SPECIAL CIRCULAR No. 56 MAY, 1939

Growing Plants In Nutrient Solution

L. J. Alexander, V. H. Morris,
and H. C. Young

OHIO AGRICULTURAL EXPERIMENT STATION
WOOSTER, OHIO

CONTENTS

GROWING PLANTS IN NUTRIENT SOLUTION

L. J. ALEXANDER, V. H. MORRIS, AND H. C. YOUNG

INTRODUCTION

Growing plants with their roots in an artificial medium instead of soil is becoming a popular hobby, if not a commercial procedure. Some of the terms used to refer to this type of culture are soilless farming, tank farming, tray agriculture, water culture, and hydroponics. The amount of publicity given this method of growing plants has led to many fantastic and erroneous notions as to its use. It is hinted, and sometimes definitely stated, that what were formerly considered high yields are now only a drop in the bucket, that every housewife will be able to grow the family supply of vegetables in the basement or garage, and that all present-day farming methods will have to be revised. As a result of this rather high-pressure publicity, many experiment stations have found it necessary to prepare bulletins which present methods of nutrient solution culture and some of the limitations of the system. The purpose of this publication is to discuss the merits of the method, including the disadvantages as well as the advantages, for the benefit of those who request information from this Station.

SOME FUNDAMENTALS OF PLANT GROWTH

Some of the yields claimed to have been produced by the nutrient solution method are so far above those obtained by successful gardeners and growers with soil that it seems in order to examine them in the light of some of the fundamental principles of plant physiology. It should be emphasized that in any living plant, two processes occur. One is the manufacture of food and the other is the utilization of this food. The rate at which food is both manufactured and utilized is largely regulated by environmental conditions. In order to produce vigorous, rapidly growing plants the environment must be such that the manufacture of food exceeds the utilization of it.

MANUFACTURE OF FOOD BY PLANTS

The process by which plants manufacture food is called "photosynthesis", which means putting together in the presence of light. The process is so complex that the best chemists have not succeeded in duplicating it. It is known, however, that photosynthesis takes place only in the presence of an adequate supply of light, either artificial or from the sun, which acts as the source of energy. With the action of the light on the green coloring matter, which is largely in the leaves, the carbon dioxide of the air is combined with the water obtained through the roots. The first products of this action are simple sugars which are further converted into more complex carbohydrates and fats, and combined with nitrogen to form proteins. Although, from the standpoint of solution culture technique, we are not interested in the details of the chemical process, we are interested in the external conditions necessary for the process, particularly an adequate supply of light.

UTILIZATION OF FOOD BY PLANTS

The food manufactured by the process just described is utilized by the plant to (1) supply energy for work, (2) construct new tissues, and (3) store for later use.

All organisms, both plant and animal, require energy to maintain life. This energy is used to carry on processes which may be described as work. Some of the more important of these processes which plants must perform are the penetration of roots through soil, elevation of stems in air, movement and other activities of the protoplasm, and evaporation of water. These energy requirements are met in the plant by a process called respiration, whereby the food already manufactured by photosynthesis is burned in the plant cells with a resulting release of energy. If there is sufficient food left after the energy requirements have been met, immature plants grow and enlarge. For growth to take place new cells must be formed. These new cells are formed from the carbohydrates, fat, and proteins produced in the leaves, plus certain mineral elements absorbed by the roots from the medium in which they grow. Thus, growth is dependent upon the manufacture of food by plants. If there is still an abundance of food left after energy and food requirements have been met, many plants store food. This storage may take place generally throughout the plant or in specialized organs, such as seeds or the tubers of potato.

INFLUENCE OF EXTERNAL CONDITIONS ON MANUFACTURE AND UTILIZATION OF FOOD

These processes of manufacturing and utilizing food can proceed only when certain external conditions prevail, regardless of whether the plants are grown in soil or by one of the nutrient solution methods.

Some of the important requirements are, first, free access of roots to water and necessary minerals; second, an adequate supply of carbon dioxide for photosynthesis; third, sufficient light of the correct quality; and fourth, proper temperature.

Through the ages soil has been the medium in which the roots of plants have grown. It furnishes excellent support, is usually porous so that roots obtain a sufficient amount of oxygen for their respiration, furnishes the plants with large quantities of water, and is of about the correct reaction. In addition, soil supplies the necessary mineral elements, of which the most important are nitrogen, potassium, phosphorus, calcium, magnesium, sulfur, manganese, iron, and boron. Many others, essential for healthy growth, are supplied in small quantities. If plants are to grow with their roots in a medium other than soil, it is necessary to ensure (1) that this medium contains the chemical elements in about the correct proportion needed by plants, (2) that the concentration of the solution is not too high, (3) that the roots have access to sufficient oxygen, and (4) that the solution is slightly acid.

Plants must have access to adequate fresh air from which they can extract the carbon dioxide necessary for photosynthesis. In nature this is not a problem, because wind movement keeps the atmosphere well mixed. In enclosures suitable for growing plants, such as greenhouses, air movement is also sufficient to ensure an adequate supply of carbon dioxide.

Plants growing in nature usually have all the light they need from the sun. Consequently, light is not a problem out of doors in the summer, but whenever an attempt is made to grow plants indoors it does become a very real problem.

In fact, it is so much of a problem during the months of January and February that greenhouse growers of vegetables do not try to ripen any fruit and only mature such leafy crops as lettuce and radishes.

To illustrate the point further, it has been shown that the tomato plant will not produce much food material when the light intensity falls below 200 foot-candles and does not reach a high rate of production with much less than about 1,000 foot-candles. Contrast this with proper home illumination, where it is considered that 20 foot-candles make a perfect light for reading. This is only one-tenth of the minimum of 200 foot-candles necessary for food manufacture, which illustrates the difficulty, as well as the expense, of providing adequate artificial illumination for plants. If it is to be attempted, however, the ordinary Mazda light is the best source, because it produces the quality of light nearest to that needed by plants.

The processes of manufacturing and utilizing food are greatly influenced by temperature. Consequently, it is necessary to grow plants at temperatures at which the manufacture of food exceeds the utilization. In the summer months the conditions of full sunlight and temperature, up to 80 or 90° F., are so favorable for the production of food materials that food can be accumulated in considerable quantities. With the low light of winter, however, plants grown at these temperatures would burn up in the process of respiration all the food produced, and growth would cease. By lowering the temperature, the rate of food utilization is reduced much faster than the rate of food manufacture; even in fairly dark weather tomato plants will make normal growth if the temperature is kept between 55 and 60° F. Of course, at these temperatures, with low light, plants cannot store much food; they can only make that needed for respiration and slow growth. Other plants probably have different temperature requirements, but they have not been as carefully worked out as those for the tomato. It has also been found that the rapidity with which plants grow is influenced by the temperature of the medium in which the roots are grown. For the tomato, the optimum is between 75 and 80° F.

Any method of growing plants must take into consideration the above briefly discussed fundamentals of plant physiology. They are just as important whether plants are grown in soil or nutrient solutions. One of the fallacies commonly held is that when growing plants in nutrient solutions it is not necessary to pay attention to these fundamental principles of plant growth, such as the above-mentioned light and temperature relationships. No thought could be farther from the truth. The use of nutrient solutions in no way changes the conditions necessary for plants to carry on the processes of photosynthesis and respiration which are essential for plant growth.

HISTORY OF NUTRIENT SOLUTIONS

The growing of plants in water culture is not new. Aristotle (300 B. C.) stated that plants absorbed their food as animals, or already prepared, in the form of humus. It required approximately 2,000 years for physiologists to refute his theory. Much of the necessary evidence came from growing plants in water culture. Edde Mariotte in 1679 grew plants in water and found that they needed earthly salts, nitre, and ammonia. Following closely was John Woodward, and in 1692 he published the first definite account of growing plants without soil. Duhamel, in 1758, was the first to grow plants to maturity in water culture. He grew *Vicia faba* (broad bean) and many other plants in Seine River water and harvested a mature crop. In most of these earlier experiments river or conduit water was used.

Definite progress in the nutrition of plants was not made until after the discovery of hydrogen, oxygen, and nitrogen about 1785. The real water culture period was started about 1860 by Sachs, Knop, and others. Determining from the ash what mineral salts were needed, they arranged the salt content of the solutions accordingly and were able to grow many plants, such as the cereals, potatoes, tomatoes, and beans. The formulas devised by them form the basis of those in use today.

Another period in water culture work began about 1900 and had to do with the balancing of the solutions. A study was made of the effect of one salt on another and the rates of absorption of each salt. It was from this type of work that attempts were made to determine the role of each chemical element in the plant.

It must be definitely stated, therefore, that the growing of crop plants without soil is not new. Until recently the method was used primarily in the study of plant nutrition. The only thing new is its application to commercial crop production.

METHODS OF NUTRIENT SOLUTION CULTURE

Since growing plants in nutrient solutions merely involves replacing soil with another medium, it is only necessary to keep in mind the uses of the soil to plants and replace them. It is important to bear in mind that replacing the soil with nutrient solution does not in any way change the conditions necessary for the aerial parts of the plant to function properly. These conditions must be met, regardless of whether plants are grown in soil or nutrient solutions.

The three general methods of growing plants in nutrient solutions are as follows: (1) the drip method, (2) the subirrigation method, and (3) the water method. With the first two, the roots of the plants grow in an inert medium which is moistened by a nutrient solution. With the third method the roots of the plants grow directly in the nutrient solution.

CONSTRUCTION OF TANKS

Tanks for containing the solution and supporting the plants may be made of cement or galvanized iron. Wooden tanks may also be used, but it is difficult to keep them from leaking. As a rule, a convenient size is 30 inches wide, 6 to 8 inches deep, and any desired length. Much better success may be had if the inside of the tank is coated with a waterproofing material. So far, the best substance found for this purpose is asphalt with a melting point of about 190° F. applied as a hot mop. Coal-tar asphalts contain substances toxic to plants; consequently it is essential that a petroleum asphalt be used. Such asphalts may be secured from some of the large oil companies.

DRIP METHOD

The drip method is the simplest and probably the most likely to be successful for amateur growers (see fig. 1). The type of tank described is used. It is well to raise it 8 to 10 inches off the floor of the greenhouse, as the solution will be warmer there than if the tank is placed on the ground. The tank should be mounted slightly sloping so that water will drain to the end with the outlet. Drainage is also facilitated by placing an inverted asphalt-coated 3-inch gutter pipe the length of the tank with one end extending over the drain.

After mounting, the tank may be filled with an inert medium, such as silica sand. Screened and washed cinders also have been used successfully. More recently calcareous gravels and shale have been found satisfactory. Best results may be secured by using about a ¼-inch-mesh material. If cinders are used, the fine dust and coarse material should be screened out. The remainder should be washed and leached with a weak acid solution containing about 5 per cent sulfuric acid and 95 per cent water. The leaching can best be done by closing the outlet in the tank and allowing the acid solution to remain in contact with the cinders for about 24 hours, then flushing several times with water. A second leaching and flushing are advisable, after which the medium is ready for use.

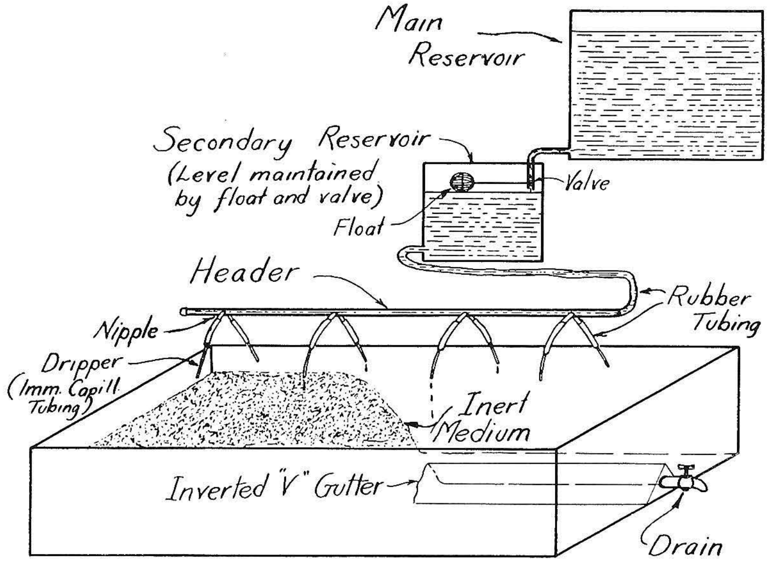

Fig. 1.—Diagrammatic illustration of an arrangement for drip culture

The nutrient solution is supplied separately to each plant a drop at a time. Small plants should receive from 1 to 2 pints per day and large plants 3 to 4 pints per day. To avoid accumulation of salts on the surface, the medium should be flushed thoroughly with water about every 2 or 3 days, more frequently in bright or hot weather, less often in dark, cool weather.

A steel drum from which the head has been removed and which has been lined with asphalt serves excellently as a reservoir for supplying the drip. A secondary reservoir of about 3 gallons connected to the primary reservoir and arranged with a float valve (a bathroom toilet float and valve are very satisfactory) is very helpful for keeping the drip at a uniform rate. The float valve maintains a constant level in the secondary reservoir, and consequently the rate of dripping will be the same regardless of whether the main reservoir is full or nearly empty. The rate of drip may be regulated by raising or lowering the level of the solution in the secondary reservoir.

An excellent header for conducting the solution from the reservoir to the plants may be made of black iron pipe fitted with ⅛-inch nipples. The size of the header should vary with the length of the culture tank, but a ¾-inch pipe will supply a 50-foot double row of drippers. The drippers are 1-millimeter bore capillary tubing and are attached to the nipples in the header by 3/16-inch rubber tubing. The nipples in the header should be spaced so that there is one dripper for each plant.

SUBIRRIGATION METHOD

The essential difference between the subirrigation and drip culture methods is the utilization of the solution over and over in the former. In order to use the solution over, it is necessary to have a reservoir below the culture tank, of about one-fourth its capacity (fig. 2). By means of a pump and electric motor automatically controlled by a time clock, the nutrient solution is pumped from the reservoir into the culture tank through the drain in the end of it. Only sufficient solution should be maintained in the reservoir to flood the medium in the culture tank. Each day the solution should be brought up to its original volume by the addition of water to take the place of that lost by evaporation and transpiration. Frequency of flooding will have to be governed by the weather and size of the plants. A suggested number of times is three, made at 6 a. m., 12 noon, and 6 p. m., but that may not be sufficient for large plants in bright, hot weather, or it may be too often for small plants in cool, dark weather. The cycle of flooding and draining should be completed in about 45 minutes. It is essential to use a valveless centrifugal pump so that the nutrient solution can drain back through it to the reservoir by gravity. Figure 3, left, shows tomato plants growing by the subirrigation method. In this case the medium used was cinders.

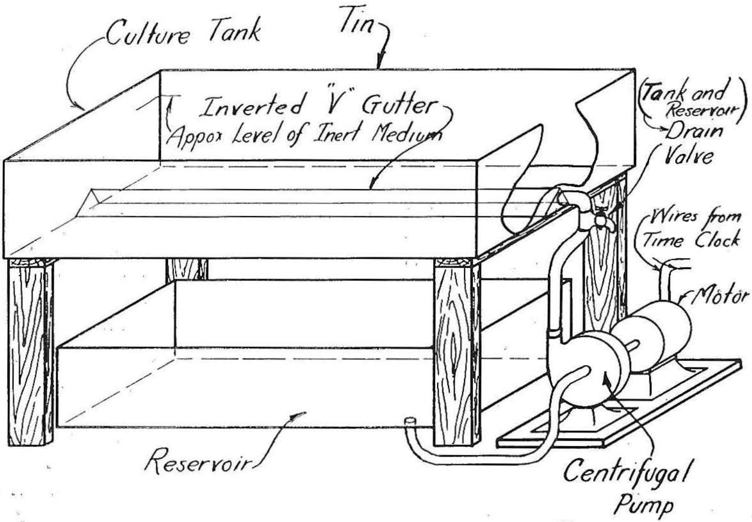

Fig. 2.—Diagrammatic illustration of an arrangement for subirrigation culture

Fig. 3.—Experimental production of tomatoes in a commercial greenhouse

Right, water culture method; left, subirrigation method using cinders as the inert medium

WATER METHOD

As the name implies, no medium, such as sand, is used in the water method. The roots are suspended directly in the nutrient solution. The same type of waterproof tank is used, but instead of being filled with sand it is filled with nutrient solution. The plants are suspended above the solution with their roots immersed in it. Plants such as tomatoes may be tied to wires just above the solution and then trained up strings tied to the same wire that supports the plants and overhead wires (fig. 3, right). Other plants may best be supported in a tray covered on the bottom with hardware screening of about ¼-inch mesh. The tray may be filled with excelsior or shavings. Usually when seedlings are started in trays, the level of the solution in the tank is raised until it just touches the screen. Then as the roots grow, the level of the solution is lowered until it is about 2 inches below the screen, where it is kept constant (fig. 4). It is important to maintain the solution at a constant level.

As discussed earlier, it is necessary for the roots of plants to have free access to oxygen for use in the process of respiration (fig. 4). Consequently, some provision must be made to replace the oxygen in the solution as fast as it is taken out by the roots of the plants. Two simple systems for aerating nutrient solutions are described. The most simple method makes use of a centrifugal circulating pump and motor operated continuously (fig. 5, lower). The solution is kept in motion by attaching the inlet of the pump to one end of the culture tank and the outlet to the other. In order to aerate at the same time the solution is circulated, an air valve is placed on the inlet and so adjusted that the pump takes in both air and water. The air thus taken in is thoroughly mixed with the water by the impeller of the pump.

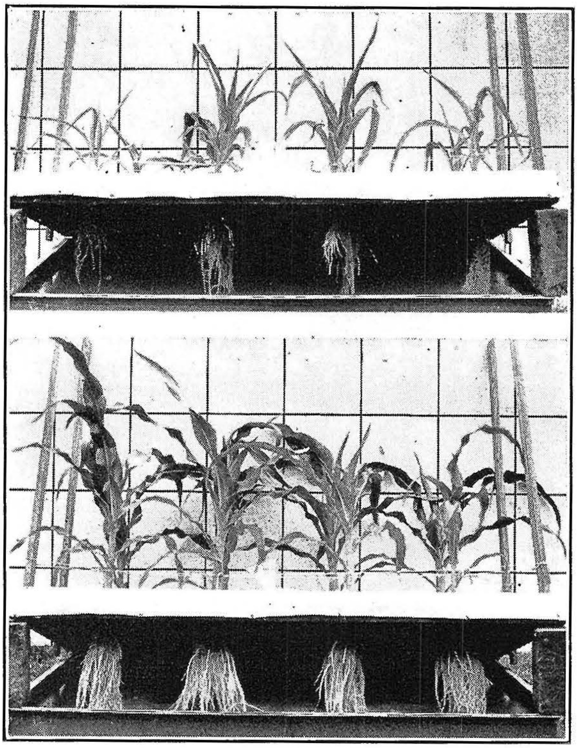

Fig. 4.—Effect of forced aeration on corn plants grown in nutrient solution

Upper, solution not aerated; lower, solution aerated 15 minutes each hour during day and four times at night

With the other method of aeration, air is bubbled through the solution in the culture tank (fig. 5, upper). The air is supplied by a motor-driven rotary air pump operated automatically by a time clock. Probably the amount of aeration necessary will vary with different plants and their rate of growth, but for corn and tomatoes growing outdoors in the summer, air is bubbled through the solution 15 minutes of every hour during the day. During the night there are only four 15-minute periods of aeration. A piece of ⅜-inch pipe capped on one end, with ¼-inch holes drilled every foot, serves as an aerator. The pipe is laid lengthwise in the bottom of the tank and is connected to the air line by means of a rubber hose.

Most plants grow better when their roots are in a warm medium, and one of the advantages of the water culture method is the ease with which the solution can be warmed. The most favorable temperatures for many plants are not known, but tomatoes seem to grow best between 75 and 80° F. As time goes on, the optimum temperatures for the growth of the roots of other plants will have to be worked out. Warming the solution may be done by means of an electric heating cable and thermostat placed in the solution in the culture tank. The solution may also be heated with a steam pipe placed lengthwise in the bottom of the culture tank. The temperature is kept constant by an electric thermostat which operates a steam valve.

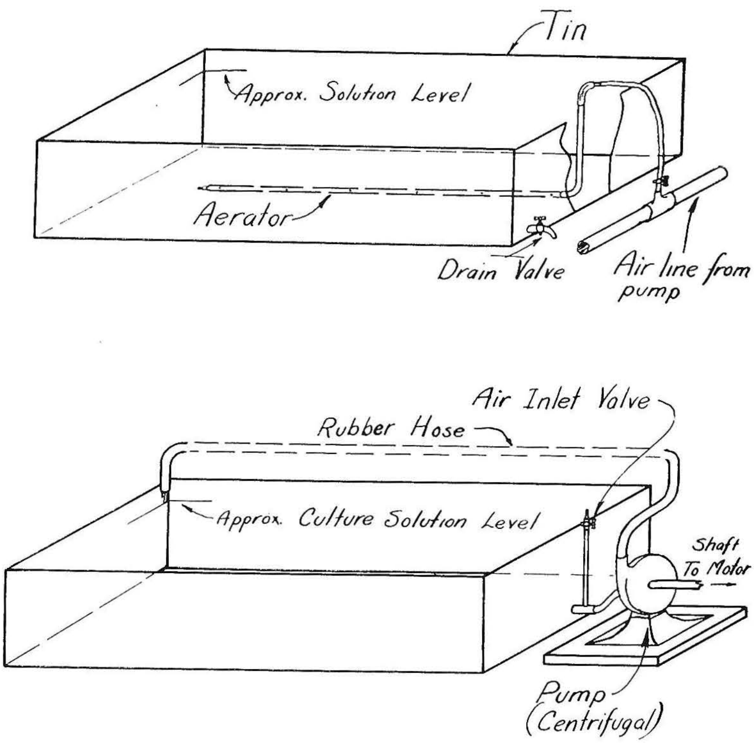

Fig. 5.—Diagrammatic illustration of two arrangements for water culture

Upper, aeration by means of bubbling air through the solution; lower, aeration by means of a circulating pump

NUTRIENT SOLUTIONS

COMPOSITION OF NUTRIENT SOLUTIONS

A nutrient solution that would be universally useful cannot be recommended at present. Adequate knowledge of the exact requirements of plants is lacking, and different species of plants may have different requirements. Furthermore, the requirements may change with the season of the year. Various magazines and books give the chemical composition of many solutions. Some of them are very much alike; others are totally different. It is also possible to buy mixed chemicals for nutrient solutions from a number of sources. Such combinations have not been tried by the Ohio Experiment Station, and consequently no recommendation can be made about them.

The suggested solution is one that works well with corn and tomatoes at the Ohio Experiment Station. It has not been tried for other plants, however. The purpose of setting it forth here is to suggest it as a starting point for beginners, beyond which they will have to determine the best combination for their needs by the trial and error method.

Suggested Nutrient Solution

Fertilizer salts	Molecular concentration	Grains for 10 gallons of solution	Grams for 10 gallons of solution	Ounces for 10 gallons of solution
Potassium nitrate, KNO_3	0.006	354	23	0.8
Calcium nitrate, $Ca(NO_3)_2$	.008	770	50	1.8
or				
Calcium sulfate, $CaSO_4 . 2H_2O$ (gypsum)	.008	770	50	1.8
Magnesium sulfate, $MgSO_4 . 7H_2O$ (Epsom salts)	.0015	231	15	.6
Potassium phosphate, KH_2PO_4	.001	77	5	.2
or				
Calcium phosphate, $CaH_4(PO_4)_2 . 2H_2O$	.0005	77	5	.2
Ammonium sulfate, $(NH_4)_2SO_4$	.0005	38	2.5	.1
Ferrous sulfate, $FeSO_4 \cdot 7H_2O$	¼ liquid oz. (7 cc.) of stock solution = ½ part per million			
or				
Ferric ammonium citrate	¼ liquid oz. (7 cc.) of stock solution = ½ part per million			
Boric acid, H_3BO_3	¼ liquid oz. (7 cc.) of stock solution = ½ part per million			

Note: Better results may be secured by using one-half the amount of ammonium sulfate during the dark winter months and the hot summer months.

To make stock solution of ferrous sulfate dissolve ½ ounce of ferrous sulfate in 1 quart of water to which 5 drops of sulfuric acid have been added.

To make stock solution of ferric ammonium citrate dissolve ⅔ ounce of ferric ammonium citrate crystals in 1 quart of water. Store in dark.

To make stock solution of boric acid dissolve ½ ounce of boric acid crystals in 1 quart of water.

To make stock solution of sulfuric acid add 2 liquid ounces of acid to 2 quarts of water. (**Important:** add acid to water, using enamel pan.)

To make stock solution of potassium hydroxide dissolve 4 ounces of potassium hydroxide in 2 quarts of water. (Note: The water gets hot; use enamel pan.)

To make stock solution of ammonium sulfate dissolve 9½ ounces of ammonium sulfate in 2 quarts of water.

The chemicals listed for the nutrient solution may be secured from chemical or pharmaceutical supply companies, such as Russell Farley & Company, Akron, Ohio; the Chemical Rubber Company or the Grasselli Chemical Department, E. I. du Pont de Nemours and Company, Cleveland, Ohio; The Kauffman-Lattimer Company, Columbus, Ohio; and The Coleman and Bell Company, Norwood, Ohio. Buyers should request a food grade of potassium or calcium phosphate; technical or commercial grades of ferric ammonium citrate, sulfuric acid, and potassium hydroxide; and fertilizer grades of potassium nitrate, calcium nitrate, calcium sulfate (gypsum), magnesium sulfate (Epsom salts), ammonium sulfate, ferrous sulfate (copperas), and boric acid. Chemically pure calcium nitrate contains a great deal of water and the suggested amount should be increased by one-fourth. If gypsum is used instead of calcium nitrate, it can best be dissolved in cold water to which 10 cubic centimeters per gallon of diluted sulfuric acid have been added. If soft water is used, less acid is necessary. Either potassium or calcium phosphate may be used. Calcium phosphate is cheaper but is hard to dissolve except in acidified water.

The minor elements are those which are needed only in minute amounts, and for commercial culture probably the addition of iron and boron is sufficient. Many others, such as manganese, copper, nickel, etc., are just as essential as iron and boron, but the impure chemicals and water apparently contain sufficient of them.

Boron is added to the solution each time it is made up, at the rate of ½ part per million. For most plants this is sufficient, but with large, rapidly growing plants in the subirrigation and water methods, it is advisable to add that quantity once a week. For the drip method, ½ part per million of boron is added each time the solution is renewed.

Iron is the most difficult chemical to keep in solution. It reacts with phosphorus to form a white precipitate and must be replaced frequently in the subirrigation and water culture systems. Usually ½ part per million daily is sufficient. With large, rapidly growing plants, however, 1 part per million of iron may be needed to keep the new plant growth from turning yellow. Whenever the stock solution acquires a brownish precipitate, it should be discarded. If this occurs in a short period of time, more acid than indicated should be used when making the solution.

Ferrous sulfate (copperas) or ferric ammonium citrate will work equally well as far as the plants are concerned. Ferrous sulfate is suggested with the subirrigation and water methods, because the addition of the citrate will cause the solutions to ferment and have an unpleasant odor. With the drip method, ferric ammonium citrate gives excellent results.

REACTION OF NUTRIENT SOLUTIONS

The reaction of a solution is usually expressed by the term pH. On this basis a pH value of 7.0 is neutral, above 7.0 alkaline, and below 7.0 acid. Plants grow best in nutrient solutions which are slightly acid, and pH readings between 5.0 and 6.0 are favorable for the growth of corn and tomatoes. Nutrient solutions are usually adjusted to an initial pH of 5.5.

In order to determine the pH of a nutrient solution, a testing set of some sort is necessary.[1] If the reaction of the solution is above 6.0, sulfuric acid should be added. If the pH is below 5.0, potassium hydroxide should be added. The amounts of acid and alkali needed for 10 gallons are small and can be determined by practice.

The frequency of checking the pH of the solutions depends a great deal upon the rapidity with which the plants are growing. Frequently it is necessary to check the solutions every day; at other times twice a week is sufficient.

A newer method of controlling the pH of nutrient solutions has been tried recently with fair results. With this method ammonium sulfate is omitted when the solutions are prepared and adjusted to a pH of 5.5. Such a solution will usually become alkaline in a short time, and when the reading exceeds pH 6.0, a small amount, perhaps ¼ fluid ounce for each 10 gallons of solution, of ammonium sulfate is added. The ammonium sulfate will usually cause the solution to drift acid until the ammonia is exhausted; the drift will then be alkaline again. As before, when the pH exceeds 6.0, more ammonium sulfate should be added. If the solution drifts below pH 5.0, less ammonium sulfate is used. It should be pointed out, however, that if plants become too soft they may absorb too much ammonia, with a possible consequence of ammonia toxicity.

CONCENTRATIONS AND RENEWAL OF SOLUTIONS

For the subirrigation and drip methods the solution should be made up as directed. With these two methods the amount of water available to the plants can be regulated by the frequency of irrigation for the former and the rate of drip and amount of flushing for the latter.

---

[1] The simplest type of kit consists of indicator test papers with an accompanying chart, such as the Nitrazine set which may be obtained from E. R. Squibb & Sons, New York. A more elaborate set consisting of a spot plate, indicator solution, and chart may be obtained from the LaMotte Chemical Co., Baltimore, Maryland.

To regulate the amount of water available to plants grown by the water method it is necessary to vary the concentration of the nutrient solution. It should be remembered that with a high concentration of salts in the solution, less water is available to the plants, and that with a lower concentration more water is available. During late spring, summer, and early fall, the concentration of the solution should be as indicated in the table. For early spring and late fall the concentration should be doubled; that is, twice the indicated amounts of chemicals should be used, and during the dark weather of the winter months, three times the amounts of chemicals should be used.

Regardless of which method is used, the grower should always keep in mind that during the long days of summer plants need large quantities of water and that during the dark, short days of winter very little water is needed.

With the drip method the solution is renewed every time the reservoir becomes empty. With the other two methods, however, the original volume is restored daily by the addition of water, and consequently the solution is never exhausted. Hence, with these methods it is necessary to change the solution completely at frequent intervals. At the present time the solutions are renewed every 3 weeks. It is hoped that a simple method of testing the solutions and replacing the elements used can be designed.

GENERAL DISCUSSION

PITFALLS

The pitfalls into which beginners may fall are so numerous that only a few can be discussed here. Probably the first in importance is a lack of appreciation of the importance of light, which is discussed in an earlier section. This difficulty can be avoided only by making ample provision for adequate light when installing the system. The second is failure to keep the reaction of the nutrient solution at the proper pH. If the nutrient solution becomes too alkaline, plants soon cease growth and may suffer permanent injury. It is almost impossible to keep sufficient iron in a solution that is even slightly alkaline. Difficulty is also encountered if the reaction of the solution is allowed to become too acid. This situation is most frequently encountered when too much acid is added to correct an alkaline reaction. The first visible effect of too much acidity is wilting of the tops, which may occur within an hour. Plants may or may not recover from such injury. To preclude such a possibility, it is always well to recheck the reaction of the nutrient solution within a short time after adding acid. The third danger is failing to aerate solution cultures regularly. When cultures are not adequately supplied with oxygen, the plants linger along but never grow or produce normal crops. The fourth pitfall is failure to add all the chemicals called for in a formula, and this is important, because it is very easy to omit some chemical or put it in twice. Such a mistake will usually cause the death of the plants. The easiest way to avoid such a mistake is to devise a checking system so that as each chemical is added it is so marked.

Some provision also must be made to eliminate any material that may be used in spraying for the control of diseases and insects. The drip method lends itself readily to removing such material, because the spray may be eliminated simply by thoroughly flushing the sand after spraying. Spray material also can be easily eliminated from the subirrigation system. To get rid of the material it is necessary to have two drains, with valves, from the culture tank.

After spraying, the sand or gravel is flushed with the valve on the drain to the reservoir closed and the valve on the drain to the sewer opened. In this manner the spray material is eliminated. Elimination of spray with the water system is a little more difficult but can be done by two methods. The first would include changing the solution every time the plants are sprayed. The second would make use of a waterproof material, such as oilcloth, to keep the spray out of the nutrient solution.

Some other pitfalls of which only mention will be made are lack of frequent addition of iron, renewing the solution with water which is too cold, failure to eliminate natural or artificial gas leaking into the enclosure where plants are grown, the heating system of nutrient solutions getting out of adjustment, and improper temperatures for growing plants.

POSSIBILITIES AND LIMITATIONS OF NUTRIENT SOLUTION CULTURE

The capital outlay necessary for the installation of a system for growing plants in nutrient solutions is so large that this method of culture will probably not replace soil for growing most crops out of doors. Exact construction figures are not available, but estimates range from $4,000 to $8,000 dollars per acre. In a climate similar to Ohio's, where the growing season is limited, it hardly seems probable that field or vegetable crops would pay dividends on such a large investment. With greenhouse-grown crops, however, the picture is entirely different because of the larger gross returns and the plant disease problems of these crops.

A very low percentage increase in yield on a $10,000 gross return per acre of glass would pay the interest on such an installation and a little more, make the installation of such a system profitable. The plant disease situation in greenhouses is so serious that it is necessary to steam-sterilize greenhouse soil at least once each year. The apparent cost of this sterilization is between $150 and $300 per acre per year, but the actual cost is much greater because of the physical and chemical damage to the soil. This loss makes itself apparent in several ways, some of which are blossom-drop, actual stunting of plants, and, in a few instances, death of plants. Such losses are difficult to estimate and impossible to eliminate as long as soil is the medium used for growing plants in greenhouses. Solution culture may provide a means for eliminating the losses from soil-borne plant diseases in greenhouses.

Up to the present, however, it has not been thoroughly demonstrated that nutrient solution culture is ready for commercial exploitation. It is an excellent research tool and has given scientists considerable insight into the nutritional requirements of plants. Efforts are being made to develop the method for popular use, but although such things as the daily addition of iron and adjustment of reaction are routine procedures where the necessary apparatus is available, they become limiting factors for commercial work where such apparatus is not available. Furthermore, there are many other problems to which the answers are unknown.

The question of whether nutrient solution culture is ready for commercial usage reduces itself to this: Is sufficient known about the nutritional requirements of plants to make rule-of-thumb directions so that plants can be grown without the care of a plant physiologist? Present attempts with small-scale commercial installations may be able to answer the question. It does seem safe to suggest that even if the point has not yet been reached where it is possible to grow plants commercially in greenhouses by the use of nutrient solutions, it may be feasible to do so in the not too distant future.

Again, it should be emphasized that the purpose of this publication is not to tell people how to make a great success of nutrient solution culture, but to present an unbiased discussion for those who are interested and request information.

REFERENCE LIST

This list of references is included for those who wish to obtain a broad knowledge of nutrient solution culture. The experiment station publications can be obtained by writing to the stations publishing them. Access to the articles published in scientific journals can be obtained at large libraries.

1. Arnon, D. I. 1938. Microelements in culture solution experiments with higher plants. Amer. Jour. Bot. **25:** 322-325.
2. Biekart, H. M., and C. H. Connors. 1935. The greenhouse culture of carnations in sand. N. J. Agr. Exp. Sta. Bull. 588: 1-24.
3. Chapman, H. D., and G. F. Liebig, Jr. 1938. Adaptation and use of automatically operated sand-culture equipment. Jour. Agr. Research **56:** 73-80.
4. Clark, H. E., and J. W. Shive. 1934. The influence of the pH of a culture solution on the assimilation of ammonium and nitrate nitrogen by the tomato plant. Soil Science **37:** 459-476.
5. Davidson, O. W., and M. A. Blake. 1938. Nutrient deficiency and nutrient balance with the peach. Proc. Amer. Soc. Hort. Science **35:** 339-346.
6. Davis, A. R., and D. R. Hoagland. 1928. An apparatus for the growth of plants in a controlled environment. Plant Physiology **3:** 277-292.
7. Eaton, F. M. 1936. Automatically operated sand-culture equipment. Jour. Agr. Research **53:** 433-444.
8. Fisher, P. L. 1935. Responses of the tomato in solution cultures with deficiencies and excesses of certain essential elements. Md. Agr. Exp. Sta. Bull. 375: 283-298.
9. Gericke, W. F. 1933. Fertilizing unit for growing plants in water. U. S. Patent Office, Patent No. 1,915,884. June 27, 1933.
10. ———— and J. R. Tavernetti. 1936. Heating of liquid culture media for tomato production. Agr. Engineering **17:** 141-142 and 182.
11. Hibbard, R. P., and B. H. Grigsby. 1934. Relation of light, potassium and calcium deficiencies to photosynthesis, protein synthesis, and translocation. Mich. Agr. Exp. Sta. Tech. Bull. 141: 1-39.
12. Hoagland, D. R., and D. I. Arnon. 1938. The water-culture method for growing plants without soil. Cal. Agr. Exp. Sta. Cir. 347: 1-39.
13. ———— and W. C. Snyder. 1933. Nutrition of strawberry plant under controlled conditions: (a) Effects of deficiencies of boron and certain other elements: (b) susceptibility to injury from sodium salts. Proc. Amer. Soc. Hort. Science **30:** 288-294.
14. Hutchison, C. B. 1938. Hydroponics as viewed by California. Market Growers Jour., Jan. 15, 1938: 46-49.

15. Jones, L. H. 1938. Soil temperature important factor in chlorosis of gardenias. Florist's Review 81: 19-20.

16. Laurie, Alex, and G. H. Poesch. 1939. Commercial flower forcing, 2nd edition, pages 112-123. P. Blakiston's Son & Co., Inc., Philadelphia, Pa.

17. Link, G. K. K. 1935. The Chicago soil-nutrient-temperature tank. Science N. S. 81: 204-207.

18. Robbins, W. R. 1929. The possibilities of sand culture for research and commercial work in Horticulture. Proc. Amer. Soc. Hort. Science 25: 368-370.

19. Shive, J. W., and W. R. Robbins. 1937. Methods of growing plants in solution and sand culture. N. J. Agr. Exp. Sta. Bull. 636: 1-24.

20. Tharp, W. H. 1938. A sand-nutrient infection technique for the study of Fusarium wilt of cotton. Phytopathology 28: 206-209.

21. Trelease, S. F., and H. M. Trelease. 1935. Changes in hydrogen-ion concentration of culture solutions containing nitrate and ammonium nitrogen. Amer. Jour. Bot. 22: 520-542.

22. Wagner, Arnold. 1938. Gravel and cinder culture. Monthly Bull. Ohio Florists' Assoc. No. 106: 1-10. July 1938. (Issued by The Ohio State University.)

23. ————. 1939. Gravel and cinder culture for greenhouse flowering crops. Mimeographed outline, Div. of Floriculture, The Ohio State University.

24. ———— and Alex Laurie. 1939. Gravel culture of flowering plants in the greenhouse. Ohio Agr. Exp. Sta. Bimonthly Bull. **XXIV**: 198: 47-52.

25. Withrow, R. B., and J. P. Biebel. 1936. A sub-irrigation method of supplying nutrient solution to plants growing under commercial and experimental conditions. Jour. Agr. Research 53: 693-702.

26. ———— and ————. 1937. Nutrient solution methods of greenhouse crop production. Ind. Agr. Exp. Sta. Cir. 232: 3-16.

This page intentionally blank.