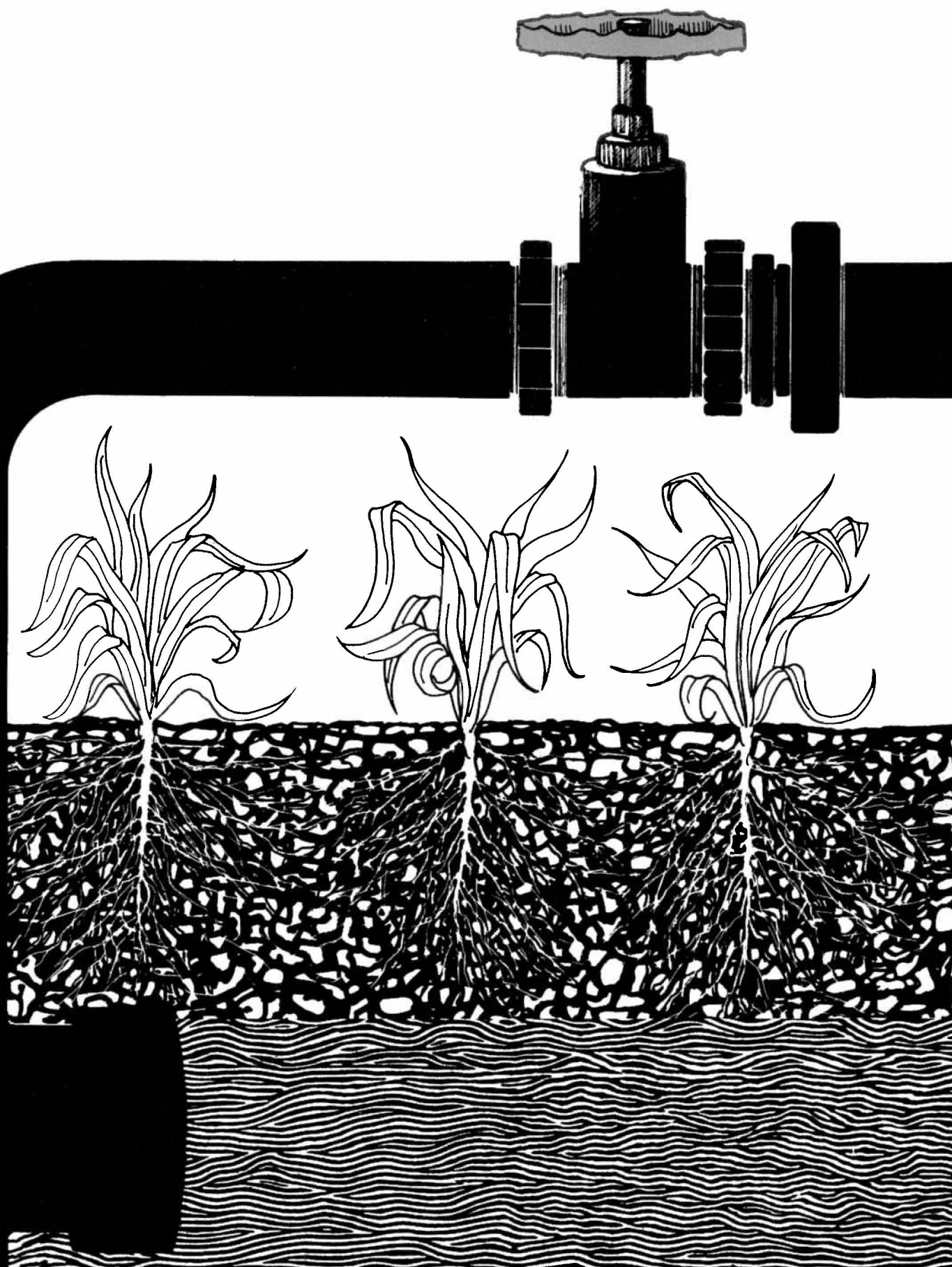


HYDROPONICS

COLORADO STATE UNIVERSITY
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HYDROPONICS

by

Joe J. Hanan

W. D. Holley*

Department of Horticulture

Colorado State University Experiment Station

Fort Collins, Colorado

**Professors, Department of Horticulture, Colorado State University, Fort Collins.*

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
What Is Hydroponics? (synonyms for the word).	1
Why Not Hydroponics? (for those interested in commercial production)	1
Advantages and Disadvantages.	2
Systems (from quart jars to large scale).	3
Construction Materials.	5
Substrates (soils and gravel)	5
Irrigation Systems (how to water)	6
Water Quality	8
Fertilizer and Nutrients (how to feed).	8
Automatic Injection	12
A Note on Special Crops	12
Appendix A - SCHEMATIC WIRING DIAGRAM	15
Appendix B - UNITS AND CONVERSIONS	16
Appendix C - DEFINITIONS	17
Appendix D - CHEMICALS, FERTILIZERS, NAMES, AND WEIGHTS.	19
Appendix E - LIST OF SUPPLIERS	20
Appendix F - LIST OF PUBLICATIONS	21

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1 Particle size distribution and moisture holding capacity of various inert media suitable for hydroponics systems	6
2 Hoagland and Arnon's solutions for general use.	9
3 Hoagland and Arnon's stock solutions for general use	10
4 Nutrient solution for carnations	10
5 Nutrient solution for roses	10
6 Translation to milliequivalents of Hoagland and Arnon's solutions in Table 3	10
7	11
8 Milliequivalents per pound of fertilizer when added to 1,000 gallons of water	11
9 Pounds per 1,000 gallons for carnations	12
10 Pounds per 1,000 gallons for roses.	12

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Carnations in inert media, non recirculating water, with gates peripheral watering system and automatic fertilizer injection	2
2	Chrysanthemums in inert media, steel beds, recirculated	2
3	Small scale hydroponics system using gravel and a sand filter	3
4	Water loss from carnations per day (E_t). One millimeter refers to depth of water, whether it covers one square inch or one acre. One millimeter over one square foot is about 6.3 tablespoons of water	4
5	Hydroponics systems	4
6	Gates system on a non recirculating gravel system 180-degree spray nozzles 20 inches apart	7
7	Ooze tube system for watering pots. Larger systems may be obtained for benches.	7
8	Double-wall low pressure system on gravel, (28-36 inch water column). Drip holes spaced every four inches.	7
9	Types of nozzles used with the gates system. To improve nozzles, ream out delivery hole until it is of equal diameter throughout the stem, and cut back plate with hacksaw to bring delivery hole ahead of back plate and remove any burrs. The white nozzle is very good, but delivers more water at equal pressures than the others	7
10	Effect of increasing salt concentration on growth. Note the effect of concentration is less if the solution is properly balanced as contrasted to the use of Na_2SO_4 to increase the concentration. A 1.0 strength solution is the standard employed for carnations at Colorado State University	8
11	Smith injector, normal dilution 1 to 200	13
12	Precision injector, variable dilution, note two injectors for different nutrients	13
13	Inexpensive "hoze-on" proportioner roughly 1 to 20 dilution, varying with pressure and flow	14
14	Surplus coal stokers modified for feeding fertilizers into a known volume of water prior to watering	14

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
15	Small Jabsco pump which is ideal for small hydroponic systems	14
16	One to forty diluter with higher precision than "hoze-on," but more expensive	14
17	Schematic wiring diagram for timer	15

INTRODUCTION

This bulletin is in response to numerous requests for information about hydroponics from hobbyists and commercial growers. It is based on work conducted at Colorado State University and information from other research stations. In this bulletin, there is sufficient information for the layman to get started, and a few items for a potential commercial operation. With the exception of nutrition, specific crops (e.g., tomatoes, lettuce) are not dealt with; rather, they are subjects requiring special treatment in separate bulletins. To the enthusiast, the approach may seem negative, but it is often observed that large sums are wasted on ill-conceived projects. Small scale plant culture is entirely different from the culture of several thousand plants for economic return. The subject is fascinating, and has contributed much to the understanding of plant growth. The general hobbyist should consult James Sholto-Douglas' "Beginner's Guide to Hydroponics" for more information.

Any plant can be grown in a hydroponics system. Part of the fascination comes from the fact that almost any system will produce acceptable growth. The following should be noted:

1. Dwellings are frequently very dry with low light, and this, coupled with high temperatures, may have more of an effect on growth than a hydroponics system; obtain the best possible light; increase humidity to 50 percent or more; and, for nontropical plants, reduce temperatures below 75° F during the day and 65° F at night, and water frequently.
2. Plants will not grow well unless all essential elements are present in reasonable amounts. Most hobbyists do not have the necessary equipment to mix solutions having a volume of less than 25 gallons and still provide the proper proportions. Any number of commercial preparations can be purchased at the supermarket. A little experimentation will determine the proper amounts.
3. The larger the particles in the substrate, the more often it must be watered. There is no need to make a special drainage system; for example, clay, plastic pots or polyethylene bags can be used.
4. For the cultural requirements of specific crops (e.g., temperatures, light, diseases) contact your local county extension agent or write to the land-grant agricultural university in your state.

What Is Hydroponics?

The word "hydroponics" was coined many years ago to describe plant culture in inert soils where nutrients and water are supplied from storage tanks, saved, and recirculated as needed. The start of the "classical system" is attributed to W. C. Gericke in the 1930's, although the idea of using solution culture and gravel preceded Gericke by many years. In the 1940's, Hoagland and Aron summed up the situation by pointing out that "hydroponics," "nutriculture," "solution culture," "slop culture," "gravel culture," and similar forms will not solve anything by themselves. At present, there are very few successful commercial producers, and hydroponics is largely confined to experiment stations where plant nutrition is being studied.

Why Not Hydroponics?

First, it should be emphasized that a hydroponics system is only part of the total plan required to grow plants. Plants respond to temperature, light, pruning, insects, disease, and just about everything else imaginable. It is not reasonable to install the finest system possible, then neglect the other factors that help produce growth. On a small scale, outstanding plants of any kind can be produced hydroponically, such as tomatoes, radishes, lettuce, carnations, roses, cabbage, spinach, and *ad infinitum*. The money spent by the hobbyist to grow plants is not expected to provide a return sufficient enough to earn a living. A reasonable living involves thousands of plants, substantial monetary investment, and substantial knowledge of the particular plant's requirements.

A person contemplating hydroponics for commercial crop production should consider the following:

1. An initial investment of \$3 to \$5 per square foot in a 20,000 to 30,000 square-foot greenhouse should be expected when using conventional soil culture. If a six percent return can be obtained merely by putting money in a savings account, then you should expect a substantial return on the same amount in



Figure 1. Carnations in inert media, non-recirculating water, with gates peripheral watering system and automatic fertilizer injection.



Figure 2. Chrysanthemums in inert media, steel beds, recirculated.

order to compensate for labor, worries, and risk. The cost of a hydroponics installation will depend upon the type of system used. The system employed by commercial carnation growers in Colorado may add little to the initial capital investment; on the other hand, a conventional hydroponics system, using water-tight benches, storage tanks, and pumps may double the unit cost.

2. Growing 50 to 100 plants takes skill, but attention can be given to each plant with all plants receiving "tender loving care." Growing 10,000 plants is another matter--a college degree is not required, but it does require knowledge and ability to observe plant growth, as well as managerial competence and basic accounting skills. The grower must be familiar with the requirements of different varieties, insects, diseases; the effects of different temperatures and light; and the use of basic pesticides, fungicides, and fertilizers. The best hydroponic system is worse than nothing, if one lacks knowledge in the other areas. Commercial hydroponics is less forgiving than soil culture--the risk of failure is higher.

3. About 25 percent of production costs are selling, grading, packaging, and transporting the product. First, the market should be examined and the following determined: who will buy it; where it will be sold; how much can be sold at what price; how far does it have to be transported; should it be packaged and graded; should advertising be purchased; and, will there be competition for the same market? The cost of borrowing capital must be added to production costs. Further considerations should include: water supply and its quality; availability of fuel and electricity; and flexible operation's plans which will allow for possible local labor supply and delays in delivery.

Information on the above aspects of commercial production is often difficult to obtain. It may be proprietary and very little is published. The specialist at the state agricultural university is a good initial information contact, as well as producers and sellers of various hydroponic products.

Advantages and Disadvantages

All plants require water. The amount they use depends upon how much energy (sunlight) is available to cause them to evaporate water, as well as the amount of water supply available to the roots. From 70 to 95 percent of all energy in sunlight goes to evaporate water

from well watered, nonwilted plants. If demand exceeds supply, the plant is stressed or wilts. A hydroponic system's major function is to provide freely available water to the root system. This cannot be done as easily in soils because too much water will cut off the oxygen supply, which kills the roots. As soils dry out between irrigations, some stress is unavoidable. Maximum amounts of water can be supplied in the usual types of hydroponic mixtures because pore space is large and their water holding capacity is usually low.

The more light available, the greater the advantage in yields hydroponics will offer. Plants in a high light intensity, arid climatic region, will show more response to a hydroponics system as contrasted to the northwestern United States or New England.

All the necessary elements for growth can theoretically be provided in correct amounts. In practice, it is difficult to supply a constant ratio and concentration of essential elements without expensive analytical equipment. It is desirable to make some provision for adding small amounts of elements to replace those exhausted by the plants during growth. It is also difficult to supply plant requirements as to correct element ratios, acidity, and tolerance to salts, because these vary with light, water, temperature, and other factors.

Not all plants require the same environment. For example, the greenhouse environment for roses is deliberately manipulated to reduce water requirements. The response of commercial roses grown directly in gravel is usually comparable to roses grown directly in good soil. On the other hand, carnations show greater response in gravel because they are grown in a drier environment.

In many regions of the world, hydroponics may be utilized because there is no soil or the available soil is unsuitable. If the water supply has high sodium, hydroponics may be the only acceptable system since excessive sodium causes soil structure to break down and lose its desirable characteristics. Obviously, hydroponics may be the only practical solution in space flights or for moon inhabitants. City dwellers may practice hydroponic culture successfully as a hobby and to provide variation in their diet. A recirculating system offers some advantage in water conservation, particularly in desert regions;

however, the high sunlight in most desert regions increases water utilization. The water requirements for a bushel of corn may be 600 to 800 pounds of water, while a succulent plant such as lettuce or tomatoes requires even more water.

Recent research information at Colorado State University, Fort Collins, indicates that hydroponics offers a solution to water pollution by preventing loss of nutrients to the ground water. Studies have shown, even in the nonrecirculating hydroponics system, that the amount of salts lost from gravel is markedly less than from soils. The research points out the possibility of increasing fertilizer efficiency by the judicious employment of appropriate nutrient concentrations and watering systems. Thus, although a hydroponics system may be less forgiving than soil, it is more flexible. In the final analysis, under suitable climatic conditions, and with all other factors being equal, hydroponics may offer a 20 to 30 percent yield increase over comparable soil culture. The important point to keep in mind is that good soil will usually forgive most mistakes; hydroponics systems will not (e.g., root media will be unbuffered, too much fertilizer can easily burn the plants, and neglected watering systems may damage plants and spread disease).

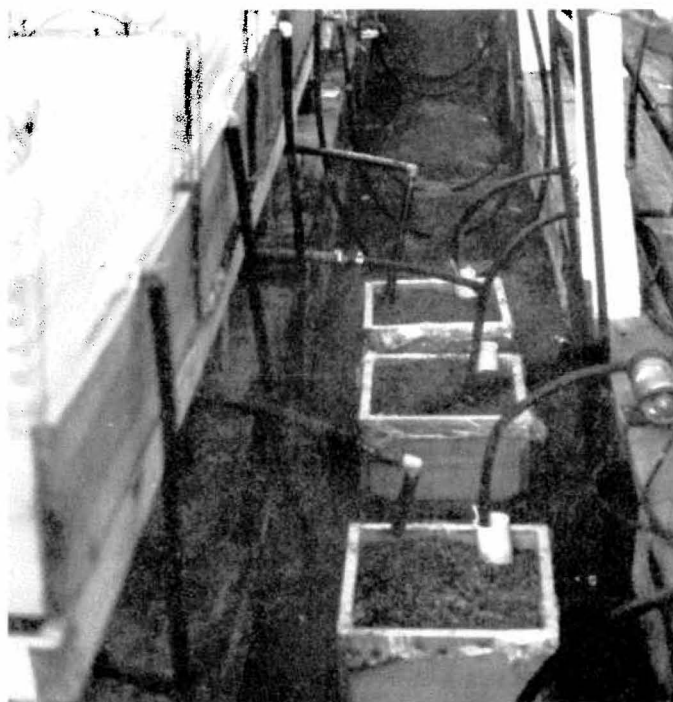


Figure 3. Small scale hydroponics system using gravel and a sand filter.

Systems

The design of hydroponics systems is practically unlimited. Quart jars and a nutrient solution are adequate. Trays with some type of netting to support the plants as they grow directly in nutrient solutions have also been employed by students in botany laboratories for years. However for best results, solutions without a supporting medium need to be vigorously aerated. Even more striking is the process of "misting" the root system with a nutrient solution. In this process, plants are supported,

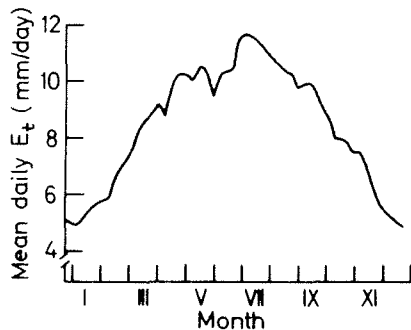


Figure 4. Water loss from carnations per day (E_t). One millimeter refers to depth of water, whether it covers one square inch or one acre. One millimeter over one square foot is about 6.3 tablespoons of water.

with the roots in a dark cabinet, and a pressure pump with spray nozzles supplies a fine mist at frequent intervals to the root system. Present information indicates this system has not been employed commercially.

A more conventional style is outlined in Figure 5. System A is the simplest and requires the following: 1) a tray to hold plants, 2) a tank for the nutrient solution, 3) a pump and control system, and 4) a suitable connecting pipe. The solution is pumped into the plant tray and allowed to drain back to the storage tank through the pumps. In all systems, an automatic clock assures that the plants receive water (see app. A). Some device or time regulator should be included to prevent an overflowing of the plant tray.

System B is complicated by separate delivery and drain lines. The storage tank could be placed above the plant tray if this is more convenient. In both A and B systems, the plant tray is usually flooded and then allowed to drain.

System C seeks to overcome debris accumulation by using a filter system under the plant tray. Most fungi and bacteria can be filtered out by passing the drain water through a diatomaceous earth filter. There are other more convenient filtration systems for removal of large debris.

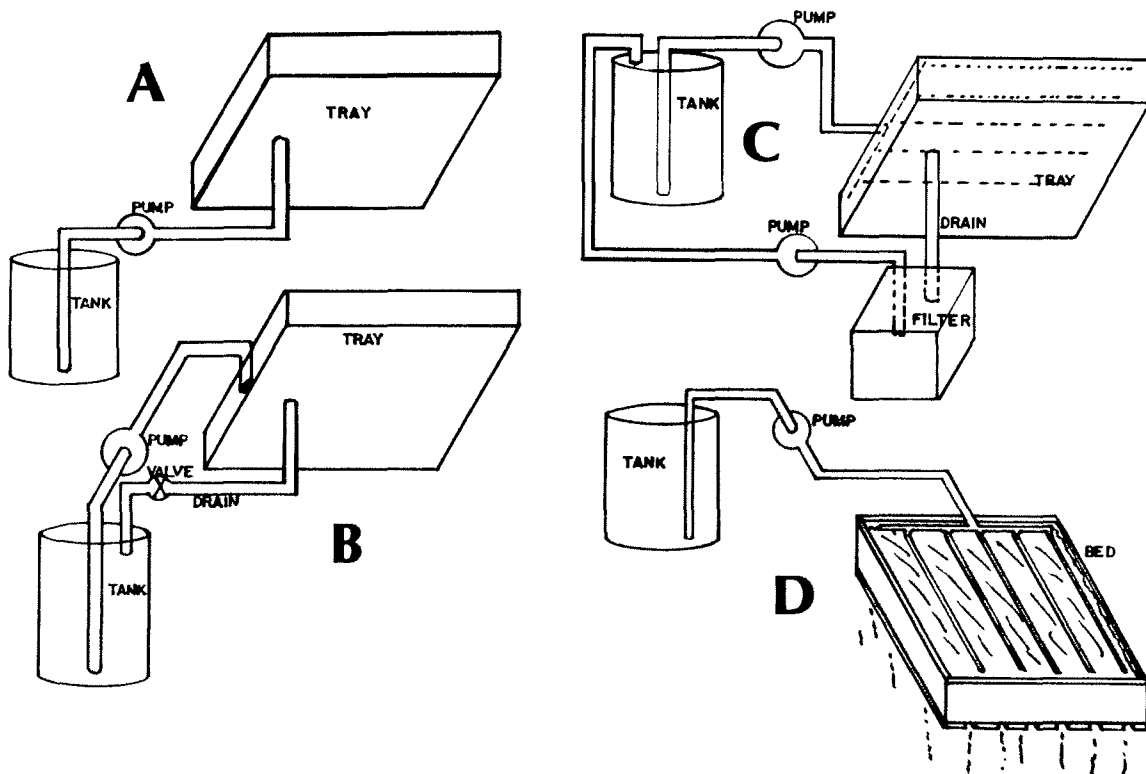


Figure 5. Hydroponics systems.

It should be noted there are numerous plant parasites that may be spread by water. Root rots caused by species of *Pythium* are the most obvious. Any organism that is capable of growing inside the plant has the potential to be spread through a recirculating system. Present information indicates this possibility has not been thoroughly examined.

The application pump in system C can be run on its own timer by applying water from the storage tank to the medium surface through an irrigation system. The drain water is returned to the storage tank whenever convenient.

Storage tanks and delivery lines should be opaque to reduce algal growth. The top of the filter box should have a layer of black plastic over its surface to prevent algal growth. Attempts to prevent or remove algal growth by adding materials to the solution are dangerous. Copper, while an important trace element necessary for all plants, becomes toxic if used in sufficiently high concentrations to prevent algae. No additions, other than those absolutely necessary for normal plant growth, should ever be made to the nutrient solution. Commercial producers may use special insecticides and fungicides that are absorbed by plants, but these are very carefully controlled to prevent toxicity and contamination. Also, the Food and Drug Administration has stringent requirements that must be met for plants that are eaten. Compounds for disease control often have high toxicity to humans and should not be used by untrained individuals.

System D is a modification of the traditional hydroponics method and similar to that employed on a large commercial scale in Colorado. This system differs from the others in that it automatically injects the nutrients as the plants are watered as opposed to a pump and storage tank system. The nutrient solution is not recirculated. Water and chemicals are wasted in this system, not to mention increasing pollution problems. However, System D has some outstanding advantages including the following: 1) there is little danger of spreading disease, 2) the same nutrient solution is applied at each watering, and 3) the cost of watertight storage and plant tanks is eliminated; on the other hand, the construction and operation of the irrigation system is critical. This system has been found commercially feasible for carnation production in Colorado. Most growers have the necessary equipment installed

and merely substitute gravel for soil; however, a period of adjustment is often necessary to become familiar with the system as it is less forgiving than soil. Some growers have converted back to soil because they are more comfortable with soil culture or are not convinced that additional yield warrants the difficulties.

There are many other types of systems to be considered. In some commercial greenhouses, the soil is formed into "V" trenches, the ground is covered by heavy plastic drain lines installed in the "V" and then the entire area is covered with six to eight inches of gravel. This provides a nonrecirculating hydroponics system which could be converted at a later date to recirculation.

Construction Materials

Fertilizer salts are corrosive. Metal parts, particularly pumps which are not made for hydroponics' use, will wear out in a short time or become clogged. On the other hand, galvanized materials may release sufficient zinc to cause toxicity symptoms. Copper materials offer the same problem. Plastic pipes and fittings, pumps with plastic impellers, and plastic tanks are noncorrosive and should be utilized. Plant trays can be built of wood and lined with plastic film such as black or clear film, at least six mil thickness.

During World War II, concrete was employed in numerous commercial operations. It has the advantages of permanence and resists corrosion admirably, but the cost is usually the highest of any material. Therefore, the availability of redwood made it the most often used construction material. With increasing costs, many commercial growers have found it more economical to grow directly in the ground or line trenches with appropriately formed plastic before placing the root substrate.

Substrates

Almost any material may be used as a substrate if it is inert, does not decompose, and is not too fine. Table 1 shows characteristics of some media that have been examined as soil for hydroponic systems. In general, river-washed, granitic gravel is competitive in price with soil mixtures. If much more than five percent of the sand and gravel passes through a 50-mesh screen, it is likely to hold too much water and not enough air. Plants may be grown in it, but the advantage over soil is lost.

Rock between 1/2 to 3/4 inch in diameter is acceptable, if irrigation frequency is increased to provide sufficient water. Volcanic ash, or scoria, has a tendency to break down, which increases the fine particles and the water holding capacity of the root medium. Under Colorado's semiarid conditions, a good medium can be watered every hour without reducing aeration enough to damage the root system. On the other hand, this frequent watering could be extremely wasteful depending on the system being used.

A coarser medium can be used at a shallower level in the plant tray; thus, a four-inch depth of 1/2 to 3/4 inch diameter gravel can be used if watered frequently. A finer mixture needs increased depth to assure drainage in the upper layers, and six to seven inches is the common depth.

Each time a hydroponics system is replanted, some roots will be left and the moisture holding capacity of the mixture gradually increases; consequently, watering frequency may need to be reduced each year. Over the years, this will result in a graveled soil and the advantage over a soil system will be lost. This change to a graveled soil may take relatively long time.

Vermiculite is not recommended as a medium since it may contain considerable potassium and tends to collapse and lose its structure after six to twelve months. The material called perlite is acceptable, but tends to float out of a flooded tray and offers little support until the root system is firmly established. Peatmoss may also be used, but

it is an organic material, definitely not inert, and has peculiar handling problems.

Irrigation Systems

With conventional hydroponics, flooding (i.e., filling the plant tray until water appears at the surface) is the usual method of watering. For example, a half-tile or a perforated plastic line about two to three inches in diameter is laid lengthways in the tray with a connection above the substrate surface, and is used to fill and drain the tray as needed.

If the nutrient solution is to be applied to the surface and allowed to drain, there are several good systems. The peripheral gates system, figure 6, is widely used on soil, but possible high pressure is likely to damage foliage and diseases can be spread through splashing water. The pressure at a single 180-degree spray nozzle should not exceed four pounds per square inch with 18 to 24 inch spacing between them. The nozzle angle should be as close to horizontal as possible. If the bed is wider than 36 inches, a third line in the center is required. The common nozzle may be improved for better spray distribution (see fig. 9).

Newer systems such as double-wall tubes or ooze tubes work well if a line is laid between each row. These systems are advantageous because no water is splashed on the foliage, but they are more expensive. In very coarse substrates, the lateral water flow in the

Table 1. Particle size distribution and moisture holding capacity of various inert media suitable for hydroponics systems.

Material	Percent of particles with diameters larger than:				Percent of particles with diameters smaller than 0.02"	Water holding capacity of the medium 7" deep. (qts/sq.ft)
	0.2"	0.12"	0.04"	0.02"		
Granitic sand and gravel	7.1	25.7	75.6	98.2	1.8	3.3
Large Idealite*	100.0	--	--	--	--	1.5
Regular Idealite*	42.3	76.7	98.9	99.4	0.5	1.8
Fine Idealite*	0.00	0.00	53.9	94.9	5.0	4.5
River sand and gravel**	23.7	83.0	95.5	98.8	1.4	2.0
Volcanic ash***	46.7	62.0	79.1	92.0	7.1	5.8

* Artificial, light-weight concrete aggregate, made from a fired illite shale.

** Commonly called "squee-gee," major portion with particles about 1/4 inch diameter.

*** Commonly called "scoria," prone to crumbling with buildup of fine particles. Water holding capacity may exceed a good greenhouse soil.



Figure 6. Gates system on a nonrecirculating gravel system, 180-degree spray nozzles 20 inches apart.



Figure 8. Double-wall low pressure system on gravel, (28-36 inch water column). Drip holes spaced every four inches.

medium may not be far enough. With frequent irrigation using spray systems on gravel, the lower parts of plants may stay wet continually and lead to large disease loss. Other "drip" systems that drip every 12 to 19 inches are not suitable. The distance should not exceed four to six inches between driphole locations. A new porous tubing that releases water along its entire length is still undergoing tests.

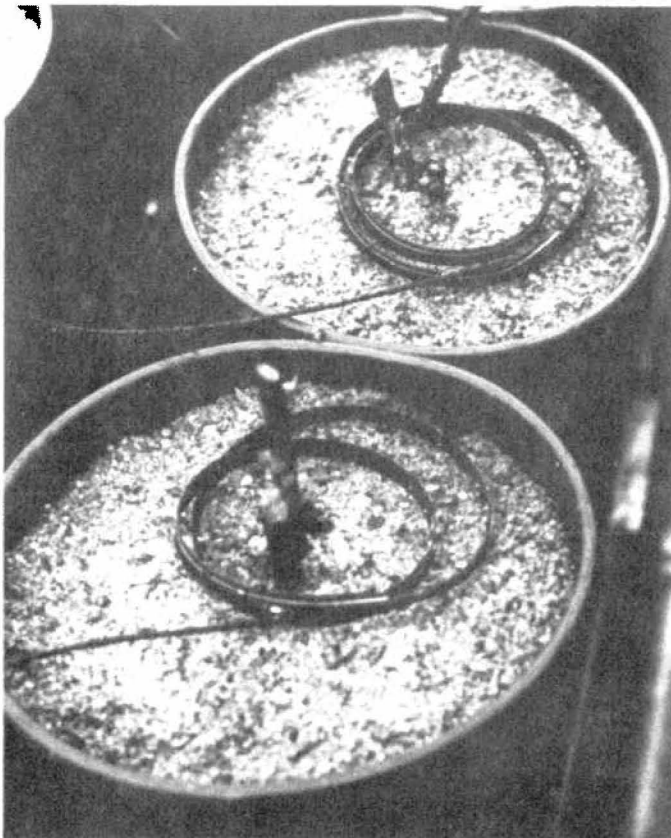


Figure 7. Ooze tube system for watering pots. Larger systems may be obtained for benches.

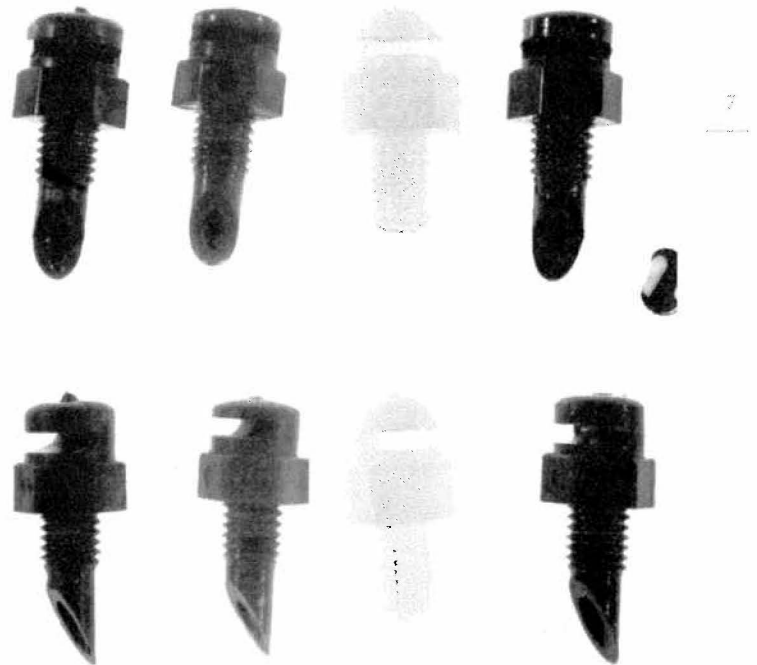


Figure 9. Types of nozzles used with the gates system. To improve nozzles, ream out delivery hole until it is of equal diameter throughout the stem, and cut back plate with hacksaw to bring delivery hole ahead of back plate and remove any burrs. The white nozzle is very good, but delivers more water at equal pressures than the others.

Watering frequency will vary with atmospheric dryness and sunlight. The frequency can be reduced to once daily in January, skipping dark and overcast days, and increasing the frequency through the spring and summer up to six times daily. Some growers, who may be into their second or third year in inert media, find it necessary to cut this frequency in half. If the water is high quality, the bed need be watered only to dripping. If salty, water may be needed until the bed drains freely for some minutes. About 45 seconds per irrigation is required with the gates system and up to eight minutes for ooze systems with good water.

Ooze systems are susceptible to blockage from sand and debris in the water supply. Salt precipitation may clog the orifices; therefore, ooze and other drip systems need good filters in the supply line. Manufacturers' recommendations suggest using 100-mesh screens which should be cleaned at regular intervals.

Water Quality

Good quality water is essential. As the salt concentration increases, growth decreases as shown in figure 10. Obviously, pure water is desired since nutrients must be added for plant growth. If salts are already present, the necessary elements will increase total salt content and growth will be correspondingly less. There is no sharp dividing line as to the economics of the system, because costs, prices received, and other factors determine the break-even point.

A grower is interested in the total salt concentration of the water and the concentration of the individual salts. Total salts may be expressed several ways, such as grains per gallon of hardness, milligrams, parts per million (ppm) and electrical conductivity in millimhos per centimeter (mmhos/cm) (see app. B for conversions). Water with an electrical conductivity (EC) below 0.5 mmhos/cm is very good. Nutrients added to such water will result in EC ranging from 2.0 to 3.0 mmhos/cm. If the water already contains 1.0 to 2.0 mmhos/cm, a final salt concentration which is near or in excess of 3.0 mmhos/cm will be unacceptable. Water having EC between 0.5 to 1.5 mmhos/cm can be utilized by modifying the nutrient solution if individual element (ion) concentrations are known.

Water from shallow wells in Colorado will generally have high levels of calcium (Ca), magnesium (Mg), bicarbonate (HCO_3), and

sulfate (SO_4). Calcium, magnesium, and sulfate may not have to be added to the nutrient solution, if there are sufficient levels in the water. Certain fertilizer salts (e.g., ammonium nitrate) partially compensate for high bicarbonate concentrations. If the well is deep, sodium may be high and to some extent can be offset by increasing potassium (K). Domestic water supplies from the Colorado mountains will generally be high quality. Even though it may cost more, the benefits of using good water usually outweigh problems in manipulating water with high salt concentrations. Sodium will not effect an inert gravel medium. A water analysis before using the water in a hydroponics system is the safest practice to follow. For assistance, contact your county cooperative extension office.

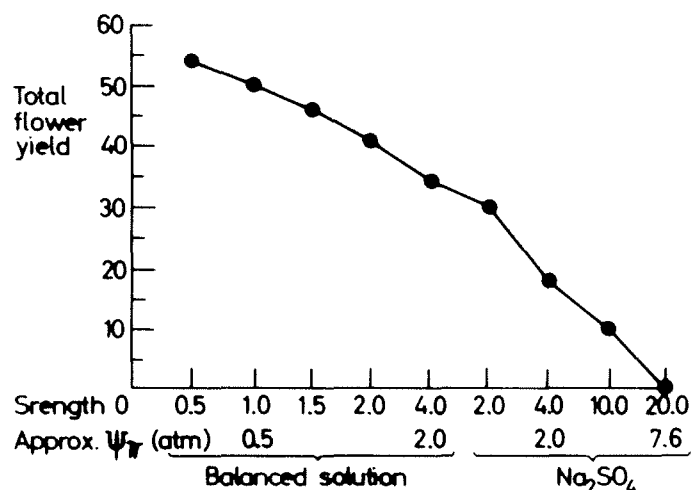


Figure 10. Effect of increasing salt concentration on growth. Note the effect of concentration is less if the solution is properly balanced as contrasted to the use of Na_2SO_4 to increase the concentration. A 1.0 strength solution is the standard employed for carnations at Colorado State University.

Fertilizer and Nutrients

All plants require certain basic nutrients including calcium (Ca), potassium (K), nitrogen (N), phosphorous (P), magnesium (Mg), manganese (Mn), sulfur (S), copper (Cu), boron (B), iron (Fe), molybdenum (Mb), and zinc (Zn). If any of these are missing from the root medium, very poor growth may result. Calcium, potassium, nitrogen, phosphorous, and magnesium are considered major elements, because the plants need more of them, and a deficiency is rapidly apparent.

Copper, boron, iron, zinc, and molybdenum are called trace elements since the plant uses very little of them. When a mature plant is transferred to a solution lacking some of these trace elements, the plant itself may contain sufficient reserves to prevent deficiency symptoms. If tap water is used, sufficient trace elements are often in the water with only a few exceptions.

For hydroponic systems with a nutrient solution storage tank, the easiest procedure for supplying the major elements is to make up stock solutions of the various fertilizer salts. Then, small amounts of each stock solution are transferred to the storage tank to make up the final solution for irrigation. Recirculating solutions should be changed about every two weeks unless provision is made for frequent analysis of the solution. Definitions and conversion factors are given in appendices B and C.

Appendix D lists the most common salts used to supply various elements, and the weight of each required to make a one molar solution or a one normal equivalent solution when dissolved in one liter of water. Not all the salts in appendix D are necessary. One quart solutions are ample for a small scale setup. Appendix D also can be used as a reference for quart solutions because the difference in volume between liters and quarts is not likely to make much change in plant growth. In mixing stock solutions, use hot water because some salts such as calcium sulfate are not very soluble. If difficulty is experienced when mixing solutions, double the amount of water and double the amounts of stock solution diluted in the final solution. If the tap water is hard, it may be impossible to dissolve all of the salt in the stock solution and distilled or de-ionized water is required.

For the general hobbyist, the following materials and amounts will grow acceptable plants. The composition in Table 2 is given for 25 gallons of nutrient solution, which is taken from Hoagland and Arnon's Circular No. 347 with some modification.

Table 2. Hoagland and Arnon's solutions for general use.

	Ounces	Tablespoons
Potassium monophosphate	1/2	1
Potassium nitrate	2	4
Calcium nitrate	3	7
Magnesium sulfate	1 - 1/2	4

or

Ammonium phosphate	1/2	2
Potassium nitrate	2 - 1/2	5
Calcium nitrate	2 - 1/2	6
Magnesium sulfate	1 - 1/2	4

In mixing solutions, always dissolve the salts before adding to a volume of less than 25 gallons. After adding all the salts, bring the final solution to 25 gallons by adding more water.

To make a stock solution of trace elements, 1) dissolve three teaspoons of boric acid and one teaspoon of manganese chloride or manganese sulfate in one gallon water; 2) dilute with another two gallons of water, and 3) use one pint for each 25 gallons of the nutrient solution. Zinc and copper may be omitted as these are usually impurities in tap water. The addition of iron will be necessary and can be accomplished by dissolving one teaspoon of iron sulfate in one quart water. One-half cup of the above iron sulfate solution should be added to 25 gallons of solution. Iron, as iron sulfate, may not be readily available to plants under certain conditions. Special iron containing compounds called chelates have the advantage over iron sulfate because if the acidity of the solution is too low, the iron gets tied up. The full name of the chelate compound most often employed is sodium ferric diethylenetriamine penta-acetate, abbreviated as Iron Sequestrene 330 or EDPA. Iron Sequestrene 138 (EDDHA) is sometimes more useful in soils or solutions with high alkalinity. One tablespoon of the material is dissolved in one quart, and one tablespoon of the stock is diluted in 25 gallons. The stock solution should not be exposed to light for long periods and should be refrigerated.

9

It may be noted from Table 2 that it is impractical to measure the required amounts for volumes less than 25 gallons and would require a very expensive scale capable of weighing to less than 0.01 ounces. Trace elements would be even more difficult. If smaller volumes are necessary, there are two alternatives the hobbyist may employ. One is to purchase a commercial preparation which is usually available in the local supermarket. Some experimentation to find the proper dilution may be necessary if the preparation is not specifically tailored for hydroponics solutions. The material must also be completely soluble in water. The second alternative is to make up stock solutions as outlined in Table 3.

For greater precision, one molar solutions (see app. C) are made up using the weights provided in appendix D. From these solutions, the following dilutions are made:

Table 3. Hoagland and Arnon's stock solutions for general use.

	Milliliters of stock solution per one liter of nutrient solution
Potassium monophosphate	1
Potassium nitrate	5
Calcium nitrate	5
Magnesium sulfate	2
or	
Ammonium phosphate	1
Potassium nitrate	6
Calcium nitrate	4
Magnesium sulfate	2

A stock trace element solution is made by dissolving the following in one liter of water:

Boric acid	2.86 grams
Manganese chloride	1.81 grams
Zinc sulfate	0.22 grams
Copper sulfate	0.08 grams
Molybdic acid	0.02 grams
Fe sequestrene 330	5.00 grams

10

Add one milliliter of the above stock to each liter of final nutrient solution. The trace element solution should be kept in the dark and refrigerated.

These solutions are acceptable for nearly all plants. In recent years, new work with nutrient solutions at Colorado State University has shown that ratios for maximum growth may shift with the season and considerable differences are apparent between species. The requirements for adequate nutrition become more stringent as the plant nears its maximum growth potential. Under these conditions, it is easier to express the concentration of the nutrient solution in terms of milliequivalents per liter (meq/l). An analogy is how many bricks there are rather than how much the bricks weigh. Each milliequivalent per liter says that there is one "brick" per liter. If there are 50 pounds of "bricks" per liter, one could have one or more "bricks," depending upon the weight of each "brick". When various ratios and proportions of "bricks" are examined, certain combinations and numbers provide better growth. For example, the best growth conditions for carnations in Colorado with good water available is provided by Table 4.

Table 4. Nutrient solution for carnations.

	Milliequivalents per liter
(K) Potassium	6
(Ca) Calcium	6
(Ma) Magnesium	1
(NH ₄) Ammonium	2
(NO ₃) Nitrate	14
(SO ₄) Sulfate	1.0
(H ₂ PO ₄) Phosphorous	1.0

For roses, however, a good solution is indicated in Table 5.

Table 5. Nutrient solution for roses.

Potassium	4
Calcium	5
Magnesium	1
Ammonium	1
Nitrate	9
Sulfate	1
Phosphorous	1

The calcium-potassium ratio is equal for carnations and has a higher level of nitrates as contrasted to roses. The total concentrations can be varied, within limits, by adjusting the irrigation frequency--for a lower concentration, a higher frequency irrigation should be used. If the water is hard, calcium, magnesium, and sulfate can usually be eliminated from the nutrient solution. If there is high bicarbonate (HCO₃⁻), ammonium (NH₄⁺) may have to be increased. The proportions of ammonium, chloride, sodium, and potassium may vary with the season.

Hoagland and Arnon's solutions, given in Table 3, translate as follows:

Table 6. Translation to milliequivalents of Hoagland and Arnon's solutions in Table 3.

	Milliequivalents per liter
Potassium	7
Calcium	10
Magnesium	4
Nitrate	15
Sulfate	4
Phosphorous	2
or	

Potassium	6
Calcium	8
Magnesium	4
Ammonium	1
Nitrate	14
Sulfate	4
Phosphorous	1

The above solutions will grow perfectly acceptable plants. Similarly, very good roses, snapdragons, chrysanthemums, gerberas, and many miscellaneous potted plants and vegetables have been grown in the carnation solution in Table 4. The same solution is used for plants in soil, gravel, artificial concrete aggregate, and volcanic ash. Growth studies show that when the plant approaches its genetic potential under suitable environmental conditions, small differences in the nutrient ratios and concentrations become increasingly important.

The solution for carnations can be made as follows.

Table 7.

Compound	Milliliters of stock solution added to one liter	Milliequivalents added per liter of final solution								
		K	Ca	Mg	NH ₄	Na	NO ₃	SO ₄	H ₂ PO ₄	Cl
KNO ₃	6	6					6			
NH ₄ NO ₃	2				2		2			
Ca(NO ₃) ₂	6		6				6			
MgSO ₄	1			1				1		
H ₃ PO ₄	1								1	
Total	16	6	6	1	2	0	14	1	1	0

11

Table 8. Milliequivalents per pound of fertilizer when added to 1,000 gallons of water.

Compound	Analysis	ppm	meq/liter	Also adds meq/liter
Ammonium nitrate (NH ₄ NO ₃)	33-0-0	40 N	1.4 NH ₄	1.4 NO ₃
Potassium chloride (KCL)	0-0-60	60 K	1.6 K	1.6 Cl
Potassium nitrate (KNO ₃)	13-0-44	16 N / 44 K	1.2 K	1.2 NO ₃
Calcium nitrate (Ca(NO ₃) ₂)	16-0-0	19 N	1.0 NO ₃	1.0 Ca
Diammonium phosphate [(NH ₄) ₂ HPD ₄]	21-53-0	25 N / 28 P	1.0 H ₂ PO ₄	1.0 NH ₄
Phosphoric Acid (H ₃ PO ₄)	0-80-0	80 P	1.5 H ₂ PO ₄	
Magnesium sulfate (MgSO ₄)		12 Mg	1.0 Mg	1.0 SO ₄

The above materials can be obtained in fertilizer grade and are correspondingly less expensive than small quantities from chemical supply houses.

One normal stock solution (see app. C) of the compounds listed are made by using the weights provided in appendix D. One milliliter of stock solution contains one milliequivalent of the ion. For each liter of final solution, six milliliters (ml) of KNO₃ are added, two ml of NH₄NO₃, and so on. In the case of KNO₃, six meq/l of K and six meq/l NO₃ are added. Once familiar with this method of making solutions, manipulation is rapid and easy, and opens unlimited opportunities to tailor the nutrient solution scientifically to the needs of the plant and its particular environment. Trace elements must be added as before, and the previous trace element stock solutions at the same concentration is included.

On a large scale with English units, it is easier to use larger units. For each 1,000 gallons of water, one pound of the following chemicals will add in parts per million or in milliequivalents per liter the amounts in Table 8.

The carnation solution is translated in Table 9.

Table 9. Pounds per 1,000 gallons for carnations.

5 lbs potassium nitrate
3 lbs calcium nitrate
1 lb ammonium nitrate
2 lbs magnesium sulfate
.67 lbs 80 percent phosphoric acid
1.0 oz borax

For roses, the solution is translated in Table 10.

Table 10. Pounds per 1,000 gallons for roses.

6.0 lbs calcium nitrate
1.66 lbs potassium nitrate
1.25 lbs potassium chloride
0.7 lbs ammonium nitrate
1.0 lbs magnesium sulfate
0.6 lbs phosphoric acid

These recommendations are for salt-free water. They will not be suitable if the water supply contains appreciable salts. The use of 1.0 ounces borax is applicable to Colorado waters where boron is usually missing. All other trace elements are generally present.

It is often easier to apply some materials dry to the root medium. Dry applications become a necessity when the water is hard. Thus, calcium in the form of limestone or gypsum, and superphosphate, will be mixed in the medium prior to planting. Calcium nitrate and phosphorous are eliminated from the solution because they may precipitate and then become unavailable to the plants, or they may clog water lines and irrigation systems if the water is hard. One inch of lime rock over the surface and 10 to 20 pounds per 100 square feet of 20 percent superphosphate before planting is adequate.

Automatic Injection

These same solutions may be injected through an automatic machine to provide constant feeding in nonrecirculating systems. For example, if a 1 to 200 dilution is available, a 50 gallon barrel will contain 50 pounds of potassium nitrate, 10 pounds of ammonium nitrate, 6.7 pounds of 80 percent phosphoric acid and 10 ounces of borax. When injected, the desired rate per 1,000 gallons will be obtained.

Note that calcium nitrate and magnesium sulfate are not included. In a concentrated form, these materials will combine with phosphorous and precipitate in the tank or water lines. A grower will often apply calcium and magnesium every other barrel, or he will employ a double-head injector with two barrels to separate the materials likely to precipitate. Borax should always be dissolved in hot water before putting it into the concentrate tank. It will not go into solution in cold water. Some fertilizer grades come pelleted and the pellet covering may settle to the bottom of the barrel. Also, salts may not go into solution completely if the water is cold. Growers often aerate the tanks to dissolve the salts or add one to two pounds of nitric acid (HNO_3) per 50 gallons to ensure solubility. Nitric acid is extremely caustic; thus, it requires special handling and is not recommended for the hobbyist.

A Note on Special Crops

Most plants are remarkably adaptive organisms. They will often survive when terribly neglected. But plants, just as humans, require a certain minimum amount of water, food, vitamins, sleep, proper temperatures, and more. Each plant species has its own particular requirements for maximum growth. In fact, a horticulturist may distinguish between varieties whose only physical differences are color, flower, or fruit on the basis of each variety's cultural requirements. Some varieties in a species require higher temperatures, others may respond to carbon dioxide fertilization, some may not tolerate high soil-water contents, still others have remarkably precise requirements in terms of daylength and alternating temperatures. Successful commercial growers are so familiar with their plants that careful observation alone will tell if temperatures have been too high or too low, if salts are too high, or if the crop has been run too dry.

This manual covers one small aspect of successful plant culture. Even the cultural requirements of one or two species is beyond the limits of this manual and information should be obtained from an agricultural state university or county extension agent. A hydroponics system may be employed in the home, a greenhouse, a growth chamber, or in a field. Publications dealing with various aspects of culture under specific conditions are available from the local authorities mentioned above who are the best information source for individual climatic conditions.

The following are references for specific crop culture.

1. Brooks, W. M. Growing Greenhouse Tomatoes in Ohio, Ohio State University Cooperative Extension Service, Columbus: Ohio State University, 1973.
2. Dalrymple, D.G. A Global Review of Greenhouse Food Production, U.S. Department of Agriculture Economic Research Serial Report No. 89, 1973.
3. Laurie, A. and D.C. Kiplinger. Commercial Flower Forcing. Philadelphia: The Blakiston Co., 1944. (There is a newer addition by Laurie, Kiplinger and Nelson.)
4. Nelson, K.S. Flower and Plant Production in the Greenhouse. Danville, Ill.: Interstate Printers and Publishers, 1967.
5. Post, K. Florist Crop Production and Marketing. New York: Orange Judd Publishing Co., 1950. (Classic in its field.)
6. Schales, F.D. and P.H. Massey, Jr. Tomato Production in Plastic Greenhouses, Publication No. 154, Blacksburg: Virginia Polytechnic Institute, 1968.
7. Wittwer, S.H. Practices for Increasing the Yields of Greenhouse Tomatoes, Michigan State University Experiment Station Circular Bulletin No. 228, East Lansing: Michigan State University, 1960.
8. Wittwer, S.H., et al. Practices for Increasing Yields of Greenhouse Lettuce, Michigan Experiment Station Research Report No. 22. East Lansing: Michigan State University, 1964.

Most of the above references deal with economic florist crops or tomatoes and lettuce. Some preliminary work at Colorado State University indicates that radishes do unusually well in gravel and have outstanding taste. Other crops that might be suitable in gravel include cucumbers, spinach, strawberries, peppers, turnips, cabbage, beets, and greens. For large scale production of these crops, particular attention should be paid to D. G. Dalrymple's Report Number 89 cited above.

As an indication of what yields might be expected in actual hydroponics practice, an anonymous survey of several greenhouse tomato producers in the Southwest showed claims of 20 pounds per plant. Excellent production of 10 pounds per plant was reported, when three square feet per plant was allowed, and five pounds was common. Dalrymple cites Liberty Hyde Bailey's statement that in 1891 the prices for tomatoes ranged from 40 cents to 80 cents per pound.

In 1970, the average Ohio wholesale price was 29 cents to 48 cents per pound. The similarity of these prices is not encouraging.

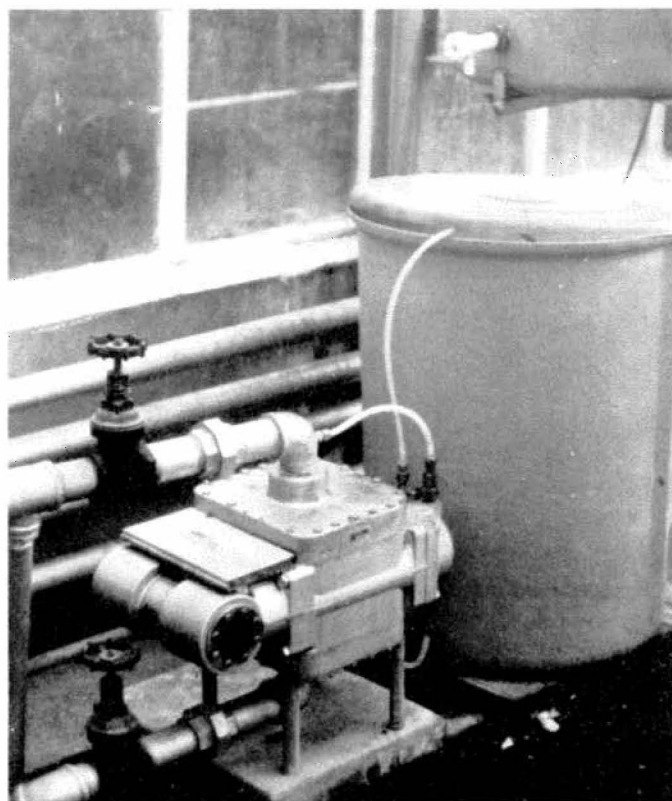


Figure 11. Smith injector, normal dilution 1 to 200.

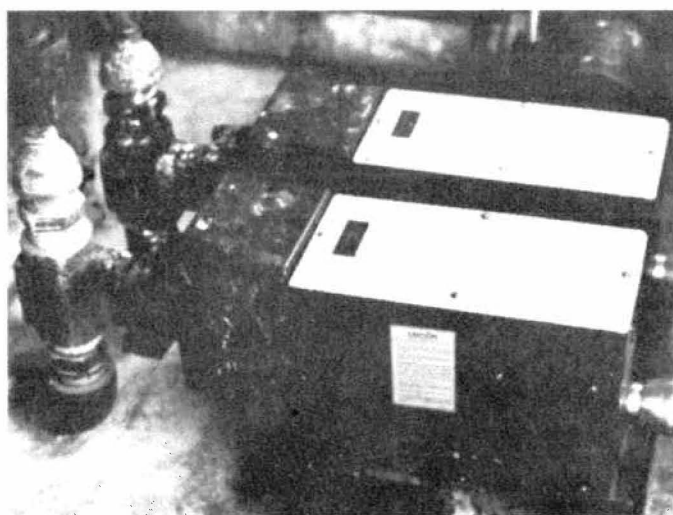


Figure 12. Precision injector, variable dilution, note two injectors for different nutrients.



14 Figure 13. Inexpensive "hoze-on" proportioner roughly 1 to 20 dilution, varying with pressure and flow.

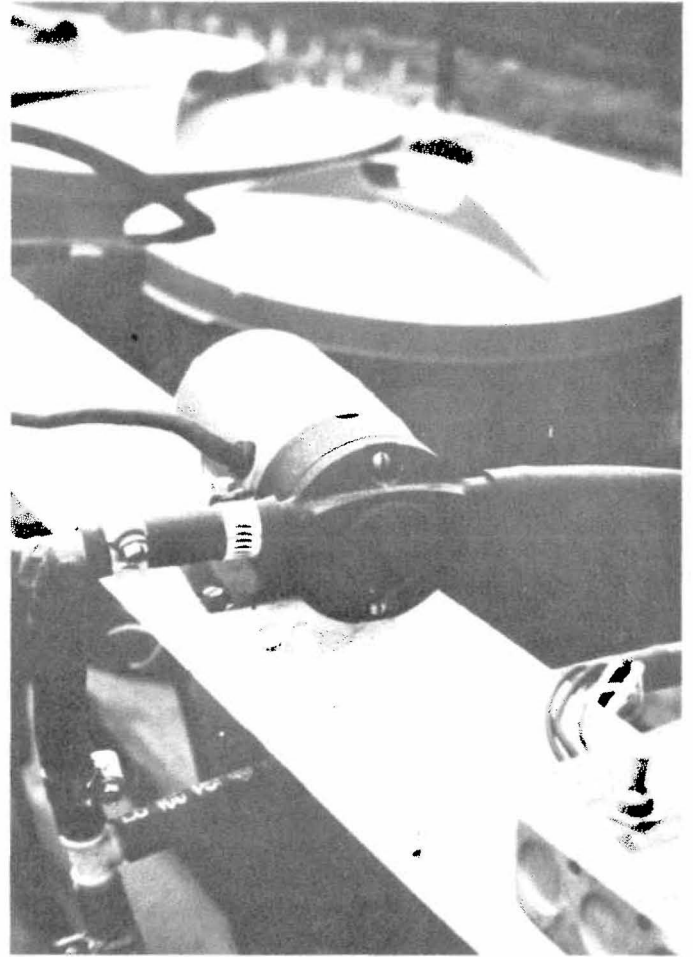


Figure 15. Small Jabsco pump which is ideal for small hydroponic systems.

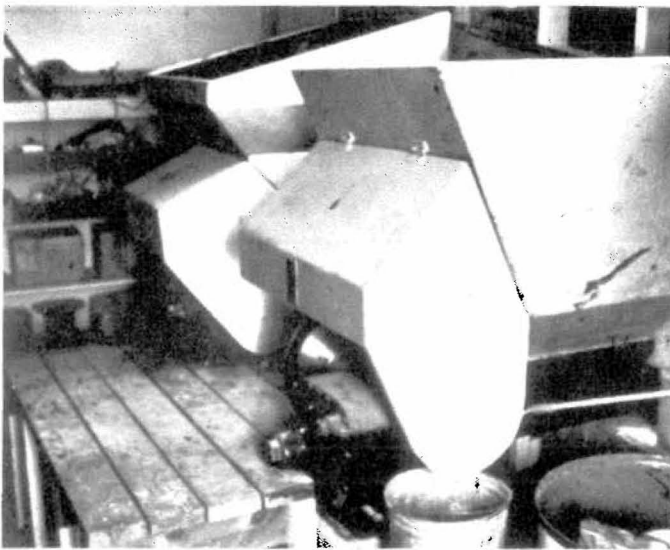


Figure 14. Surplus coal stokers modified for feeding fertilizers into a known volume of water prior to watering.

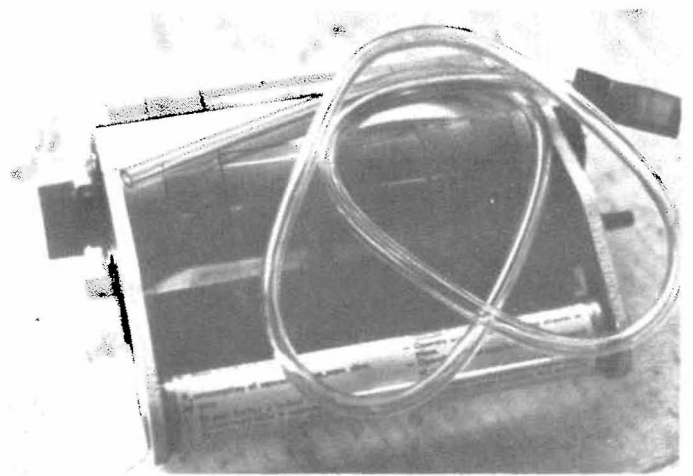


Figure 16. One to forty diluter with higher precision than "hoze-on," but more expensive.

Appendix A SCHEMATIC WIRING DIAGRAM

The schematic wiring diagram, Figure 17 shows an inexpensive timer (about \$50) to automatically water hydroponics systems.

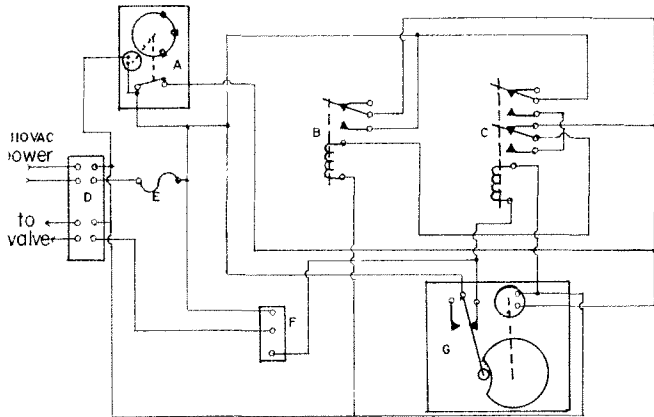


Figure 17. Schematic wiring diagram for timer.

- Parts list:
1. Item A: 24-hour clock, adjustable times, maximum number of "on" periods, once per hour, single-pole-single-throw (SPST) switch, normally open, Dayton, No. 2E025.
 2. Item B: Single-pole-double-throw (SPDT) relay, coil 110 volts alternating current (vac), Potter-Brumfield Series AB.
 3. Item C: Double-pole-double-throw (DPDT) relay, coil 110 vac, Potter-Brumfield Series AB.

4. Item D: Four junction terminal strip.
5. Item E: Cartridge fuse, two or three amp. Slo-Blo.
6. Item F: SPDT toggle switch, center position "off."
7. Item G: Cramer 527A-AH1150, or industrial timer, four revolutions per hour, adjustable cam.

- Notes:
1. If the system is used to start pumps, a heavy duty relay should be installed between switch F and the pump, rated for 25 amperes. A Potter-Brumfield Series PR relay is adequate for pumps up to 1/2 horse power.
 2. Adjustable cams on the 24-hour timer "A" will fail to operate if set too close to zero; or, if set more than 15 minutes, will cause timer "G" to go through another cycle.
 3. Timer "G" may be adjusted from about 30 seconds to 8 minutes "on."

Operation: Timer "A" initiates a cycle. A cycle may be initiated by manually flipping the switch on the timer. Relay "B" is locked in so that when "A" times out, timer "G" will continue to operate. Timer "G" makes one complete revolution in a cycle. When the switch cam reaches the detent, relay "C" operates to supply power to the irrigation system and to keep timer "G" operating. Relay "B" unlocks. When the switch cam comes out of the detent on the timer "G's" cam, relay "C" is released, stopping the system, shutting off the irrigation, and then is ready for another cycle.

Appendix B UNITS AND CONVERSIONS

For conversions of more than one of this unit	Multiply by the factor shown in this column
One cubic centimeter - - - - - (cc) or (cm ³)	0.034 oz (fluid): 0.06 in ³ : 1 ml
One gallon - - - - - (gal)	128 oz (fluid): 231 in ³ : 3.79 liters: 3785.4 cm ³ : 16 cups
One grain - - - - - (gr)	0.002 oz: 0.065 g: 64.8 mg
One gram - - - - - (g)	0.002 lbs: 0.035 g: 15.43 grains: 1,000 mg
One liter - - - - - (ℓ)	0.26 gal: 0.04 ft ³ : 1.06 qt: 61.0 in ³ : 1,000 ml: 1,000 cc
One milligram - - - - - (mg)	0.015 gr: 0.001 g: 3.5 x 10 ⁻⁵ oz
One milliliter - - - - - (ml)	0.034 oz (fluid): 0.06 in ³ : 0.001 liters
One ounce (fluid) - - - - - (oz)	0.008 gal: 1.8 in ³ : 0.030 liters: 29.57 ml: 2 tablespoons: 6 teaspoons
One ounce (avoir.) - - - - - (oz)	437.5 gr: 28.3 g
16 — One quart - - - - - (qt)	0.03 ft ³ : 0.25 gal: 2 pints: 32 oz: 57.7 in ³ : 0.95 liters: 946.4 cc
One cup - - - - -	8 oz: 16 tablespoons

One cubic yard will cover 81 square feet 4 inches deep; 108 square feet 3 inches deep; 162 square feet 2 inches deep and 324 square feet 1 inch deep.

Crushed rock or gravel weighs between 120 to 150 pounds per cubic foot.

Vermiculite weighs between three to five pounds per cubic foot.

Perlite weighs between five to fifteen pounds per cubic foot.

Multiply the number of bushels by 1.244 to get the number of cubic feet.

Multiply the number of cubic feet by 0.037 to get the number of cubic yards.

Multiply the number of cubic feet by 0.804 to get the number of bushels.

One part per million (ppm) is equivalent to one microliter in one liter, or one milligram in one liter, or one milligram in one kilogram.

To convert ppm to percent, move the decimal point four places to the left (e.g., 100 ppm = 0.01%, 1,000 ppm = 0.1%).

To convert electrical conductivity to ppm, multiply EC in micromhos by 0.64.

To convert grains per gallon to ppm, multiply grains by 17.1.

Appendix C DEFINITIONS

1. Atomic weight -- The relative weight of the atom on the basis of oxygen as 16.

Element	Atomic Weight	Symbol	Element	Atomic Weight	Symbol
Boron	10.8	B	Nitrogen	14.0	N
Calcium	40.1	Ca	Oxygen	16.0	O
Chlorine	35.5	Cl	Phosphorous	31.1	P
Copper	63.5	Cu	Potassium	39.1	K
Hydrogen	1.0	H	Sulfur	32.1	S
Iron	55.9	Fe	Zinc	65.4	Z
Magnesium	24.3	Mg	Molybdenum	96.0	Mo
Manganese	54.9	Mn	Carbon	12.0	C
			Sodium	23.0	Na

2. Equivalent weight -- The atomic weight or formula weight of a compound, divided by its valence (i.e., the number of positive or negative charges). Chemicals combine in direct proportion to their equivalent weights.

Material	Valence	Equivalent Weight
Calcium (Ca)	2	20.0
Potassium (K)	1	39.1
Magnesium (Mg)	2	12.2
Sodium (Na)	1	23.0
Nitrate (NO ₃)	1	62.0
Sulfate (SO ₄)	2	48.0
Phosphate (H ₂ PO ₄)	1	97.0
Chlorine (Cl)	1	35.5
Bicarbonate (HCO ₃)	1	61.0

3. Gram-molecular weight--weight in grams equal to the molecular weight of the material.
4. Gram-formula weight--weight in grams equal to the formula weight (may be the molecular weight of the compound) of the material.
5. Gram-equivalent weight--weight in grams of the equivalent weight of the material, or the formula weight or molecular weight divided by the valence--1/1000 of an equivalent weight is one milliequivalent (meq.)
6. Molal solution--1,000 grams of solution which contains one molecular weight of the material.
7. Molar solution--one liter of solution which contains one molecular weight of the material. (Note the difference between this and no. 6 above.) In each case, the material is dissolved in a small amount of water, and then enough water is added to bring the weight to 1,000 grams or the volume to one liter.

8. Mole--weight of a material equal to one molecular weight of that material.
9. Molecular weight--the sum of the atomic weights of all the atoms in a molecule.
10. Normal solution--one liter of solution containing one equivalent weight of a material, or the molecular weight divided by its valence. One milliliter of a one normal solution contains one milliequivalent of the material in solution.
11. Milliequivalent--1/1000 of an equivalent, 1,000 meq = 1 equivalent.
12. Ion--an electrically charged atom, may be positive (e.g., Ca^{++} , K^+) or negative (e.g., SO_4^{--} , Cl^-).
13. Cations--positively charged ions (e.g., Ca^{++} , K^+ , Mg^{++} , Na^+ , NH_4^+ ,).
14. Anions--negatively charged ions (e.g., SO_4^{--} , NO_3^- , HCO_3^- ,).

Appendix D CHEMICALS, FERTILIZERS, NAMES, AND WEIGHTS

Name	Formula	Weight dissolved in one liter for	
		a one molar solution	a one normal solution
Ammonium nitrate	NH_4NO_3	80.1g, 2.8oz	80.1g 2.8oz
Ammonium sulfate	$(\text{NH}_4)_2\text{SO}_4$	132.2g, 4.7oz	66.1g 2.3oz
Ammonium phosphate	$\text{NH}_4\text{H}_2\text{PO}_4$	115.1g, 4.1oz	115.1g 4.1oz
Boric acid*	H_3BO_3	61.8	
Calcium carbonate	CaCO_3	100.1g, 3.9oz	50.1g 1.8oz
Calcium chloride	CaCl_2	111.0g, 3.9oz	55.5g 2.0oz
Calcium nitrate	$\text{Ca}(\text{NO}_3)_2$	164.1g, 5.8oz	82.1g 2.9oz
Calcium diphosphate	$\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}^{***}$	172.1g, 6.1oz	172.1g 6.1oz
Calcium sulfate (gypsum)	CaSO_4^{**}	136.2g, 4.8oz	68.1g 2.4oz
Copper sulfate*	Cu_2SO_4	223.2g, 7.9oz	
Iron sulfate*	$\text{FeSO}_4 \cdot \text{H}_2\text{O}^{***}$	169.9g, 6.0oz	
Magnesium sulfate (Epsom Salts)	MgSO_4	120.4g, 4.3oz	60.2g 2.1oz
Magnesium nitrate	$\text{Mg}(\text{NO}_3)_2$	148.3g, 5.3oz	74.2g 2.6oz
Manganese chloride*	$\text{MnCl}_2 \cdot 4\text{H}_2\text{O}^{***}$	19% 9g, 7.0oz	
Manganese sulfate*	MnSO_4	151.0g, 5.3oz	
Molybdcic acid*	H_2MoO_4	162.0g, 5.7oz	
Phosphoric acid	H_3PO_4 (liquid)	98.0g (technical grade may be 80% actual)	
Potassium chloride (potash or muriate of potash)	KCl	74.6g, 2.6oz	74.6g 2.6oz
Potassium nitrate (saltpeter)	KNO_3	101.1g, 3.6oz	101.1g 3.6oz
Potassium monophosphate	K_2HPO_4	174.2g, 6.2oz	87.1g 3.1oz
Potassium diphosphate	KH_2PO_3	120.1g, 4.2oz	120.1g 4.2oz
Sodium nitrate	NaNO_3	85.0g, 3oz	85.0g 3oz
Zinc sulfate*	ZnSO_4	161.4g, 5.7oz	

* Materials supplying trace elements, usually made in a separate solution.

** Very insoluble, difficult to dissolve one-half normal concentration.

*** Materials may have varying amounts of water attached to the molecule. Required weight to make a molar or normal solution may change. One molecule of water has a mole weight of 18 which can be added to the above weight given in grams. Note the formula usually provided in the chemical analysis on the container.

Appendix E LIST OF SUPPLIERS

Note: Colorado State University does not indorse any product or service, nor has made any attempt to make this list complete. It is provided as a service to the reader.

-
1. W. W. Grainger. 695 Bryant, Denver, Colorado 80204: Pumps, plastic fittings and relays.
 2. Cole-Parmer, 7425 No. Oak Ave., Chicago, Ill. 60648: Pumps, plastic fittings, plastic containers, laboratory supplies.
 3. American Clay Works, 857 Bryant, Denver, Colorado 80204: Bulk fertilizer, plastic film.
 4. Warren Engineering Corp., 2496 W. 2nd Ave., Denver, Colorado 80223: Automatic valves.
 5. Herbach-Rademan, Inc., 401 E. Erie Ave., Pittsburgh, Pa. 19134: Timers.
 6. Cramer/Denver, 5465 E. Evans Pl., Denver, Colorado 80222: Relays, timers, terminal strips, fuses and fuse holders, and more.
 7. Waco Electronics, 4616 Ironston, Denver, Colorado: Timers.
 8. Electronic Parts Co., 1212 S. Broadway, Denver, Colorado: Timers, relays, switches, and more.

9. Van Waters and Rogers, Inc., 4300 Holly, Denver, Colorado: Chemicals, laboratory equipment, fertilizers, pumps, fittings, and more.
10. Sargent-Welch Scientific Co., 4040 Dahlia, Denver, Colorado: Laboratory equipment, pumps, fittings, and more.
11. Gloeckner, Inc., 15E. 26th St., New York, N.Y. 10010: Irrigation supplies, seeds, fertilizer injectors, and more.
12. Brighton By-Products, Co., Inc., P.O. Box 23, New Brighton, Pa. 15006: Greenhouse supplies, injectors, and more.
13. Stuppy Floral, Inc., 120 E. 12th Ave., North Kansas City, Mo. 64116: Greenhouse supplies, irrigation equipment, valves, and more.
14. E. C. Geiger, Box 285, Harleysville, Pa. 19438: Greenhouse supplies, irrigation systems, and more.

Note: Some of these companies have branches in major cities throughout the United States. Listing of names here is no guarantee of available supply, as some are wholesale only.

Appendix F LIST OF PUBLICATIONS

For those who desire to read further, the following is a selected list of publications:

- Gericke, W. F. "Aquaculture: A Means of Crop Production." American Journal of Botany, Vol. 16, 1929, p. 862.
- Gericke, W. F. "Crop Production Without Soil." Nature, Vol. 141, 1938, pp. 536-540.
- Gericke, W. F. The Complete Guide to Soilless Gardening. New York: Prentice-Hall, 1940.
- Hanan, J. J. and W. D. Holley. "Introduction of Hydroponics in Colorado: Technique and Implications in a Semiarid Region," Agriculture Meteor. Vol. 7, 1970, pp. 29-38.
- Hoagland, D. R. and D. I. Arnon. The Water-Culture Method for Growing Plants Without Soil, California Agricultural Experiment Circular 347, Davis: University of California, 1950.
- Hollis, H. F. Profitable Growing Without Soil. London: The English University Press, 1964.
- Kiplinger, D. C. and A. Laurie. Growing Ornamental Greenhouse Crops in Gravel Culture, Ohio Agricultural Experiment Station Research Bulletin 679, Columbus: Ohio State University, 1948.
- Robbins, W. R. "Growing Plants in Sand Cultures for Experimental Work," Soil Science, Vol. 62, 1946, pp. 3-22.
- Schwarz, M. and Y. Vaadia. "Limestone Gravel as Growth Medium in Hydroponics." Plant and Soil, Vol. 31, 1969, pp. 122-128.
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Appendix E LIST OF SUPPLIERS

Note: Colorado State University does not indorse any product or service, nor has made any attempt to make this list complete. It is provided as a service to the reader.

-
1. W. W. Grainger. 695 Bryant, Denver, Colorado 80204: Pumps, plastic fittings and relays.
 2. Cole-Parmer, 7425 No. Oak Ave., Chicago, Ill. 60648: Pumps, plastic fittings, plastic containers, laboratory supplies.
 3. American Clay Works, 857 Bryant, Denver, Colorado 80204: Bulk fertilizer, plastic film.
 4. Warren Engineering Corp., 2496 W. 2nd Ave., Denver, Colorado 80223: Automatic valves.
 5. Herbach-Rademan, Inc., 401 E. Erie Ave., Pittsburgh, Pa. 19134: Timers.
 6. Cramer/Denver, 5465 E. Evans Pl., Denver, Colorado 80222: Relays, timers, terminal strips, fuses and fuse holders, and more.
 7. Waco Electronics, 4616 Ironston, Denver, Colorado: Timers.
 8. Electronic Parts Co., 1212 S. Broadway, Denver, Colorado: Timers, relays, switches, and more.

9. Van Waters and Rogers, Inc., 4300 Holly, Denver, Colorado: Chemicals, laboratory equipment, fertilizers, pumps, fittings, and more.
10. Sargent-Welch Scientific Co., 4040 Dahlia, Denver, Colorado: Laboratory equipment, pumps, fittings, and more.
11. Gloeckner, Inc., 15E. 26th St., New York, N.Y. 10010: Irrigation supplies, seeds, fertilizer injectors, and more.
12. Brighton By-Products, Co., Inc., P.O. Box 23, New Brighton, Pa. 15006: Greenhouse supplies, injectors, and more.
13. Stuppy Floral, Inc., 120 E. 12th Ave., North Kansas City, Mo. 64116: Greenhouse supplies, irrigation equipment, valves, and more.
14. E. C. Geiger, Box 285, Harleysville, Pa. 19438: Greenhouse supplies, irrigation systems, and more.

Note: Some of these companies have branches in major cities throughout the United States. Listing of names here is no guarantee of available supply, as some are wholesale only.

8. Mole--weight of a material equal to one molecular weight of that material.
9. Molecular weight--the sum of the atomic weights of all the atoms in a molecule.
10. Normal solution--one liter of solution containing one equivalent weight of a material, or the molecular weight divided by its valence. One milliliter of a one normal solution contains one milliequivalent of the material in solution.
11. Milliequivalent--1/1000 of an equivalent, 1,000 meq = 1 equivalent.
12. Ion--an electrically charged atom, may be positive (e.g., Ca^{++} , K^+) or negative (e.g., SO_4^{--} , Cl^-).
13. Cations--positively charged ions (e.g., Ca^{++} , K^+ , Mg^{++} , Na^+ , NH_4^+ ,).
14. Anions--negatively charged ions (e.g., SO_4^{--} , NO_3^- , HCO_3^- ,).

Appendix B UNITS AND CONVERSIONS

For conversions of more than one of this unit	Multiply by the factor shown in this column
One cubic centimeter - - - - - (cc) or (cm ³)	0.034 oz (fluid): 0.06 in ³ : 1 ml
One gallon - - - - - (gal)	128 oz (fluid): 231 in ³ : 3.79 liters: 3785.4 cm ³ : 16 cups
One grain - - - - - (gr)	0.002 oz: 0.065 g: 64.8 mg
One gram - - - - - (g)	0.002 lbs: 0.035 g: 15.43 grains: 1,000 mg
One liter - - - - - (ℓ)	0.26 gal: 0.04 ft ³ : 1.06 qt: 61.0 in ³ : 1,000 ml: 1,000 cc
One milligram - - - - - (mg)	0.015 gr: 0.001 g: 3.5 x 10 ⁻⁵ oz
One milliliter - - - - - (ml)	0.034 oz (fluid): 0.06 in ³ : 0.001 liters
One ounce (fluid) - - - - - (oz)	0.008 gal: 1.8 in ³ : 0.030 liters: 29.57 ml: 2 tablespoons: 6 teaspoons
One ounce (avoir.) - - - - - (oz)	437.5 gr: 28.3 g
16 — One quart - - - - - (qt)	0.03 ft ³ : 0.25 gal: 2 pints: 32 oz: 57.7 in ³ : 0.95 liters: 946.4 cc
One cup - - - - -	8 oz: 16 tablespoons

One cubic yard will cover 81 square feet 4 inches deep; 108 square feet 3 inches deep; 162 square feet 2 inches deep and 324 square feet 1 inch deep.

Crushed rock or gravel weighs between 120 to 150 pounds per cubic foot.

Vermiculite weighs between three to five pounds per cubic foot.

Perlite weighs between five to fifteen pounds per cubic foot.

Multiply the number of bushels by 1.244 to get the number of cubic feet.

Multiply the number of cubic feet by 0.037 to get the number of cubic yards.

Multiply the number of cubic feet by 0.804 to get the number of bushels.

One part per million (ppm) is equivalent to one microliter in one liter, or one milligram in one liter, or one milligram in one kilogram.

To convert ppm to percent, move the decimal point four places to the left (e.g., 100 ppm = 0.01%, 1,000 ppm = 0.1%).

To convert electrical conductivity to ppm, multiply EC in micromhos by 0.64.

To convert grains per gallon to ppm, multiply grains by 17.1.



14 Figure 13. Inexpensive "hoze-on" proportioner roughly 1 to 20 dilution, varying with pressure and flow.

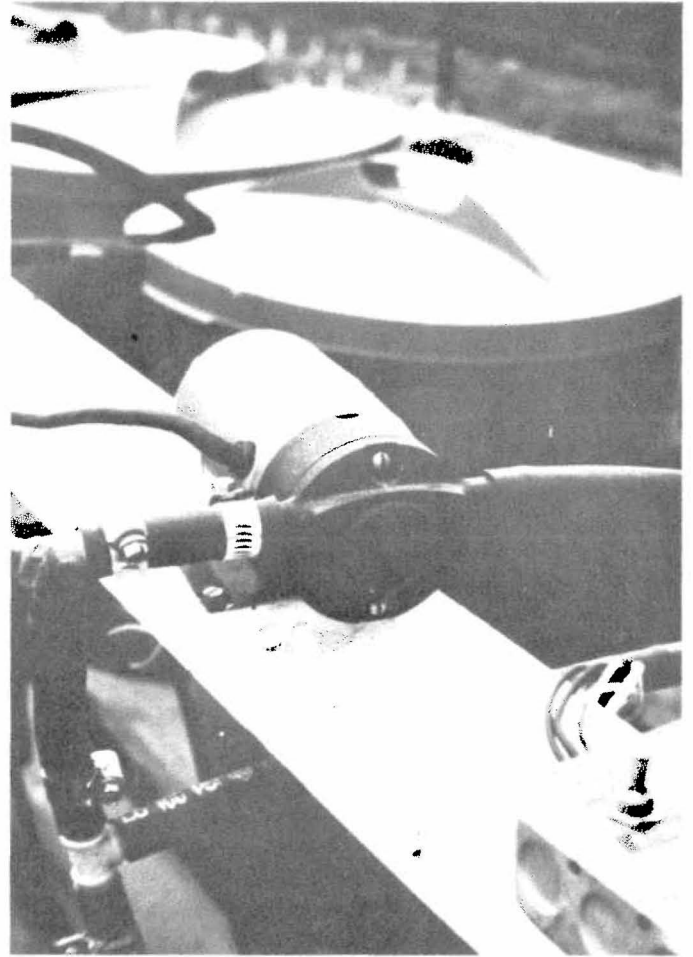


Figure 15. Small Jabsco pump which is ideal for small hydroponic systems.

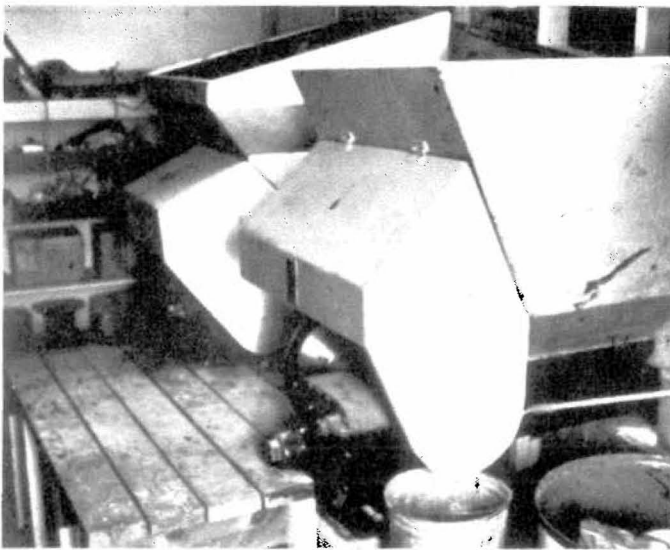


Figure 14. Surplus coal stokers modified for feeding fertilizers into a known volume of water prior to watering.

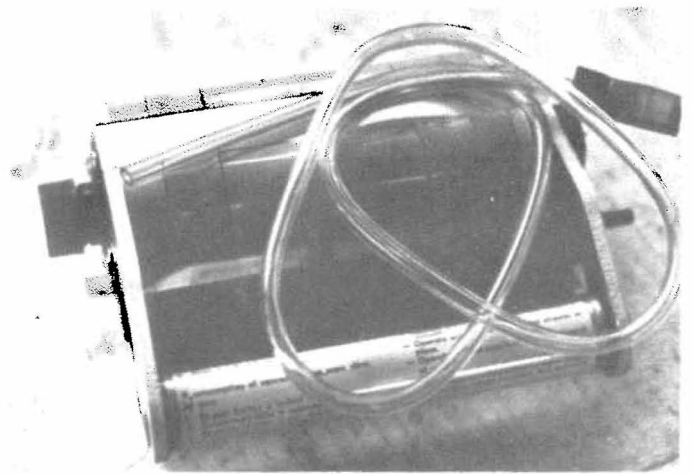


Figure 16. One to forty diluter with higher precision than "hoze-on," but more expensive.

The carnation solution is translated in Table 9.

Table 9. Pounds per 1,000 gallons for carnations.

5 lbs potassium nitrate
3 lbs calcium nitrate
1 lb ammonium nitrate
2 lbs magnesium sulfate
.67 lbs 80 percent phosphoric acid
1.0 oz borax

For roses, the solution is translated in Table 10.

Table 10. Pounds per 1,000 gallons for roses.

6.0 lbs calcium nitrate
1.66 lbs potassium nitrate
1.25 lbs potassium chloride
0.7 lbs ammonium nitrate
1.0 lbs magnesium sulfate
0.6 lbs phosphoric acid

These recommendations are for salt-free water. They will not be suitable if the water supply contains appreciable salts. The use of 1.0 ounces borax is applicable to Colorado waters where boron is usually missing. All other trace elements are generally present.

It is often easier to apply some materials dry to the root medium. Dry applications become a necessity when the water is hard. Thus, calcium in the form of limestone or gypsum, and superphosphate, will be mixed in the medium prior to planting. Calcium nitrate and phosphorous are eliminated from the solution because they may precipitate and then become unavailable to the plants, or they may clog water lines and irrigation systems if the water is hard. One inch of lime rock over the surface and 10 to 20 pounds per 100 square feet of 20 percent superphosphate before planting is adequate.

Automatic Injection

These same solutions may be injected through an automatic machine to provide constant feeding in nonrecirculating systems. For example, if a 1 to 200 dilution is available, a 50 gallon barrel will contain 50 pounds of potassium nitrate, 10 pounds of ammonium nitrate, 6.7 pounds of 80 percent phosphoric acid and 10 ounces of borax. When injected, the desired rate per 1,000 gallons will be obtained.

Note that calcium nitrate and magnesium sulfate are not included. In a concentrated form, these materials will combine with phosphorous and precipitate in the tank or water lines. A grower will often apply calcium and magnesium every other barrel, or he will employ a double-head injector with two barrels to separate the materials likely to precipitate. Borax should always be dissolved in hot water before putting it into the concentrate tank. It will not go into solution in cold water. Some fertilizer grades come pelleted and the pellet covering may settle to the bottom of the barrel. Also, salts may not go into solution completely if the water is cold. Growers often aerate the tanks to dissolve the salts or add one to two pounds of nitric acid (HNO_3) per 50 gallons to ensure solubility. Nitric acid is extremely caustic; thus, it requires special handling and is not recommended for the hobbyist.

A Note on Special Crops

Most plants are remarkably adaptive organisms. They will often survive when terribly neglected. But plants, just as humans, require a certain minimum amount of water, food, vitamins, sleep, proper temperatures, and more. Each plant species has its own particular requirements for maximum growth. In fact, a horticulturist may distinguish between varieties whose only physical differences are color, flower, or fruit on the basis of each variety's cultural requirements. Some varieties in a species require higher temperatures, others may respond to carbon dioxide fertilization, some may not tolerate high soil-water contents, still others have remarkably precise requirements in terms of daylength and alternating temperatures. Successful commercial growers are so familiar with their plants that careful observation alone will tell if temperatures have been too high or too low, if salts are too high, or if the crop has been run too dry.

This manual covers one small aspect of successful plant culture. Even the cultural requirements of one or two species is beyond the limits of this manual and information should be obtained from an agricultural state university or county extension agent. A hydroponics system may be employed in the home, a greenhouse, a growth chamber, or in a field. Publications dealing with various aspects of culture under specific conditions are available from the local authorities mentioned above who are the best information source for individual climatic conditions.

Table 3. Hoagland and Arnon's stock solutions for general use.

	Milliliters of stock solution per one liter of nutrient solution
Potassium monophosphate	1
Potassium nitrate	5
Calcium nitrate	5
Magnesium sulfate	2
or	
Ammonium phosphate	1
Potassium nitrate	6
Calcium nitrate	4
Magnesium sulfate	2

A stock trace element solution is made by dissolving the following in one liter of water:

Boric acid	2.86 grams
Manganese chloride	1.81 grams
Zinc sulfate	0.22 grams
Copper sulfate	0.08 grams
Molybdic acid	0.02 grams
Fe sequestrene 330	5.00 grams

Add one milliliter of the above stock to each liter of final nutrient solution. The trace element solution should be kept in the dark and refrigerated.

These solutions are acceptable for nearly all plants. In recent years, new work with nutrient solutions at Colorado State University has shown that ratios for maximum growth may shift with the season and considerable differences are apparent between species. The requirements for adequate nutrition become more stringent as the plant nears its maximum growth potential. Under these conditions, it is easier to express the concentration of the nutrient solution in terms of milliequivalents per liter (meq/l). An analogy is how many bricks there are rather than how much the bricks weigh. Each milliequivalent per liter says that there is one "brick" per liter. If there are 50 pounds of "bricks" per liter, one could have one or more "bricks," depending upon the weight of each "brick". When various ratios and proportions of "bricks" are examined, certain combinations and numbers provide better growth. For example, the best growth conditions for carnations in Colorado with good water available is provided by Table 4.

Table 4. Nutrient solution for carnations.

	Milliequivalents per liter
(K) Potassium	6
(Ca) Calcium	6
(Ma) Magnesium	1
(NH ₄) Ammonium	2
(NO ₃) Nitrate	14
(SO ₄) Sulfate	1.0
(H ₂ PO ₄) Phosphorous	1.0

For roses, however, a good solution is indicated in Table 5.

Table 5. Nutrient solution for roses.

Potassium	4
Calcium	5
Magnesium	1
Ammonium	1
Nitrate	9
Sulfate	1
Phosphorous	1

The calcium-potassium ratio is equal for carnations and has a higher level of nitrates as contrasted to roses. The total concentrations can be varied, within limits, by adjusting the irrigation frequency--for a lower concentration, a higher frequency irrigation should be used. If the water is hard, calcium, magnesium, and sulfate can usually be eliminated from the nutrient solution. If there is high bicarbonate (HCO₃⁻), ammonium (NH₄⁺) may have to be increased. The proportions of ammonium, chloride, sodium, and potassium may vary with the season.

Hoagland and Arnon's solutions, given in Table 3, translate as follows:

Table 6. Translation to milliequivalents of Hoagland and Arnon's solutions in Table 3.

	Milliequivalents per liter
Potassium	7
Calcium	10
Magnesium	4
Nitrate	15
Sulfate	4
Phosphorous	2
or	

Watering frequency will vary with atmospheric dryness and sunlight. The frequency can be reduced to once daily in January, skipping dark and overcast days, and increasing the frequency through the spring and summer up to six times daily. Some growers, who may be into their second or third year in inert media, find it necessary to cut this frequency in half. If the water is high quality, the bed need be watered only to dripping. If salty, water may be needed until the bed drains freely for some minutes. About 45 seconds per irrigation is required with the gates system and up to eight minutes for ooze systems with good water.

Ooze systems are susceptible to blockage from sand and debris in the water supply. Salt precipitation may clog the orifices; therefore, ooze and other drip systems need good filters in the supply line. Manufacturers' recommendations suggest using 100-mesh screens which should be cleaned at regular intervals.

Water Quality

Good quality water is essential. As the salt concentration increases, growth decreases as shown in figure 10. Obviously, pure water is desired since nutrients must be added for plant growth. If salts are already present, the necessary elements will increase total salt content and growth will be correspondingly less. There is no sharp dividing line as to the economics of the system, because costs, prices received, and other factors determine the break-even point.

A grower is interested in the total salt concentration of the water and the concentration of the individual salts. Total salts may be expressed several ways, such as grains per gallon of hardness, milligrams, parts per million (ppm) and electrical conductivity in millimhos per centimeter (mmhos/cm) (see app. B for conversions). Water with an electrical conductivity (EC) below 0.5 mmhos/cm is very good. Nutrients added to such water will result in EC ranging from 2.0 to 3.0 mmhos/cm. If the water already contains 1.0 to 2.0 mmhos/cm, a final salt concentration which is near or in excess of 3.0 mmhos/cm will be unacceptable. Water having EC between 0.5 to 1.5 mmhos/cm can be utilized by modifying the nutrient solution if individual element (ion) concentrations are known.

Water from shallow wells in Colorado will generally have high levels of calcium (Ca), magnesium (Mg), bicarbonate (HCO_3), and

sulfate (SO_4). Calcium, magnesium, and sulfate may not have to be added to the nutrient solution, if there are sufficient levels in the water. Certain fertilizer salts (e.g., ammonium nitrate) partially compensate for high bicarbonate concentrations. If the well is deep, sodium may be high and to some extent can be offset by increasing potassium (K). Domestic water supplies from the Colorado mountains will generally be high quality. Even though it may cost more, the benefits of using good water usually outweigh problems in manipulating water with high salt concentrations. Sodium will not effect an inert gravel medium. A water analysis before using the water in a hydroponics system is the safest practice to follow. For assistance, contact your county cooperative extension office.

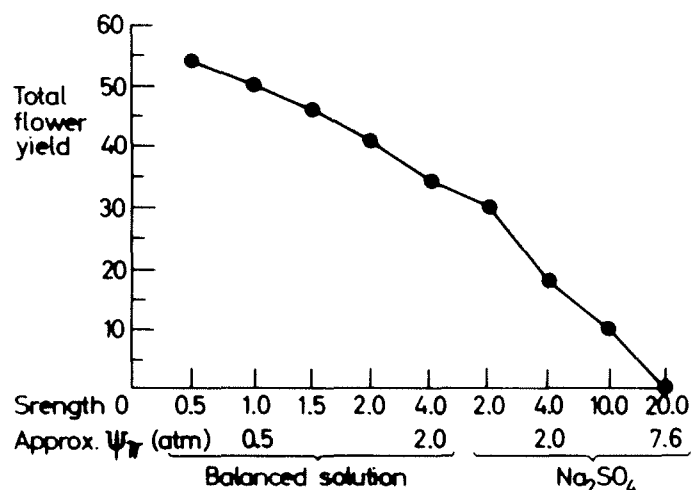


Figure 10. Effect of increasing salt concentration on growth. Note the effect of concentration is less if the solution is properly balanced as contrasted to the use of Na_2SO_4 to increase the concentration. A 1.0 strength solution is the standard employed for carnations at Colorado State University.

Fertilizer and Nutrients

All plants require certain basic nutrients including calcium (Ca), potassium (K), nitrogen (N), phosphorous (P), magnesium (Mg), manganese (Mn), sulfur (S), copper (Cu), boron (B), iron (Fe), molybdenum (Mb), and zinc (Zn). If any of these are missing from the root medium, very poor growth may result. Calcium, potassium, nitrogen, phosphorous, and magnesium are considered major elements, because the plants need more of them, and a deficiency is rapidly apparent.

Rock between 1/2 to 3/4 inch in diameter is acceptable, if irrigation frequency is increased to provide sufficient water. Volcanic ash, or scoria, has a tendency to break down, which increases the fine particles and the water holding capacity of the root medium. Under Colorado's semiarid conditions, a good medium can be watered every hour without reducing aeration enough to damage the root system. On the other hand, this frequent watering could be extremely wasteful depending on the system being used.

A coarser medium can be used at a shallower level in the plant tray; thus, a four-inch depth of 1/2 to 3/4 inch diameter gravel can be used if watered frequently. A finer mixture needs increased depth to assure drainage in the upper layers, and six to seven inches is the common depth.

Each time a hydroponics system is replanted, some roots will be left and the moisture holding capacity of the mixture gradually increases; consequently, watering frequency may need to be reduced each year. Over the years, this will result in a graveled soil and the advantage over a soil system will be lost. This change to a graveled soil may take relatively long time.

Vermiculite is not recommended as a medium since it may contain considerable potassium and tends to collapse and lose its structure after six to twelve months. The material called perlite is acceptable, but tends to float out of a flooded tray and offers little support until the root system is firmly established. Peatmoss may also be used, but

it is an organic material, definitely not inert, and has peculiar handling problems.

Irrigation Systems

With conventional hydroponics, flooding (i.e., filling the plant tray until water appears at the surface) is the usual method of watering. For example, a half-tile or a perforated plastic line about two to three inches in diameter is laid lengthways in the tray with a connection above the substrate surface, and is used to fill and drain the tray as needed.

If the nutrient solution is to be applied to the surface and allowed to drain, there are several good systems. The peripheral gates system, figure 6, is widely used on soil, but possible high pressure is likely to damage foliage and diseases can be spread through splashing water. The pressure at a single 180-degree spray nozzle should not exceed four pounds per square inch with 18 to 24 inch spacing between them. The nozzle angle should be as close to horizontal as possible. If the bed is wider than 36 inches, a third line in the center is required. The common nozzle may be improved for better spray distribution (see fig. 9).

Newer systems such as double-wall tubes or ooze tubes work well if a line is laid between each row. These systems are advantageous because no water is splashed on the foliage, but they are more expensive. In very coarse substrates, the lateral water flow in the

Table 1. Particle size distribution and moisture holding capacity of various inert media suitable for hydroponics systems.

Material	Percent of particles with diameters larger than:				Percent of particles with diameters smaller than 0.02"	Water holding capacity of the medium 7" deep. (qts/sq.ft)
	0.2"	0.12"	0.04"	0.02"		
Granitic sand and gravel	7.1	25.7	75.6	98.2	1.8	3.3
Large Idealite*	100.0	--	--	--	--	1.5
Regular Idealite*	42.3	76.7	98.9	99.4	0.5	1.8
Fine Idealite*	0.00	0.00	53.9	94.9	5.0	4.5
River sand and gravel**	23.7	83.0	95.5	98.8	1.4	2.0
Volcanic ash***	46.7	62.0	79.1	92.0	7.1	5.8

* Artificial, light-weight concrete aggregate, made from a fired illite shale.

** Commonly called "squee-gee," major portion with particles about 1/4 inch diameter.

*** Commonly called "scoria," prone to crumbling with buildup of fine particles. Water holding capacity may exceed a good greenhouse soil.

Systems

The design of hydroponics systems is practically unlimited. Quart jars and a nutrient solution are adequate. Trays with some type of netting to support the plants as they grow directly in nutrient solutions have also been employed by students in botany laboratories for years. However for best results, solutions without a supporting medium need to be vigorously aerated. Even more striking is the process of "misting" the root system with a nutrient solution. In this process, plants are supported,

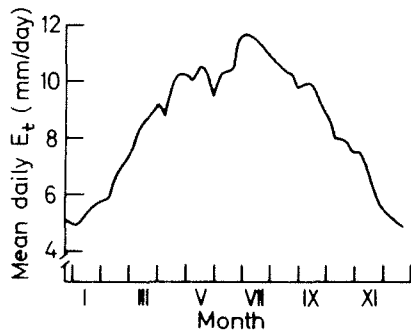


Figure 4. Water loss from carnations per day (E_t). One millimeter refers to depth of water, whether it covers one square inch or one acre. One millimeter over one square foot is about 6.3 tablespoons of water.

with the roots in a dark cabinet, and a pressure pump with spray nozzles supplies a fine mist at frequent intervals to the root system. Present information indicates this system has not been employed commercially.

A more conventional style is outlined in Figure 5. System A is the simplest and requires the following: 1) a tray to hold plants, 2) a tank for the nutrient solution, 3) a pump and control system, and 4) a suitable connecting pipe. The solution is pumped into the plant tray and allowed to drain back to the storage tank through the pumps. In all systems, an automatic clock assures that the plants receive water (see app. A). Some device or time regulator should be included to prevent an overflowing of the plant tray.

System B is complicated by separate delivery and drain lines. The storage tank could be placed above the plant tray if this is more convenient. In both A and B systems, the plant tray is usually flooded and then allowed to drain.

System C seeks to overcome debris accumulation by using a filter system under the plant tray. Most fungi and bacteria can be filtered out by passing the drain water through a diatomaceous earth filter. There are other more convenient filtration systems for removal of large debris.

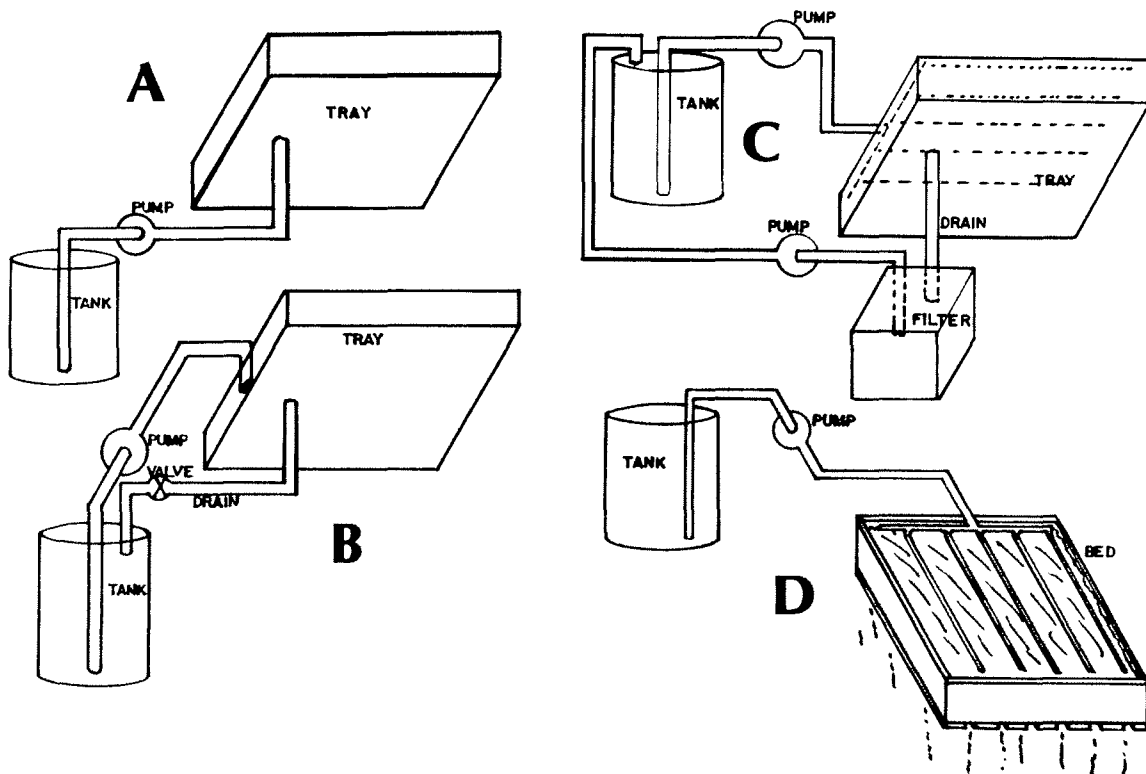


Figure 5. Hydroponics systems.



Figure 1. Carnations in inert media, non-recirculating water, with gates peripheral watering system and automatic fertilizer injection.



Figure 2. Chrysanthemums in inert media, steel beds, recirculated.

order to compensate for labor, worries, and risk. The cost of a hydroponics installation will depend upon the type of system used. The system employed by commercial carnation growers in Colorado may add little to the initial capital investment; on the other hand, a conventional hydroponics system, using water-tight benches, storage tanks, and pumps may double the unit cost.

2. Growing 50 to 100 plants takes skill, but attention can be given to each plant with all plants receiving "tender loving care." Growing 10,000 plants is another matter--a college degree is not required, but it does require knowledge and ability to observe plant growth, as well as managerial competence and basic accounting skills. The grower must be familiar with the requirements of different varieties, insects, diseases; the effects of different temperatures and light; and the use of basic pesticides, fungicides, and fertilizers. The best hydroponic system is worse than nothing, if one lacks knowledge in the other areas. Commercial hydroponics is less forgiving than soil culture--the risk of failure is higher.

3. About 25 percent of production costs are selling, grading, packaging, and transporting the product. First, the market should be examined and the following determined: who will buy it; where it will be sold; how much can be sold at what price; how far does it have to be transported; should it be packaged and graded; should advertising be purchased; and, will there be competition for the same market? The cost of borrowing capital must be added to production costs. Further considerations should include: water supply and its quality; availability of fuel and electricity; and flexible operation's plans which will allow for possible local labor supply and delays in delivery.

Information on the above aspects of commercial production is often difficult to obtain. It may be proprietary and very little is published. The specialist at the state agricultural university is a good initial information contact, as well as producers and sellers of various hydroponic products.

Advantages and Disadvantages

All plants require water. The amount they use depends upon how much energy (sunlight) is available to cause them to evaporate water, as well as the amount of water supply available to the roots. From 70 to 95 percent of all energy in sunlight goes to evaporate water

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
15	Small Jabsco pump which is ideal for small hydroponic systems	14
16	One to forty diluter with higher precision than "hoze-on," but more expensive	14
17	Schematic wiring diagram for timer	15

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
What Is Hydroponics? (synonyms for the word).	1
Why Not Hydroponics? (for those interested in commercial production)	1
Advantages and Disadvantages.	2
Systems (from quart jars to large scale).	3
Construction Materials.	5
Substrates (soils and gravel)	5
Irrigation Systems (how to water)	6
Water Quality	8
Fertilizer and Nutrients (how to feed).	8
Automatic Injection	12
A Note on Special Crops	12
Appendix A - SCHEMATIC WIRING DIAGRAM	15
Appendix B - UNITS AND CONVERSIONS	16
Appendix C - DEFINITIONS	17
Appendix D - CHEMICALS, FERTILIZERS, NAMES, AND WEIGHTS.	19
Appendix E - LIST OF SUPPLIERS	20
Appendix F - LIST OF PUBLICATIONS	21

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1 Particle size distribution and moisture holding capacity of various inert media suitable for hydroponics systems	6
2 Hoagland and Arnon's solutions for general use.	9
3 Hoagland and Arnon's stock solutions for general use	10
4 Nutrient solution for carnations	10
5 Nutrient solution for roses	10
6 Translation to milliequivalents of Hoagland and Arnon's solutions in Table 3	10
7	11
8 Milliequivalents per pound of fertilizer when added to 1,000 gallons of water	11
9 Pounds per 1,000 gallons for carnations	12
10 Pounds per 1,000 gallons for roses.	12

