbitrary procedure may be adopted of draining out the old solution every week or two, immediately refilling the tank with water and adding acid and salts as at the beginning of the culture. The number of changes of solution required will depend on the size of plants, how fast they are growing, and on volume of solution. Distribute the acid and salts to different parts of the tank. In order to effect proper mixing, it may be well to fill the tank at first only partly full (but keep most of the roots immersed) and then after adding the acid and salts, to complete the filling to the proper level with a rapid stream of water, which should be so directed as not to injure the roots.

TESTING AND ADJUSTING THE ACIDITY OF WATER AND NUTRIENT SOLUTION

Ordinarily some latitude is permissible in the degree of acidity (pH) of the nutrient solution. For most plants, a moderately acid reaction (from pH 5.0 to 6.5) is suitable. If distilled water is used in the preparation of nutrient solution, no adjustment of its reaction is necessary. If tap water is used, a preliminary test of its reaction should be made; if the water is found alkaline, it should be acidified before adding the nutrient salts.

As already stated, the reaction (pH) of the nutrient solution is subject to change as the plant grows. The reaction of the culture solution should be tested from time to time and corrected if found alkaline.

The chemicals required for testing acidity of water or nutrient solution are:

1. Bromthymol blue indicator. This can be obtained, with directions for use, from chemical supply houses, in the form of solutions or impregnated strips of paper.

Strips of other test papers covering a wide range of acidity are also now available on the market and may be found, by the amateur who understands their use, very convenient for adjusting the acidity of water as well as that of the nutrient solution.

2. Sulfuric acid. Purchase a supply of 3 per cent (by volume) acid of chemically pure grade. (Concentrated, chemically pure sulfuric acid may be purchased and diluted to 3 per cent strength, *but the concentrated acid is dangerous to handle by inexperienced persons.*) This 3 per

cent acid may be further diluted with water if a preliminary test indicates that only small additions of acid are required to bring about a desirable reaction.

Test the degree of acidity of a measured sample of the water or nutrient solution (a quart, for example) by noting the color of the added indicator or test paper immersed in the solution. When bromthymol blue indicator is used, a yellow color indicates an acid reaction (with no further adjustment necessary), green a neutral reaction, blue an alkaline reaction.

If the original color is green or blue, add the dilute sulfuric acid (3 per cent or less in strength) slowly with stirring until the color *just* changes to yellow (indicating approximately pH 6). Do not add more beyond this point, since the yellow color will also persist when excessive amounts of acid are added. Record the amount of acid required.

Finally, add a proportionate amount of the acid to the water or nutrient solution in the culture tank or vessel, having first determined how much it holds.

MODIFICATION OF NUTRIENT SOLUTION BASED ON ANALYSIS OF WATER

If tap water is used in making the nutrient solution, a chemical analysis of it is useful. Some waters may contain so much calcium, and perhaps magnesium and sulfate, that further additions of these nutrient elements are unnecessary, or even undesirable. The objective should be to approximate the intended composition of the nutrient solution, taking into account the salts already present in the water. Since, however, considerable latitude is permissible in the composition of nutrient solutions, analysis of the water is not indispensable, unless the content of mineral matter is very high.

SELECTION OF A NUTRIENT SOLUTION

As stated before, there is no one nutrient solution which is always superior to every other solution. Among many solutions which might be employed, those described below have been found to give good results with various species of plants in experiments conducted in Berkeley, with a source of good water. Other solutions can also be used with good results.

The composition of the solutions is given in two forms: (*A*) by rough measurements adapted to the amateur without special weighing or measuring instruments, and (*B*) in more exact terms for those with some knowledge of chemistry, who have proper facilities for more accurate experimentation. These facilities would include chemical glass-ware, a chemical balance and a supply of C. P. chemicals.

PREPARATION OF NUTRIENT SOLUTIONS: METHOD A, FOR AMATEURS

Either one of the solutions given in table 2 may be tried. Solution 2 may often be preferred because the ammonium salt delays the development of undesirable alkalinity. The salts are added to the water, preferably in the order given.

To either of the solutions, add the elements iron, boron, manganese, and in some cases, zinc, and copper, which are required by plants in minute quantities. There is danger of toxic effects if much greater quantities of these elements are added than those indicated later in the text. Molybdenum and possibly other elements required by plants in minute amounts will be furnished by impurities in the nutrient salts or in the water, and need not be added deliberately.

TABLE 2

COMPOSITION OF NUTRIENT SOLUTIONS*

(The amounts given are for 25 gallons of solution)

Salt	Grade of salt	Approximate amount, in ounces	Approximate amount, in level tablespoons
Solution 1†			
Potassium phosphate (monobasic)	Technical	½	1
Potassium nitrate	Fertilizer	2	4 (of powdered salt)
Calcium nitrate	Fertilizer	3	7
Magnesium sulfate (Epsom salt)	Technical	1½	4
Solution 2†			
Ammonium phosphate (monobasic)	Technical	½	2
Potassium nitrate	Fertilizer	2½	5 (of powdered salt)
Calcium nitrate	Fertilizer	2½	6
Magnesium sulfate (Epsom salt)	Technical	1½	4

* The University does not sell or give away any salts for growing plants in water culture. Chemicals may be purchased from local chemical supply houses, or possibly may be obtained through fertilizer dealers. Some of the chemicals may be obtained from druggists. If purchased in fairly large lots, the present price of the ingredients contained in 1 pound of a complete mixture of nutrient salts is approximately 5 to 10 cents for either solution described above.

† To either of these solutions, supplements of elements required in minute quantity must be added; see directions in the text.

a) *Boron and Manganese Solution.*—Dissolve 3 teaspoons of powdered boric acid and 1 teaspoon of chemically pure manganese chloride ($MnCl_2 \cdot 4H_2O$) in a gallon of water. (Manganese sulfate could be substituted for the chloride.) Dilute 1 part of this solution with 2 parts of water, by volume. Use a pint of the *diluted* solution for each 25 gallons of nutrient solution.

The elements in group *a* are added when the nutrient solution is first prepared and at all subsequent changes of solution. If plants develop symptoms characteristic of lack of manganese or boron (see plate 4, *B*, and plate 3, *H*), solution *a*, in the amount indicated in the preceding paragraph, may be added between changes of the nutrient solution or between addition of salts needed in large quantities.[16] But care is needed, for injury may easily be produced by adding too much of these elements.

b) *Zinc and Copper Solution.*—Ordinarily this solution may be omitted, because these elements will almost certainly be supplied as impurities in water or chemicals, or from the containers. When it is needed (plate 4, *C*) additions are made as for solution *a*. To prepare solution *b*, dissolve 4 teaspoons of chemically pure zinc sulfate ($ZnSO_4 \cdot 7H_2O$) and 1 teaspoon of chemically pure copper sulfate ($CuSo_4 \cdot 5H_2O$) in a gallon of water. Dilute 1 part of this solution with 4 parts of water. Use 1 *teaspoon* of the *diluted* solution for each 25 gallons of nutrient solution.

c) *Additions of Iron to Nutrient Solution.*—Generally, iron solution will need to be added at frequent and regular intervals, for example, once or twice a week. If the leaves of the plant tend to become yellow (see plate 4, *A*), even more frequent additions may be required. However, a yellowing or mottling of leaves can also arise from many other causes.

The iron solution is prepared as follows: Dissolve 1 level teaspoon of iron tartrate (iron citrate or iron sulfate can be substituted, but the tartrate or citrate is often more effective than the sulfate) in 1 quart of water. Add ½ cup of this solution to 25 gallons of nutrient solution each time iron is needed.

PREPARATION OF NUTRIENT SOLUTIONS: METHOD B, FOR SCHOOLS OR TECHNICAL LABORATORIES

For experimental purposes, the use of distilled water and chemically pure salts is recommended. Molar stock solutions (except when otherwise indicated) are prepared for each salt, and the amounts indicated below are used.

SOLUTION 1	cc in a liter of nutrient solution
M KH_2PO_4, potassium acid phosphate	1
M KNO_3, potassium nitrate	5
M $Ca(NO_3)_2$, calcium nitrate	5
M $MgSO_4$, magnesium sulfate	2

[16] The University is not prepared to diagnose symptoms on samples of plant tissues sent in for examination.

SOLUTION 2	cc in a liter of nutrient solution
M $NH_4H_2PO_4$, ammonium acid phosphate	1
M KNO_3, potassium nitrate	6
M $Ca(NO_3)_2$, calcium nitrate	4
M $MgSO_4$, magnesium sulfate	2

To either of these solutions add solutions *a* and *b* below.

a) Prepare a supplementary solution which will supply boron, manganese, zinc, copper, and molybdenum, as follows:

Compound	Grams dissolved in 1 liter of H_2O
H_3BO_3, boric acid	2.86
$MnCl_2 \cdot 4H_2O$, manganese chloride	1.81
$ZnSO_4 \cdot 7H_2O$, zinc sulfate	0.22
$CuSO_4 \cdot 5H_2O$, copper sulfate	0.08
$H_2MoO_4 \cdot H_2O$, molybdic acid (assaying 85 per cent MoO_3)	0.09

Add 1 cc of this solution for each liter of nutrient solution, when solution is first prepared or subsequently changed, or at more frequent in tervals if necessary.

This will give the following concentrations:

Element	Parts per million of nutrient solution
Boron	0.5
Manganese	0.5
Zinc	0.05
Copper	0.02
Molybdenum	0.05

b) Add iron in the form of 0.5 per cent iron tartrate solution or other suitable iron salt, at the rate of 1 cc per liter, about once or twice a week or as indicated by appearance of plants.

The reaction of the solution is adjusted to approximately pH 6 by adding 0.1 N H_2SO_4 (or some other suitable dilution).

Molar Solutions.—The concentrations of stock solutions of nutrient salts used in preparation of nutrient solutions are conveniently expressed in terms of molarity. A molar solution is one containing 1 gram-molecule (mol) of dissolved substance in 1 liter of solution. (In all nutrient-solution work, the solvent is water.) A gram-molecule or mol of a compound is the number of grams corresponding to the molecular weight.

Example 1, how to make a molar solution of magnesium sulfate: The molecular weight of magnesium sulfate, $MgSO_4 \cdot 7H_2O$ is 246.50. One mol of magnesium sulfate consists of 246.50 grams. Hence to make a molar solution of magnesium sulfate, dissolve 246.50 grams of $MgSO_4 \cdot 7H_2O$ in water and make to 1 liter volume.

Example 2, how to make a one-twentieth molar (0.05 M) solution of monocalcium phosphate, $Ca(H_2PO_4)_2 \cdot H_2O$ (used in deficiency studies, below) : The molecular weight of monocalcium phosphate, $Ca(H_2PO_4)_2 \cdot H_2O$ is 252.17. Hence 0.05 mol of $Ca(H_2PO_4)_2 \cdot H_2O$ is $\frac{252.17 \text{ grams}}{20} = 12.61$ grams. Therefore, to make a 0.05 *M* solution of monocalcium phosphate, dissolve 12.61 grams of $Ca(H_2PO_4)_2 \cdot H_2O$ in water and make to 1 liter volume.

NUTRIENT SOLUTIONS FOR USE IN DEMONSTRATING MINERAL DEFICIENCIES IN PLANTS

In any experiment to demonstrate mineral deficiencies in plants, solution 1 or solution 2 should be used as a control to show normal growth in a complete solution. Below are given six solutions, each lacking in one of the essential elements. Similar solutions were used in producing the deficiency symptoms shown in plates 2 and 3, with plants which had previously been grown for several weeks in complete nutrient solutions.

Distilled water should be used in making these solutions.

a, Solution lacking nitrogen	cc in a liter of nutrient solution
0.5 *M* K_2SO_4	5
M $MgSO_4$	2
0.05 *M* $Ca(H_2PO_4)_2$	10
0.01 *M* $CaSO_4$	200

b, Solution lacking potassium	cc in a liter of nutrient solution
M $Ca(NO_3)_2$	5
M $MgSO_4$	2
0.05 *M* $Ca(H_2PO_4)_2$	10

c, Solution lacking phosphorus	cc in a liter of nutrient solution
M $Ca(NO_3)_2$	4
M KNO_3	6
M $MgSO_4$	2

d, Solution lacking calcium	cc in a liter of nutrient solution
M KNO_3	5
M $MgSO_4$	2
M KH_2PO_4	1

e, Solution lacking magnesium	cc in a liter of nutrient solution
M $Ca(NO_3)_2$	4
M KNO_3	6
M KH_2PO_4	1
0.5 *M* K_2SO_4	3

f, Solution lacking sulfur

	cc in a liter of nutrient solution
M $Ca(NO_3)_2$	4
M KNO_3	6
M KH_2PO_4	1
M $Mg(NO_3)_2$	2

To any of these solutions, add iron and the supplementary solution suppying boron, manganese, zinc, copper, and molybdenum as previously described (p. 37). For use with solution *f*, lacking sulfur, a special supplementary solution should be prepared in which chlorides replace the sulfates. Also, sulfuric acid should not be used in adjusting the reaction of the nutrient solution.

In order to produce iron-deficiency symptoms, plants should be grown in glass containers and no iron should be added to the otherwise complete nutrient solution. Similarly, it may be possible to produce boron- or manganese-deficiency symptoms with certain plants (tomatoes, for example) by omitting either one of these elements from the supplementary solution. Zinc-, copper-, and molybdenum-deficiency symptoms can usually be produced only by the use of a special technique, the description of which exceeds the scope of this circular.

30*m*-1,'39(5984)