HYDROPONIC Food Production

A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower SEVENTH EDITION

Howard M. Resh

CRC Press
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Preface to the Seventh Edition

The first edition of this book was published in 1978. Generally, the book gets updated about every four years. However, the last edition, the sixth, was revised in 2001 and it has been over ten years now. As a result, the seventh edition has undergone some major changes to keep it state of the art in the field of hydroponics. The author has maintained the book in its same format, but expanded many of the chapters and added a new chapter (Chapter 11) on coco coir culture. Also, new applications and concepts of hydroponics are discussed with a sustainable yield approach. The book is not highly technical in providing the basics of hydroponics in the initial chapters with regard to plant function and nutrition. The objective is to make the reader aware of the present advances in hydroponics using the various substrates and systems that have proved successful with specific vegetable crops. While most of the material presented relates to greenhouse hydroponic systems, a few are of outdoor hydroponic systems under favorable climates. This book is meant to be a practical guide for persons interested in entering hydroponics commercially or as a hobby. Whatever the size of operation the reader may be interested in, the book presents the principles of getting started and gives many examples and illustrations to clarify these methods.

The first four chapters introduce the reader to the history of hydroponics: plant nutrition, essential plant elements, nutrient uptake, nutritional disorders, sources of nutrients, and then a detailed explanation of composing nutrient solutions. Sources of the nutrients are given with conversion tables to facilitate the calculations of nutrients the plant requires to the volumes of nutrient solution makeup. Concentrated nutrient stock solutions are explained and calculations are clearly exemplified. Many nutrient formulations are given as a reference to start the formulation for specific crops that can be optimized for specific conditions with experience. Various media or substrates most suitable to hydroponics or “soilless culture” are presented to explain their characteristics and assist the reader in choosing the best for his or her specific crop and growing system.

In Chapter 5, water culture systems are explained and illustrated. This includes raft or floating systems on a relatively small scale to large commercial operations. This section contains a lot of new material on commercial raceway or raft culture. Aeroponic systems are described with automated rotational systems by Omega Garden as either hobby or commercial application of aeroponics. An alfalfa and bean sprout operation is presented to demonstrate the principles of growing sprouts. Another new section is on microgreens, which are increasingly in demand as a new product, superior to sprouts in nutrition and taste. A do-it-yourself method is given so that one can easily set up such a system in the residence.

Chapter 6 on nutrient film technique (NFT) expands this culture to the most up-to-date automated systems presently in operation in Europe and North America. It also expands on the ebb-and-flow (flood) system for growing seedlings. A new section has been added on the commercial application of an A-frame NFT system exemplified by a commercial operation in Colombia.

Chapters 7 through 9 on gravel, sand, and sawdust cultures, respectively, have been changed mainly to emphasize present applications.

Chapter 10 on rockwool culture has been updated substantially. It has been updated with statistics on area and crops in North American and world greenhouse vegetable industries giving locations and sizes of large growers. In this chapter, commercial state-of-the-art greenhouse operations are presented. New technology in harvesting, grading, and packing equipment is illustrated. The move toward recycling the nutrient solution is exemplified with rockwool culture. The use of raised beds and the design of this recirculation of nutrient solution show where the industry is focusing such efforts to reduce the environmental impact and support the "green" concept toward the environment. Presented are examples and details of growing the main vine crops of tomatoes, peppers, and cucumbers with rockwool culture. In addition, the new crop of greenhouse eggplants is introduced.

Chapter 11 on coco coir is entirely new. The sources, grades, and characteristics of coco coir are discussed with the available products of cubes, blocks, and slabs that are used in this system. Greenhouse culture is moving toward such sustainable substrates to utilize normal waste products from other industries. This was the case with sawdust culture in British Columbia, Canada, some years ago as illustrated in Chapter 9. Sawdust later was used in manufactured wood products, so is not as readily available as a substrate presently. With the concern of the environmental impact or "footprint" of the industry under close scrutiny, especially in Europe, new greenhouse technologies emphasizing "sustainable" methods have become very important. The integration of closed recirculation hydroponic systems and greenhouse environmental control factors are explained. The trend toward recycling the nutrient solution and minimizing energy requirements of the greenhouse environment through use of solar panels, carbon dioxide recovery, and closed "positive pressure" greenhouse atmospheres is well illustrated. Details of growing tomatoes using coco coir substrate are given.

Chapter 12 dealing with other soilless cultures covers the use of rice hulls, peatlite, and perlite cultures. The section on perlite culture has been expanded to elaborate on perlite products such as blocks and slabs and to include culture of eggplants using perlite.

In Chapter 13, new sections have been added under "Special Applications" in the application of hydroponic rooftop greenhouses. Several locations are described with illustrations in New York and Montreal, Canada. This is another area where hydroponics will continue to become more applied as the "green" concept spreads into city centers. Ultimately, as illustrated, the concept of vertical high-rise buildings in the city core will become another future application of hydroponics. A new automated vertical hydroponic system (VertiCrop by Valcent) is presented in this chapter. Educational applications of hydroponics in school rooftop hydroponic gardens and the public display of the Science Barge on the Hudson River in New York are described.

Plant culture techniques of Chapter 14 are expanded in much more detail to illustrate the training of plants, growing of seedlings, varieties, and pest and disease management using integrated pest management (IPM). Eggplant culture is included with these cropping techniques. Green grafting of vine crops is now a common practice to mitigate diseases with the crops. This is explained in detail using illustrations.

Included in the appendices are websites for all of the hydroponic and greenhouse resources and supplies to make access to them readily available.

Howard M. Resh

Acknowledgments

This book is based on over 35 years of personal working experience, visits with many growers, discussions with researchers and growers at conferences, and participation in many conferences such as the Asociacion Hidroponica Mexicana, AC; Centro Nacional de Jardineria Corazon Verde, Costa Rica; Encontro Brasileiro de Hidroponia, Brazil; Greenhouse Crop Production and Engineering Design Short Course, University of Arizona, CEAC; Hydroponic Society of America; International Society of Soilless Culture; and the Research Center for Hydroponics and Mineral Nutrition, Universidad Nacional Agraria, La Molina, Lima, Peru. Much appreciated thanks to the organizers of these conferences including Gloria Samperio Ruiz, Laura Perez, Dr. Pedro Ferlani, Dr. Gene Giacomelli, and Alfredo Rodriguez Delfin.

In addition, some information has been acquired over the years from numerous sources from books, scientific journals, and government publications whose recognition is given in the references following each chapter and in the general bibliography.

Special thanks to Dr. Silvio Velandia of Hidroponias Venezolanas C.A. of Caracas, Venezuela, for the hospitality and inspiration given to me during our association over the years in developing his hydroponic farm. He gave me the opportunity to gain experience in tropical hydroponics and encouraged me to write a chapter about it.

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In no way is the use of trade names intended to imply approval of any particular source or brand name over other similar ones not mentioned in this book.

Author

Howard M. Resh (born January 11, 1941) is a recognized authority worldwide on hydroponics. His website: www.howardresh.com provides information on hydroponic culture of various vegetable crops. In addition, he has written five books on hydroponic culture both for commercial growers and backyard hobbyists. While a graduate student at the University of British Columbia, in Vancouver, Canada, in 1971, he was asked by a private group to assist them in the construction of hydroponic greenhouses in the Vancouver area. He continued with outside work in greenhouses and soon was asked to conduct evening extension courses in hydroponics.

Upon graduation with his doctorate degree in horticulture, in 1975, he became the urban horticulturist for the faculty of plant science at the University of British Columbia. He held that position for three years before the call of commercial hydroponics took him to many projects in countries such as Venezuela, Taiwan, Saudi Arabia, the United States, and in 1999 to Anguilla, British West Indies, in the Eastern Caribbean, where he is to date.

While in the position of urban horticulturist, Resh taught courses in horticulture, hydroponics, plant propagation, greenhouse design, and production. During this period, while he was urban horticulturist and later general manager for a large plant nursery, he continued doing research and production consultation for a commercial hydroponic farm growing lettuce, watercress, and other vegetables in Venezuela. Later, during the period 1995–1996, Resh became project manager for a Venezuelan farm to develop hydroponic culture of lettuce, watercress, peppers, tomatoes, and European cucumbers using a special medium of rice hulls and coco coir from local sources. He also designed and constructed a mung bean and alfalfa sprout facility to introduce sprouts into the local market.

In the late 1980s, Resh worked with a company in Florida in the growing of lettuce in a floating raft culture system.

From 1990 to 1999, Resh worked as the technical director and project manager for hydroponic projects in the growing of watercress and herbs in California. He designed and constructed several 3-acre outdoor hydroponic watercress facilities using a unique NFT system. These overcame production losses due to drought conditions in the area.

From there in mid-1999, Resh became the hydroponic greenhouse farm manager for the first hydroponic farm associated with a high-end resort, CuisinArt Resort & Spa, in Anguilla, British West Indies, in the northeastern Caribbean. The hydroponic farm is unique in being the only one in the world owned by a resort growing its own fresh salad crops and herbs exclusively for the resort. This farm has become a key component of the resort in attracting guests to experience real homegrown types of vegetables, including tomatoes, cucumbers, peppers, eggplants, lettuce, bok choy, and herbs. The resort, together with its hydroponic farm, has gained worldwide recognition as one of the leading hotels of the world.

Resh continues to consult on many unique hydroponic greenhouse operations such as Lufa Farms in Montreal, Canada. There, he has established the growing techniques and hydroponic systems for a rooftop hydroponic greenhouse in downtown Montreal. All vegetables are marketed through a community supported agriculture (CSA) program.

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1 Introduction

1.1 THE PAST

While hydroponics is a fairly recent term used for growing plants without soil, the method dates back much earlier. The hanging gardens of Babylon, the floating gardens of the Aztecs of Mexico, and those of the Chinese were a form of "hydroponic" culture, although not referred to as that. Even Egyptian hieroglyphic records of several hundred years B.C. describe the growing of plants in water. Theophrastus (372–287 B.C.) undertook various experiments in crop nutrition. Botanical studies by Dioscorides date back to the first century A.D.

The earliest recorded scientific approach to discover plant constituents was in 1600 when Belgian Jan van Helmont showed in his classic experiment that plants obtain substances from water. He planted a 5-lb willow shoot in a tube containing 200 lb of dried soil that was covered to keep out dust. After 5 yr of regular watering with rainwater, he found that the willow shoot increased in weight by 160 lb, while the soil lost less than 2 oz. His conclusion that plants obtain substances for growth from water was correct. However, he failed to realize that they also require carbon dioxide and oxygen from the air. In 1699, an Englishman, John Woodward, grew plants in water containing various types of soil and found that the greatest growth occurred in water that contained the most soil. He thereby concluded that plant growth was a result of certain substances in the water, derived from soil, rather than simply from water itself.

Further progress in identifying these substances was slow until more sophisticated research techniques were developed and advances were made in the field of chemistry. In 1804, De Saussure proposed that plants are composed of chemical elements obtained from water, soil, and air. This proposition was verified later in 1851 by Boussingault, a French chemist, in his experiments with plants grown in sand, quartz, and charcoal to which were added solutions of known chemical composition. He concluded that water was essential for plant growth in providing hydrogen and that plant dry matter consisted of hydrogen plus carbon and oxygen, which came from air. He also stated that plants contain nitrogen and other mineral elements.

Researchers had demonstrated by that time that plants could be grown in an inert medium moistened with a water solution containing minerals required by the plants. The next step was to eliminate the medium entirely and grow the plants in a water solution containing these minerals. This was accomplished in 1860–1861 by two German scientists, Sachs and Knop. This was the origin of "nutriculture," and similar techniques are still used today in laboratory studies of plant physiology and nutrition. These early investigations in plant nutrition demonstrated that normal plant growth can be achieved by immersing the roots of a plant in a water solution containing salts of nitrogen (N), phosphorus (P), sulfur (S), potassium (K), calcium (Ca), and magnesium (Mg), which are now defined as the macroelements or macronutrients (elements required in relatively large amounts).

With further refinements in laboratory techniques and chemistry, scientists discovered seven elements required by plants in relatively small quantities—the microelements or trace elements. These include iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo).

In the following years, researchers developed many diverse basic formulae for the study of plant nutrition. Some of these workers were Arnon, Hoagland, Robbins, Shive, Tollens, Tottingham, and Trelease. Many of their formulae are still used in laboratory research on plant nutrition and physiology.

Interest in practical application of this "nutriculture" did not develop until about 1925 when the greenhouse industry expressed interest in its use. Greenhouse soils had to be replaced frequently to overcome problems of soil structure, fertility, and pests. As a result, research workers became aware of the potential use of nutriculture to replace conventional soil cultural methods. Between 1925 and 1935, extensive development took place in modifying the laboratory techniques of nutriculture to large-scale crop production.

In the early 1930s, W.F. Gericke of the University of California put laboratory experiments in plant nutrition on a commercial scale. In doing so, he termed these nutriculture systems *hydroponics*. The word was derived from two Greek words *hydro* ("water") and *ponos* ("labor")—literally "water working."

Hydroponics can be defined as the science of growing plants without the use of soil, but by the use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, rice hulls, or other substrates, to which is added a nutrient solution containing all the essential elements needed by a plant for its normal growth and development. Since many hydroponic methods employ some type of medium it is often termed "*soilless culture*," while water culture alone would be true hydroponics.

Using hydroponics, Gericke grew vegetables, including root crops such as beets, radishes, carrots, and potatoes; cereal crops; fruits; ornamentals; and flowers. Using water culture in large tanks, he grew tomatoes to such heights that he had to harvest them with a ladder. The American press made many irrational claims, calling it the discovery of the century. After an unsettled period in which unscrupulous people tried to cash in on the idea by selling useless equipment, more practical research was done and hydroponics became established on a sound scientific basis in horticulture, with recognition of its two principal advantages, high crop yields and its special utility in nonarable regions of the world.

Gericke's application of hydroponics soon proved itself by providing food for troops stationed on nonarable islands in the Pacific in the early 1940s. In 1945, the U.S. Air Force solved its problem of providing its personnel with fresh vegetables by practicing hydroponics on a large scale on the rocky islands normally incapable of producing such crops.

After World War II, the military command continued to use hydroponics. For example, the U.S. Army established a 22-ha project at Chofu, Japan. The commercial use of hydroponics expanded throughout the world in the 1950s to countries such as Italy, Spain, France, England, Germany, Sweden, the USSR, and Israel.

1.2 THE PRESENT

With the development of plastics, hydroponics took another large step forward. Plastics freed growers from the costly construction associated with the concrete beds and tanks previously used. With the development of suitable pumps, time clocks, plastic plumbing, solenoid valves, and other equipment, the entire hydroponic system can now be automated, reducing both capital and operational costs. Many modern greenhouse operations now use automation in the moving of growing channels within the greenhouse and automated, robotic transplanting and harvesting. Such operations exist in Europe and the United States. Hortiplan is such a company from Belgium that engineers and manufactures nutrient film technique (NFT) water-culture systems for automation, used at present in Belgium, Holland, and United States and soon to be used in Chile. This system is elaborated upon in Chapter 6.

Hydroponics has become a reality for greenhouse growers in virtually all climates. Large hydroponic installations exist throughout the world for growing both flowers and vegetables. Many hydroponic vegetable production greenhouses exist in the United States, Canada, and Mexico that are 50 acres or larger in area. Large U.S. growers include Village Farms, L.P., with operations (seven partner growers) in Western Canada, with the majority in Delta, British Columbia (60 acres), and Fort Davis and Marfa, Texas (40 acres). They have six partner growers in Mexico and two partner growers in Pennsylvania, with a total of 315 acres. Eurofresh Farms based in Wilcox, Arizona, has a total of 318 acres. Houweling Nurseries Ltd. in Oxnard, California, has 130 acres of greenhouse production. In Canada, greenhouses larger than 50 acres include Houweling Nurseries Ltd., Delta, British Columbia; Mastron Enterprises Ltd., Leamington, Ontario; Great Northern Hydroponics, Leamington, Ontario; and DiCiocco's, Leamington, Ontario.

The breakdown of Canada's hydroponic greenhouse vegetable production according to 2008 data (Hickman, 2011) is as follows: tomato—466 ha (1,152 acres); cucumber—277 ha (683 acres); pepper—306 ha (756 acres); and lettuce—15 ha (36 acres), totaling 1,064 ha (2,627 acres).

The largest Mexican hydroponic greenhouse operation is Bionatur Invernaderos Biologicos de Mexico, Jocotitlan, Mexico. It operates on 80 ha (200 acres), growing tomatoes and employing 1,000 people. There are numerous other hydroponic greenhouse vegetable production facilities such as Agros S.A. de C.V., presently 13 ha (32 acres), in the state of Queretaro.

World hydroponic production has increased from 5,000–6,000 ha (12,500–15,000 acres) in the 1980s to 20,000–25,000 ha (50,000–62,500 acres) in 2001 according to information by Carruthers. A more recent publication by Gary W. Hickman, *Greenhouse Vegetable Production Statistics—2011 Edition*, claims that world hydroponic vegetable production is about 35,000 ha (86,500 acres). He also points out that commercial greenhouse vegetable production varies from 330,000 ha (815,000 acres) to 1.2 million ha (3 million acres) because of the definition of "greenhouse" and "hydroponic production."

Greenhouse hydroponic production is one that uses soilless culture, and not one that just covers the existing soil with a very light-weight poly structure such as poly tunnels and plastic low tunnels, applying water and some nutrients by a drip irrigation system, as it occurs in places such as the Canary Islands, Spain, China, and Mexico. For example, Hickman points out that Mexico produces about 3,770 ha (9,300 acres) of natural ventilated, unheated, high-tunnel structures of plastic-covered metal structures with insect sidewalls. These "greenhouses" often have computerized irrigation and fertilization systems, but are growing in the local soil and therefore cannot be termed "hydroponic." One project of this nature in Sinaloa, Mexico, has 865 acres (350 ha) of tomato, cucumber, and pepper greenhouses.

Holland, on the other hand, has 4,600 ha (11,300 acres) of hydroponic vegetable production with sophisticated, high-technology greenhouses of metal and glass with computer-controlled environments. Other statistics report an area of 10,000 ha (25,000 acres), but that would include flower production. While Holland is still the largest, Spain now has about 4,000 ha; however, the greenhouse structures there are much lower cost polyethylene structures unlike most Dutch glass greenhouses. Belgium and Germany each have about 600 ha, with New Zealand and Australia continuing to expand beyond their present 500 ha. Australia has the largest commercial hydroponic lettuce production in the world, with over 240 ha (600 acres). However, more than half (55.6%) is grown outdoors without greenhouses (Bailey, 1999). NFT and rockwool cultures are the principal hydroponic methods employed. The greater portion of hydroponic growers is located in New South Wales.

It must be noted that the areas of hydroponic production include flowers and ornamental houseplants unless otherwise stated. The most important commercial hydroponic crops include tomatoes, cucumbers, peppers, lettuce, and flowers.

Nichols and Christie (2008) reported in *Practical Hydroponics & Greenhouses* that, in 2007 Japan had 52,000 ha of greenhouses, mainly of plastic, with only 5% glass, but only 1,500 ha (3%) were in a hydroponic system.

Hydroponics is now used in almost every country in the world. G.W. Hickman in his study of greenhouse vegetable production reported information on 83 countries that produce greenhouse vegetables commercially. While the majority of this greenhouse vegetable production is in the soil, hydroponics is generally also part of this industry, even if on a smaller scale. Even countries such as Turkey claim over 54,000 ha (135,000 acres) of greenhouse production.

As mentioned earlier, such as in the case of Spain and Mexico, a large part of that production would be in plastic tunnels and low-profile cold frames that may be misnamed greenhouses. Nonetheless, Satici (2010) states that Turkey has about 400 ha (1,000 acres) of modern greenhouse production area, which is expanding by 50% every year. Their principal production includes tomatoes, cucumbers, peppers, watermelons, eggplants, and strawberries.

In arid regions of the world, such as Mexico and the Middle East, hydroponic complexes combined with desalination units are being developed to use sea water as a source of fresh water. With less expensive desalination equipment, such as reverse osmosis (RO), water can be generated in these arid regions at an economically feasible cost for use in greenhouses. The complexes are located near the ocean and plants are often grown in the existing sand.

1.3 THE FUTURE

In a relatively short period, over about 65 yr, hydroponics has adapted to many situations, from outdoor field culture and indoor greenhouse culture to highly specialized culture in the space program. It is a space-age science, but at the same time can be used in developing countries of the Third World to provide intensive food production in limited area. Its only restraints are sources of fresh water and nutrients. In areas where fresh water is not available, hydroponics can use seawater through desalination. Therefore, it has potential application in providing food in areas having vast regions of nonarable land, such as deserts. Hydroponic operations can be located along coastal regions in combination with petroleum-fueled, solar, or atomic desalination units, using beach sand as the medium for growing the plants.

Hydroponics is a valuable culture method to grow fresh vegetables in countries having little arable land and those that are very small in area yet have a large population. It could also be particularly useful in some smaller countries whose chief industry is tourism.

In such countries, tourist facilities, such as resort hotels, can grow their own products instead of importing them from many thousands of miles away, with long shipping periods.

Typical examples of such regions are the West Indies and Hawaii, which have a large tourist industry and very little farm land in vegetable production.

Hydroponic greenhouse operations will be linked with industries having waste heat or alternative sources of energy. Such cogeneration projects already exist in California, Colorado, Nevada, and Pennsylvania. Anaerobic digesters of animal waste products can have hydroponic greenhouses associated with them in the Midwest where lots of dairy farms exist. The anaerobic digesters can generate heat and electricity. Electric power generating stations use water in their cooling towers. This heated water can be used both for heating the greenhouse and for providing distilled water free of minerals for growing plants in recirculation systems. This clean water is of particular advantage to growers in areas normally having hard raw water. In most of the sun-belt locations where sunlight is favorable to high production of vegetables, waters are very hard with high levels of minerals, which are often in excess of normal plant requirements. The hard water also creates problems with corrosion of equipment, plugging of cooling pads, fogging systems, and structural breakdown of growing media.

With the introduction of new technology in artificial lighting, growing plants using artificial lighting will become economically feasible, especially in the more northern latitudes where sunlight is limited during the year, from late fall to early spring. During this period, of course, the prices for produce are much higher than in summer months. The new LED lights have this potential, but at present are too expensive and needed in large numbers to supply adequate light. Heat generated from the lights could be used to supplement the heating of the growing operation.

There are many locations in western North America having geothermal sources of heat. Such sites exist in Alaska, California, Colorado, Idaho, Montana, Oregon, Utah, Washington, Wyoming, and British Columbia. In the future, large greenhouses should be located close to geothermal sites to utilize the heat, as is presently done in Hokkaido, Japan.

At present, a lot of research is being carried out to develop hydroponic systems for growing vegetables on the space station. Closed-loop recirculation systems are being designed and tested to operate under microgravity (very low gravity) environments. Such hydroponic systems will grow food to nourish astronauts on long space missions.

In large cities where fresh vegetables are often transported long distances from their growing facilities, there is potential for hydroponic greenhouse roof-top gardens. In a recent issue of *Scientific American* (November 2009), an article was written by D. Despommier (2009) describing how vertical high-rise buildings of 30 stories could grow produce within large cities. Hydroponic systems would be used in conjunction with solar cells and incineration of plant waste to create power and treated wastewater from the city would irrigate the plants. Sunlight and artificial lighting would provide light.

1.4 SUITABLE SITE CHARACTERISTICS

When considering a hydroponic greenhouse site location, try to meet as many as possible of the following requirements to improve success.

1. In the northern latitudes, a site that has full east, south, and west exposure to sunlight with a windbreak on the north.
2. An area that is as near level as possible or one that can be easily leveled.
3. Good internal drainage with minimum percolation rate of 1 in./h.

4. Availability of natural gas, three-phase electricity, telephone, and good-quality water, with capability to supply at least one-half gallon of water per plant per day. If the raw water is high in salts, an RO desalination unit will be needed.
5. Location on or near a main road close to a population center for wholesale market and retail market at the greenhouses if one chooses to sell retail.
6. Location close to residence for ease of checking the greenhouse during extremes of weather. All modern computer-controlled greenhouses have alarm and call-up systems to alert the grower. Parameters can also be checked through a laptop computer or mobile phone.
7. North–south oriented greenhouses, with rows also north–south in the northern latitudes.
8. A region that has a maximum amount of sunlight.
9. Areas not having excessive strong winds.
10. Areas that are not of high water table or are not in a flood plain. Fill would be required in such areas, which will add to capital costs.

1.5 SOIL VERSUS SOILLESS CULTURE

The large increases in yields under hydroponic culture over that of soil may be due to several factors. In some cases, the soil may lack nutrients and have poor structure; therefore, soilless culture would be very beneficial. The presence of pests or diseases in the soils greatly reduces overall production. Under greenhouse conditions, when environmental conditions other than the medium are similar for both soil and soilless cultures, the increased production of tomatoes grown hydroponically is usually 20%–25%. Such greenhouses practice soil sterilization and use adequate fertilizers; as a result, many of the problems encountered under field conditions in soil would be overcome. This would account for the smaller increases in yields using soil culture under greenhouse conditions over the very striking 4–10 times increase in yields obtained by soilless culture outdoors over conventional soil-grown conditions.

Specific greenhouse varieties have been bred to produce higher yields under greenhouse culture than field-grown varieties could under the same conditions. These greenhouse varieties cannot tolerate the daily temperature fluctuations of outdoor culture; therefore, their use is restricted to greenhouse growing. Nonetheless, given optimum growing conditions of hydroponic greenhouse culture, they will far out-yield field varieties. The principal vegetable crops grown in hydroponic greenhouse culture include tomatoes, cucumbers, peppers, lettuce, and other leafy greens and herbs.

These greenhouse varieties have also been bred to resist or tolerate diseases of the foliage and roots, thereby increasing production. Now rootstocks are green grafted to tomatoes, peppers, and eggplants. The tomato root stock is more vigorous than the scion (commercial variety) and resists root diseases.

The main disadvantages of hydroponics are the high initial capital cost; some diseases caused by organisms such as *Fusarium* and *Verticillium*, which can spread rapidly through the system; and the complex nutritional problems encountered. Most of these disadvantages can be overcome by rootstocks, new varieties having more disease resistance, and better nutrient testing devices.

Overall, the main advantages of hydroponics over soil culture are more efficient nutrition regulation, availability in regions of the world having nonarable land, efficient use of water and fertilizers, ease and low cost of sterilization of the medium, and higher density planting, leading to increased yields per acre (Table 1.1).

TABLE 1.1
Advantages of Soilless Culture versus Soil Culture

Cultural Practice	Soil Culture	Soilless Culture
Sterilization of growing medium	Steam, chemical fumigants; labor intensive; time required is lengthy; minimum 2–3 wk	Steam, chemical fumigants with some systems; others can use bleach or HCl; short time needed to sterilize
Plant nutrition	Highly variable, localized deficiencies; often unavailable to plants because of poor soil structure or pH; unstable conditions; difficult to sample, test, and adjust	Controlled; relatively stable; homogeneous to all plants; readily available in sufficient quantities; good control of pH; easily tested, sampled, and adjusted
Plant spacing	Limited by soil nutrition and available light	Limited only by available light, making, closer spacing possible; increased number of plants per unit area, resulting in more efficient use of space and greater yields per unit area
Weed control, cultivation	Weeds present, cultivate regularly	No weeds, no cultivation
Diseases and soil inhabitants	Many soil-borne diseases, nematodes, insects, and animals, which can attack crop; frequent use of crop rotation to overcome buildup of infestation	No diseases, insects, animals in medium; no need for crop rotation
Water	Plants often subjected to water stress because of poor soil–water relations, soil structure, and low water-holding capacity. Saline waters cannot be used. Inefficient use of water; much is lost as deep percolation past the plant root zone and also by evaporation from the soil surface	No water stress. Complete automation by use of moisture-sensing devices and a feedback mechanism. Reduces labor costs, can use relatively high saline waters, efficient water use, no loss of water to percolation beyond root zone or surface evaporation; if managed properly, water loss should equal transpirational loss
Fruit quality	Often fruit is soft or puffy because of potassium and calcium deficiencies. This results in poor shelf life	Fruit is firm, with long shelf life. This enables growers to pick vine-ripened fruit and ship it long distances. In addition, little, if any, spoilage occurs at the supermarket. Some tests have shown higher vitamin A content in hydroponically grown tomatoes than in those grown in soil
Fertilizers	Uses large quantities over the soil, nonuniform distribution to plants, large amount leached past plant root zone (50%–80%), inefficient use	Uses small quantities, uniformly distributed to all plants, no leaching beyond root zone, efficient use
Sanitation	Organic wastes used as fertilizers onto edible portions of plants cause many human diseases	No biological agents added to nutrients; no human disease organisms present on plants

continued

TABLE 1.1 (continued)
Advantages of Soilless Culture versus Soil Culture

Cultural Practice	Soil Culture	Soilless Culture
Transplanting	Need to prepare soil and uproot plants, which leads to transplanting shock. Difficult to control soil temperatures and disease organisms, which may retard or kill transplants	No preparation of medium required before transplanting; transplanting shock minimized, faster “take” and subsequent growth. Medium temperature can be maintained optimum. No disease present
Plant maturity	Often slowed by nonoptimum conditions	With adequate light conditions, plant can mature faster under a soilless system than in soil
Permanence	Soil in a greenhouse must be changed regularly every several years since fertility and structure break down	No need to change medium in gravel, sand, or water cultures; no need to fallow. Sawdust, peat, coco coir, vermiculite, perlite, rockwool may last for several years between changes with sterilization
Yields	Greenhouse tomatoes 15–20 lb/yr/plant	Greenhouse tomatoes 50–70 lb/yr/plant

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2 Plant Nutrition

2.1 PLANT CONSTITUENTS

The composition of fresh plant matter includes about 80%–95% water. The exact percentage of water depends on the plant species and the turgidity of the plant at the time of sampling, which is a result of the time of day, amount of available moisture in the soil, temperature, wind velocity, and other factors. Because of the variability in fresh weight, chemical analyses of plant matter are usually based on the more stable dry matter. Fresh plant material is dried at 70°C for 24–48 h. The dry matter remaining constitutes roughly 10%–20% of the initial fresh weight. Over 90% of the dry weight of most plant matter consists of three elements: carbon (C), oxygen (O), and hydrogen (H). Water supplies hydrogen and oxygen. Oxygen also comes from carbon dioxide from the atmosphere, as does carbon.

If only 15% of the fresh weight of a plant is dry matter, and 90% of this is represented by carbon, oxygen, and hydrogen, then all the remaining elements in the plant account for roughly 1.5% of the fresh weight of the plant ($0.15 \times 0.10 = 0.015$).

2.2 MINERAL AND ESSENTIAL ELEMENTS

Although a total of 92 natural mineral elements are known, only 60 elements have been found in various plants. Although many of these elements are not considered essential for plant growth, plant roots probably absorb to some extent from the surrounding soil solution any element existing in a soluble form. However, plants do have some ability to select the rate at which they absorb various ions, so absorption is usually not in direct proportion to nutrient availability. Furthermore, different species vary in their ability to select particular ions.

An element must meet each of the three criteria to be considered essential for plant growth (Arnon and Stout, 1939; Arnon, 1950, 1951). (1) The plant cannot complete its life cycle in the absence of the element. (2) Action of the element must be specific; no other element can wholly substitute for it. (3) The element must be directly involved in the nutrition of the plant, that is, be a constituent of an essential metabolite or, at least, be required for the action of an essential enzyme, and not simply cause some other element to be more readily available or antagonize a toxic effect of another element.

Only 16 elements are generally considered to be essential for the growth of higher plants. They are arbitrarily divided into the macronutrients (macroelements), those required in relatively large quantities, and the micronutrients (trace or minor elements), those needed in considerably smaller quantities.

Macroelements include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), and magnesium (Mg). Microelements include iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), and

TABLE 2.1
Elements Essential for Most Higher Plants

Element	Symbol	Available Form	Atomic Weight	Parts per Million (ppm)	Concentration in Dry Tissue (%)
		Macronutrients			
Hydrogen	H	H_2O	1.01	60,000	6
Carbon	C	CO_2	12.01	450,000	45
Oxygen	O	O_2, H_2O	16.00	450,000	45
Nitrogen	N	NO_3^-, NH_4^+	14.01	15,000	1.5
Potassium	K	K^+	39.10	10,000	1.0
Calcium	Ca	Ca^{2+}	40.08	5,000	0.5
Magnesium	Mg	Mg^{2+}	24.32	2,000	0.2
Phosphorus	P	$H_2PO_4^-$, HPO_4^{2-}	30.98	2,000	0.2
Sulfur	S	SO_4^{2-}	32.07	1,000	0.1
		Micronutrients			
Chlorine	Cl	Cl^-	35.46	100	0.01
Iron	Fe	Fe^{3+}, Fe^{2+}	55.85	100	0.01
Manganese	Mn	Mn^{2+}	54.94	50	0.005
Boron	B	BO_3^{2-}, $B_4O_7^{2-}$	10.82	20	0.002
Zinc	Zn	Zn^{2+}	65.38	20	0.002
Copper	Cu	Cu^{2+}, Cu^+	63.54	6	0.0006
Molybdenum	Mo	MoO_4^{2-}	95.96	0.1	0.00001

Source: Modified from Stout P.R., *Proc. of the 9th Ann. Calif. Fert. Conf.* 1961. pp. 21–23.

molybdenum (Mo). The relative concentrations of these elements found in most higher plants are given in Table 2.1.

Although most higher plants require only the 16 essential elements, certain species may need others. They may, at least, accumulate these other elements even if they are not essential to their normal growth. Silicon (Si), nickel (Ni), aluminum (Al), cobalt (Co), vanadium (V), selenium (Se), and platinum (Pt) are a few of these elements absorbed by plants and used in their growth. Cobalt is used by legumes for N_2 fixation. Nickel is now believed to be an essential element. It is essential for the urease enzyme activity. Silicon is needed for support. It adds strength to tissues, giving resistance to fungal infection, especially in cucumbers, where it is now a common practice to include 100 ppm in the nutrient solution through the use of potassium silicate. Vanadium works with molybdenum (Mo) and can substitute for it. Platinum can increase growth of plants by 20% if pure chemicals (laboratory reagents), which have no impurities as do the fertilizer grades, are used. However, it is toxic at very low levels, so care must be taken when using it. Normally, commercial growers use fertilizer salts containing many of the above elements in trace amounts.

The roles of the essential elements are summarized in Table 2.2. All of them play some role in the manufacture and breakdown of various metabolites required for plant growth. Many are found in enzymes and coenzymes that regulate the rate of biochemical reactions. Others are important in energy-carrying compounds and food storage.

TABLE 2.2
Functions of the Essential Elements within the Plant

1. Nitrogen
   Part of a large number of necessary organic compounds, including amino acids, proteins, coenzymes, nucleic acids, and chlorophyll
2. Phosphorus
   Part of many important organic compounds, including sugar phosphates, ATP, nucleic acids, phospholipids, and certain coenzymes
3. Potassium
   Acts as a coenzyme or activator for many enzymes (e.g., pyruvate kinase). Protein synthesis requires high potassium levels. Potassium does not form a stable structural part of any molecules inside plant cells
4. Sulfur
   Incorporated into several organic compounds including amino acids and proteins. Coenzyme A and the vitamins thiamine and biotin contain sulfur
5. Magnesium
   An essential part of the chlorophyll molecule and required for activation of many enzymes, including those involved in ATP bond breakage. Essential to maintain ribosome structure
6. Calcium
   Often precipitates as crystals of calcium oxalate in vacuoles. Found in cell walls as calcium pectate, which cements together primary walls of adjacent cells. Required to maintain membrane integrity and is part of the enzyme α-amylase. Sometimes interferes with the ability of magnesium to activate enzymes
7. Iron
   Required for chlorophyll synthesis and is an essential part of the cytochromes, which act as electron carriers in photosynthesis and respiration. Is an essential part of ferredoxin and possibly nitrate reductase. Activates certain other enzymes
8. Chlorine
   Required for photosynthesis, where it acts as an enzyme activator during the production of oxygen from water. Additional functions are suggested by effects of deficiency on roots
9. Manganese
   Activates one or more enzymes in fatty acid synthesis, the enzymes responsible for DNA and RNA formation, and the enzyme isocitrate dehydrogenase in the Krebs cycle. Participates directly in the photosynthetic production of O_2 from H_2O and may be involved in chlorophyll formation
10. Boron
    Role in plants not well understood. May be required for carbohydrate transport in the phloem
11. Zinc
    Required for the formation of the hormone indoleacetic acid. Activates the enzymes alcohol dehydrogenase, lactic acid dehydrogenase, glutamic acid dehydrogenase, and carboxypeptidase
12. Copper
    Acts as an electron carrier and as part of certain enzymes. Part of plastocyanin, which is involved in photosynthesis, and also of polyphenol oxidase and possible nitrate reductase. May be involved in N_2 fixation

continued

TABLE 2.2 (continued)
Functions of the Essential Elements within the Plant

13. Molybdenum
    Acts as an electron carrier in the conversion of nitrate to ammonium and is also essential for N_2 fixation
14. Carbon
    Constituent of all organic compounds found in plants
15. Hydrogen
    Constituent of all organic compounds of which carbon is a constituent. Important in cation exchange in plant–soil relations
16. Oxygen
    Constituent of many organic compounds in plants. Only a few organic compounds, such as carotene, do not contain oxygen. Also involved in anion exchange between roots and the external medium. It is a terminal acceptor of H^+ in aerobic respiration

2.3 PLANT MINERAL AND WATER UPTAKE

Plants normally obtain their water and mineral needs from the soil. In a soilless medium, the plants must still be provided with water and minerals. Therefore, in order to understand plant relations in a hydroponic system, we must understand the soil–plant relations under which they normally grow.

2.3.1 SOIL

Soil provides for four needs of a plant: (1) supply of water, (2) supply of essential nutrients, (3) supply of oxygen, and (4) support for the plant root system. Mineral soils consist of four major components, namely, mineral elements, organic matter, water, and air. For example, a volume composition of a representative silt loam soil in optimum condition for plant growth may consist of 25% water space, 25% air space, 45% mineral matter, and 5% organic matter. The mineral (inorganic) matter is made up of small rock fragments and minerals of various kinds. The organic matter represents an accumulation of partially decayed plant and animal residues. The soil organic matter consists of two general groups: (1) original tissue and its partially decomposed equivalents and (2) humus. The original tissue includes undecomposed plant and animal matter, which is subject to attack by soil organisms, both plant and animal, which use it as a source of energy and as tissue-building material. Humus is the more resistant product of decomposition, both synthesized by the microorganism and modified from the original plant tissue.

Soil water is held within the soil pores and together with its dissolved salts makes up the soil solution, which is important as a medium for supplying nutrients to growing plants. Soil air located in the soil pores has a higher carbon dioxide and lower oxygen content than that found in the atmosphere. Soil air is important in providing oxygen and carbon dioxide to all soil organisms and plant roots.

The ability of soil to provide adequate nutrition to the plant depends on four factors: (1) the amounts of the various essential elements present in the soil, (2) their forms of combination, (3) the processes by which these elements become available to plants, and (4) the soil solution and its pH. The amounts of the various elements present in the soil depend on the nature of the soil and on its organic matter content, since it is a source of several nutrient elements. Soil nutrients exist both as complex, insoluble compounds and as simple forms usually soluble in soil water and readily available to plants. The complex forms must be broken down through decomposition to the simpler and more available forms in order to benefit the plant. These available forms are summarized in Table 2.1. The reaction of the soil solution (pH) determines the availability of the various elements to the plant. The pH value is a measure of acidity or alkalinity. A soil is acidic if the pH is less than 7, neutral if the pH is at 7, and alkaline if the pH is above 7. Since pH is a logarithmic function, a one-unit change in pH is a 10-fold change in H^+ concentration. Therefore, any unit change in pH can have a large effect on the ion availability to plants. Most plants prefer a pH level between 6.0 and 7.0 for optimum nutrient uptake. The effect of pH on the availability of essential elements is shown in Figure 2.1.

Iron, manganese, and zinc become less available as the pH is raised from 6.5 to 7.5 or 8.0. Molybdenum and phosphorus availability, on the other hand, is affected in the opposite way, being greater at higher pH levels. At very high pH, bicarbonate ion (HCO_3^-) may be present in sufficient quantities to interfere with the normal uptake of other ions and thus is detrimental to optimum growth.

When inorganic salts are placed in a dilute solution, they dissociate into electrically charged units called *ions*. These ions are available to the plant from the surface of soil

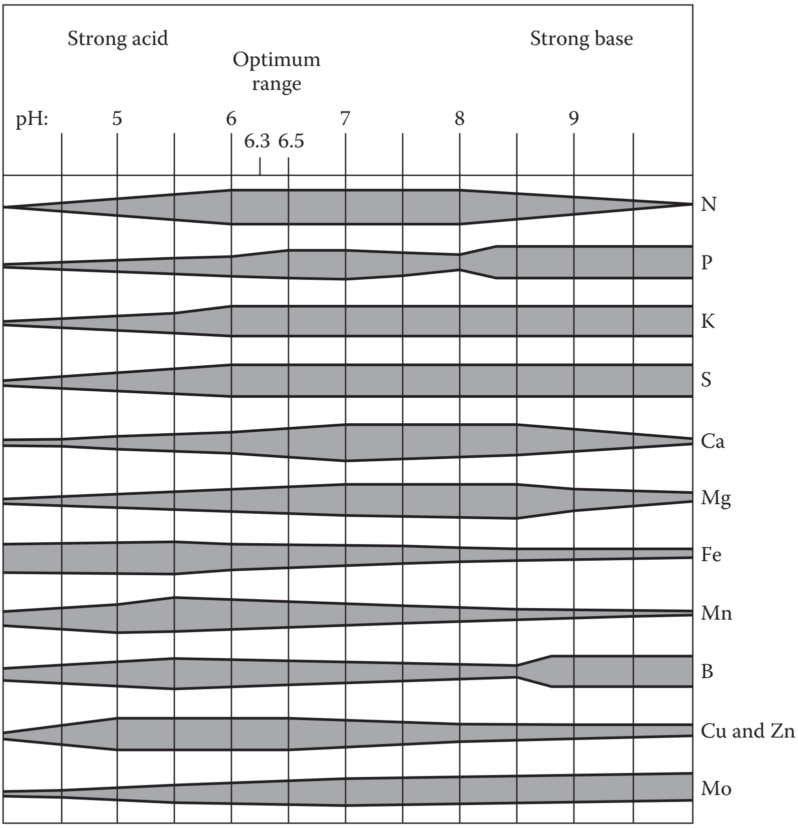

FIGURE 2.1 The effect of soil pH on the availability of plant nutrients. (Modified from Sprague, H.B., *Hunger Signs in Crops*. 1964. p. 18. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

colloids and from salts in the soil solution. Positively charged ions (*cations*), such as potassium (K^+) and calcium (Ca^{2+}), are mostly absorbed by the soil colloids, whereas negatively charged ions (*anions*), such as chloride (Cl^-) and sulfate (SO_4^{2-}), are found in the soil solution.

2.3.2 SOIL AND PLANT INTERRELATIONS

Plant rootlets and root hairs are in very intimate contact with soil colloidal surfaces. Nutrient uptake by the plants' roots takes place at the surface of the soil colloids and through the soil solution proper, as shown in Figure 2.2. Ions are interchanged between the soil colloids and soil solution. Movement of ions takes place between plant root surfaces and soil colloids and between plant root surfaces and soil solution in both directions. A good review of soil properties is presented by Buckman and Brady (1984) and that of plant and soil interrelations by Kramer (1969).

2.3.3 CATION EXCHANGE

The soil solution is the most important source of nutrients for absorption by plant roots. Since it is very dilute, as plants deplete the nutrients from the soil solution, they must be replenished from the soil particles. The solid phase of the soil releases mineral elements into the soil solution partly by solubilization of soil minerals and organic matter, partly by solution of soluble salts, and partly by cation exchange. The negatively charged clay particles and solid organic matter of the soil hold cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and hydrogen ions (H^+). Anions, such as nitrate (NO_3^-), phosphate (HPO_4^{2-}), sulfate (SO_4^{2-}), chloride (Cl^-), and others are found almost exclusively in the soil solution. Cations are also found in the soil solution, and their ability to exchange freely with cations absorbed on the soil colloids enables cation exchange to take place.

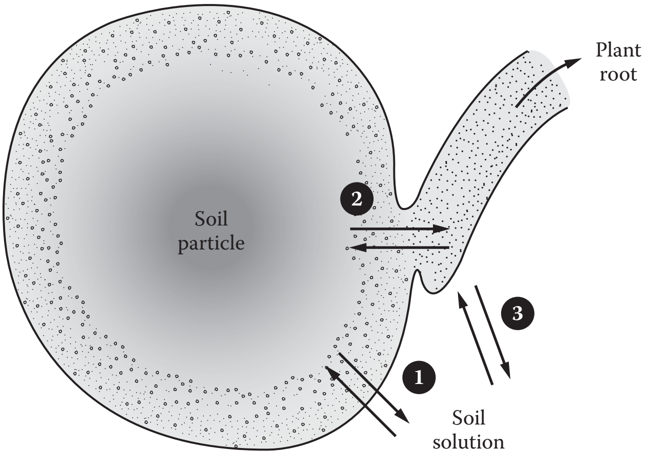

FIGURE 2.2 The movement of nutrients between plant roots and soil particles. (1) Interchange between soil particles and the soil solution. (2) Movement of the ions from the soil colloids (particles) to the plant root surface and vice versa. (3) Interchange between the soil solution and the absorbing surface of plant root systems. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

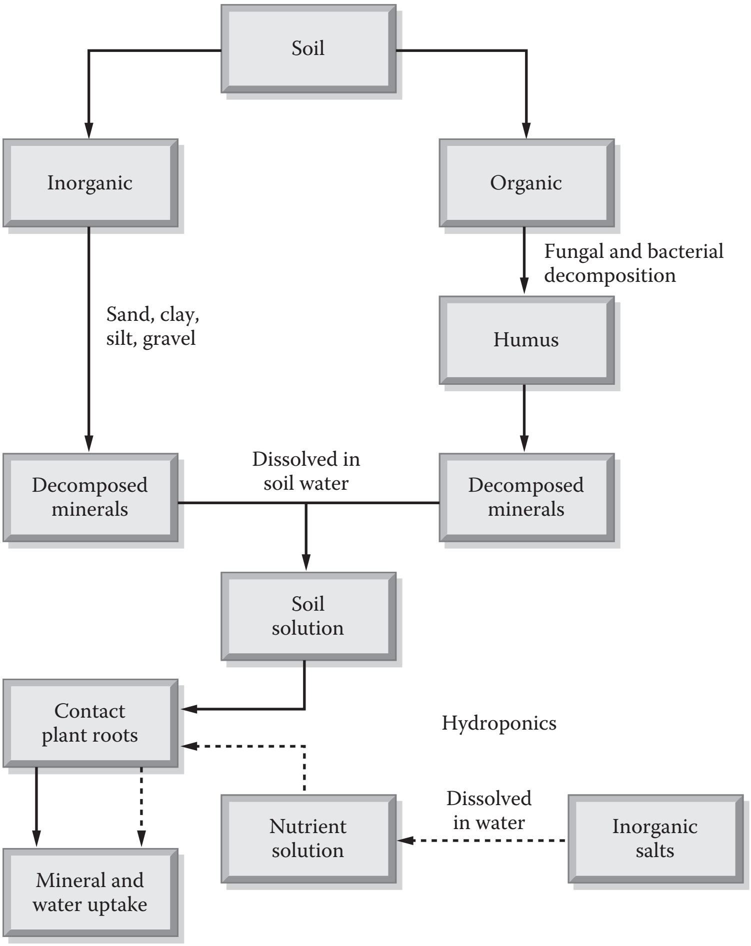

FIGURE 2.3 Origin of essential elements in soil and hydroponics. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

2.3.4 SOIL VERSUS HYDROPONICS

There is no physiological difference between plants grown hydroponically and those grown in soil. In soil, both the organic and inorganic components must be decomposed into inorganic elements, such as calcium, magnesium, nitrogen, potassium, phosphorus, iron, and others before they are available to the plant (Figure 2.3). These elements adhere to the soil particles and are exchanged into the soil solution where they are absorbed by the plants. In hydroponics, the plant roots are moistened with a nutrient solution containing the elements. The subsequent processes of mineral uptake by the plant are the same, as detailed in Sections 2.3.5 and 2.3.6.

2.3.5 TRANSFER OF WATER AND SOLUTES FROM SOIL (OR NUTRIENT SOLUTION) TO ROOT

The use of the term "organic" in the marketing of vegetables is really a misnomer as all plants are organic and use the same essential mineral elements. The term "organic" refers to the non-use of synthetic pesticides and therefore should be called "free of synthetic pesticides." The question of organic versus inorganic gardening can be clarified by a discussion of mineral uptake by the plant.

In 1932, E. Munch of Germany introduced the apoplast–symplast concept to describe water and mineral uptake by plants. He suggested that water and mineral ions move into the plant root via the interconnecting cell walls and intercellular spaces, including the xylem elements, which he called the *apoplast*, or via the system of interconnected protoplasm (excluding the vacuoles), which he termed the *symplast*. However, whatever the movement may be, uptake is regulated by the endodermal layer of cells around the stele, which constitutes a barrier to free movement of water and solutes through the cell walls. There is a waxy strip, the Casparian strip, around each endodermal cell, which isolates the inner portion of the root (stele) from the outer epidermal and cortex regions in which water and mineral movement is relatively free.

If the root is in contact with a soil (nutrient) solution, ions will diffuse into the root via the apoplast across the epidermis, through the cortex, and up to the endodermal layer. Some ions will pass from the apoplast into the symplast by an active respiration-requiring process. Since the symplast is continuous across the endodermal layer, ions can move freely into the pericycle and other living cells within the stele (Figure 2.4).

2.3.6 MOVEMENT OF WATER AND MINERALS ACROSS MEMBRANES

If a substance is moving across a cell membrane, the number of particles moving per unit of time through a given area of the membrane is termed the *flux*. The flux is equal to the permeability of the membrane multiplied by the driving force causing diffusion. The driving force is due to the difference in concentration (the chemical potential) of that ion on the two sides of the membrane. If the chemical potential of the solute is higher outside the membrane than inside, the transport inward is passive. That is, energy is not expended by

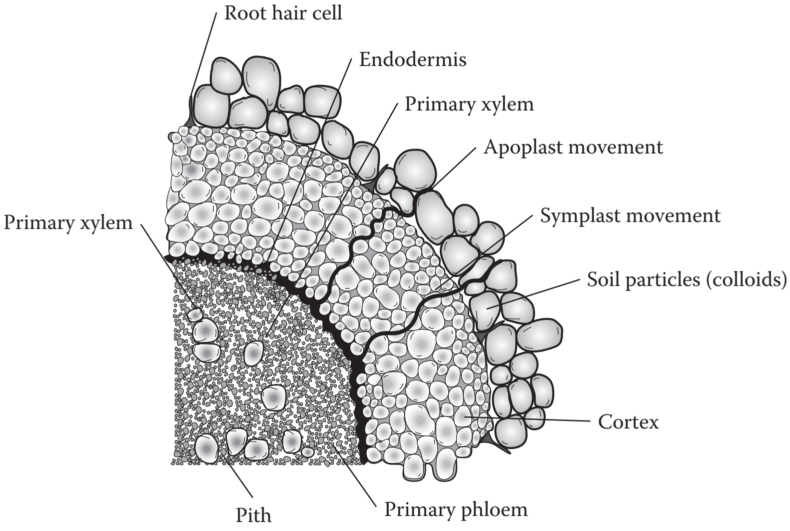

FIGURE 2.4 A cross section of a root with movement of water and nutrients. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

the plant to take up the ion. If, however, a cell accumulates ions against a chemical potential gradient, it must provide energy sufficient to overcome the difference in chemical potential. Transport against a gradient is active since the cells must actively metabolize in order to carry out the solute uptake.

When ions are transported across membranes, the driving force is composed of both a chemical and electrical potential difference. That is, an electrochemical potential gradient exists across the membrane. The electrical potential difference arises from cations diffusing across more rapidly than the corresponding anions of a salt. Thus, the inside will become positive with respect to the outside. Whether the transport of an ion is active or passive depends on the contribution of both the electrical potential difference and the chemical potential difference. Sometimes, these two factors will act in the same direction, while in other cases, they act oppositely. For example, a cation might have a higher concentration inside the cell and yet be transported inward passively with no energy expenditure on the part of the cell if the electrical potential is sufficiently negative. On the other hand, anion absorption against both a chemical potential gradient and a negative electrical potential would always be an active process.

There are a number of theories proposed to explain how respiration and active absorption are coupled, but most of them employ the mechanism of a carrier. For example, when an ion contacts the outside of a membrane of a cell, neutralization may occur as the ion is attached to some molecular entity that is a part of the membrane. The ion attached to this carrier might then diffuse readily across the membrane, being released on the opposite side. The attachment may require the expenditure of metabolic energy and can occur on only one side of the membrane, while release can occur only on the other side of the membrane. The ions separate and move into the cell, and the carrier becomes available to move more ions (Figure 2.5). Selectivity in ion accumulation could be controlled by differences in the ability of carriers to form specific combinations with various ions. For example, potassium absorption is inhibited competitively by rubidium, indicating that the two ions use the same carrier or the same site on the carrier.

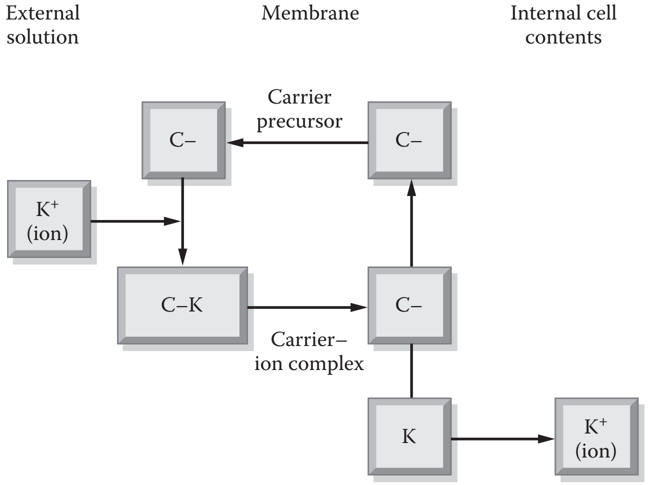

FIGURE 2.5 Movement of ions across cell membranes by a carrier. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

As previously indicated, the foregoing explanation of mineral uptake by plant roots has been presented in an effort to clarify the question of organic versus inorganic gardening. The existence of specific relationships between ions and their carriers, which enables their transport across cell membranes to enter the cell, demonstrates that mineral uptake functions in the same manner whether the source of such minerals is from organic matter or from fertilizers. Large organic compounds making up soil humus are not absorbed by the plant, but must first undergo decomposition into the basic inorganic elements. They can be accumulated by their contact with plant cell membranes only in their ionic form. Thus, organic gardening cannot provide to the plant any compound that cannot exist in a hydroponic system. The function of organic matter in soil is to supply inorganic elements for the plant and at the same time maintain the structure of the soil in an optimum condition so that these minerals will be available to the plant. Thus, the indiscriminate application of large amounts of fertilizers to soil without addition of organic matter results in a breakdown of the soil structure and subsequently makes the abundant supply of minerals unavailable to the plant. This is not the fault of the fertilizer but its misuse in soil management.

2.4 UPWARD MOVEMENT OF WATER AND NUTRIENTS

Water, with its dissolved minerals, moves primarily upward in the plant through the xylem tissue. The xylem, composed of several cell types, forms a conduit system within the plant. This vascular tissue is commonly termed *vein*. Veins are actually composed of xylem and phloem tissue. The phloem tissue is the main conduit of manufactured food. The actual phloem translocation of photosynthates is still not fully understood. In general, water and minerals move upward in the xylem to the sites of photosynthesis, and photosynthates move from this source of manufacture to other parts of the plant.

The ascent of sap within a plant was suggested by Dixon and Renner in their cohesion hypothesis. They claimed that the force sucking up water and nutrients from the soil into the plant root comes from water evaporation from cell walls in the leaves. The binding force is in the inherent tensile strength of water, a property arising from cohesion of the water molecules (the forces of attraction between water molecules).

This cohesion of water in the xylem is due to the capillary dimensions of the xylem elements. Water uptake from the soil comes from the negative water potential, which is transferred down the plant to the root cells and soil by the upward driving force of evaporation.

The leaves of plants have a waxy cuticle cover on the outside surface to prevent excessive water loss by evaporation (Figure 2.6). Small pores (*stomates*) in the epidermis, particularly numerous in the lower epidermis, regulate the passage of carbon dioxide and oxygen in and out of the leaf. Water vapor also moves through these openings. Therefore, water loss is regulated largely by the stomates. Water moves from the xylem vessels in the veins to the leaf mesophyll cells, evaporates, and diffuses through the stomates into the atmosphere. This water loss in evapotranspiration must be replaced by water entering the plant roots, or water stress will result, which if continued, will lead to death of the plant. In the process of water uptake, minerals are transported to chlorophyll-containing cells (palisade parenchyma, spongy mesophyll, and bundle sheath cells, if present), where they are used in the manufacture of foods through the process of photosynthesis.

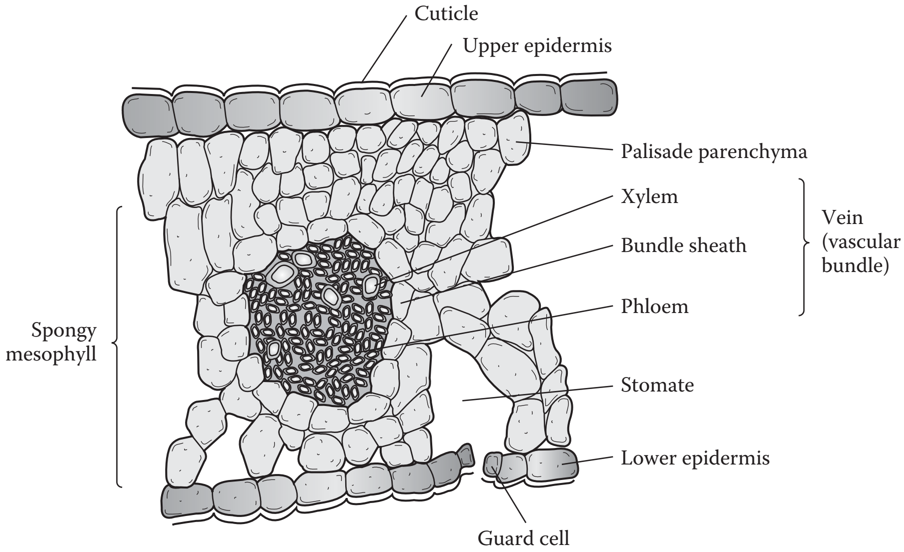

FIGURE 2.6 Cross section of a typical broad-leaved plant leaf. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

2.5 PLANT NUTRITION

As mentioned in Chapter 1, hydroponics developed through studies of plant constituents, which led to the discovery of plant essential elements. Plant nutrition is therefore the basis of hydroponics. Anyone intending to employ hydroponic techniques must have a thorough knowledge of plant nutrition. The management of plant nutrition through management of the nutrient solution is the key to successful hydroponic growing.

The absorption and transport of plant nutrients within the plant has already been discussed. The next question is how to maintain the plant in an optimum nutrient status. Hydroponics enables us to do this, but it also presents the risk of error, which could result in rapid starvation or other adverse effects on the plant. A diagnostic program to determine the nutritional level of the plant at any time is extremely important to avoid nutritional stresses that limit plant growth.

The ideal method of diagnosing the nutritional status of plants is to take tissue analyses of plant leaves periodically and in conjunction with these tests, nutrient solution analyses. The level of each essential element in the plant tissue and nutrient solution must be determined and correlated so that, if needed, adjustments can be made in the nutrient solution to avoid potential nutritional problems. Of course, such a program is costly in terms of time and labor and is not always economically feasible. These analyses can be done by commercial laboratories (Appendix 2), but sometimes results are slow and crop damage may occur before recommendations are received.

The alternative to such laboratory analyses is visual diagnosis of nutrient stress symptoms expressed by the plant. However, it must be emphasized that once the plant shows symptoms, it has already undergone severe nutritional stress and will take some time to regain its health after remedial steps have been taken. Therefore, it is important to correctly identify the nutrient problem immediately in order to prevent the plant from losing vigor.

For further study of plant physiology and nutrition, refer to Salisbury and Ross (1992), Epstein and Bloom (2005), and Gauch (1972).

2.5.1 NUTRITIONAL DISORDERS

A nutritional disorder is a malfunction in the physiology of a plant, resulting in abnormal growth caused by either a deficiency or excess of a mineral element(s). The disorder is expressed by the plant externally and/or internally in the form of symptoms. Diagnosis of a nutritional disorder involves accurate description and identification of the disorder. A deficiency or excess of each essential element causes distinct plant symptoms, which can be used to identify the disorder.

Elements are grouped basically as those that are mobile and those that are immobile, with some having gradations of mobility. Mobile elements are those that can be retranslocated. They will move from their original site of deposition (older leaves) to the actively growing region of the plant (younger leaves) when a deficiency occurs.

As a result, the first symptoms will appear on the older leaves on the lower portion of the plant. The mobile elements are magnesium, phosphorus, potassium, zinc, and nitrogen. When a shortage of the immobile elements occurs; they are not retranslocated to the growing region of the plant, but remain in the older leaves where they were originally deposited. Deficiency symptoms, therefore, first appear on the upper young leaves of the plant. The immobile elements include calcium, iron, sulfur, boron, copper, and manganese.

It is important to detect nutritional disorders early, since as they increase in severity the symptoms spread rapidly over the entire plant, resulting in the death of much of the plant tissue. Then symptom characteristics, such as chlorosis (yellowing) and necrosis (browning) of the plant tissue, become very general. In addition, disorders of one element often upset the plant’s ability to accumulate other elements, and shortly, two or more essential elements are simultaneously deficient or in excess. This is particularly true of nutrient deficiencies. When two or more elements are deficient simultaneously, the composite picture or syndrome expressed by the symptoms may resemble no given deficiency. Under such conditions, it is generally impossible to determine visually which elements are responsible for the symptoms.

Often a deficiency of one element leads to antagonism toward the uptake of another element. For instance, boron deficiency can also cause calcium deficiency. Calcium deficiency may lead to potassium deficiency and vice versa. The need for accurate and fast identification of a symptom expression cannot be overemphasized. It is often beneficial to grow an indicator plant along with the regular crop. The susceptibility of different plant species to various nutritional disorders varies greatly. For example, if a crop of tomatoes is being grown, plant a few cucumbers, lettuce, or even a weed or two if it is known to be very sensitive to nutritional disorders. Cucumbers are very sensitive to boron and calcium deficiency. If such a deficiency occurs, the cucumbers will express symptoms from several days to a week before they appear on the tomatoes. Such early warning enables the grower to adjust the nutrient solution to prevent a deficiency in the tomato crop. In addition, weaker plants of the same species will show symptoms before the more vigorous ones. Every possible tactic must be employed to avoid a nutritional disorder in the main crop, since once symptoms are expressed in the crop, some reduction in yield is inevitable.

Once a nutritional disorder has been identified, steps to remedy it can be taken. In a hydroponic system, the first step is to change the nutrient solution. This should be done as soon as a nutritional disorder is suspected, even before it is identified. If the disorder has been diagnosed as a deficiency, a foliar spray can be applied for a rapid response. However, care must be taken not to use a concentration high enough to burn the plants. It is best to try the recommended foliar spray on a few plants and then observe the results for several days before treating the whole crop. The nutrient formulation probably will have to be adjusted (Chapter 3) to overcome the disorder. If a nutrient deficiency is present, the level of deficient nutrient should be increased to an above-normal level (up to 25%–30%). As the plants come out of the deficiency, the increase in the identified nutrient could be lowered to about 10%–15% above the level at which the deficiency occurred. Depending on the severity of the disorder, weather conditions, and the element itself, it may take 7–10 d before response toward the control measure is evident.

If toxicity has occurred, the soilless medium will have to be flushed with water alone to reduce residual levels in the medium. Flushing may have to be done over a period of a week or so depending again on the severity of the disorder. However, nutrient deficiencies are far more common than toxicities in hydroponics. For this reason, nutrient deficiencies are emphasized in the following discussion on symptomatology.

2.5.2 SYMPTOMATOLOGY

One of the first steps in identifying a nutritional disorder is to describe the symptoms in distinct, accurate terms. Table 2.3 summarizes terms commonly used in symptomatology.

TABLE 2.3
Terminology Used in the Description of Symptoms on Plants

Term	Description
Localized	Symptoms limited to one area of plant or leaf
Generalized	Symptoms not limited to one area but spread generally over entire plant or leaf
Drying (firing)	Necrosis—scorched, dry, papery appearance
Marginal	Chlorosis or necrosis—on margins of leaves initially; usually spreads inward as symptom progresses
Interveinal chlorosis	Chlorosis (yellowing) between veins of leaves only
Mottling	Irregular spotted surface—blotchy pattern of indistinct light and dark areas; often associated with virus diseases
Spots	Discolored area with distinct boundaries adjacent to normal tissue
Color of leaf undersides	Often a particular coloration occurs mostly or entirely on the lower surface of the leaves, for example, phosphorus deficiency—purple coloration of leaf undersides
Cupping	Leaf margins or tips may cup or bend upward or downward, for example, copper deficiency—margins of leaves curl into a tube; potassium deficiency—margins of leaves curl inward
Checkered (reticulate)	Pattern of small veins of leaves remaining green while interveinal tissue yellows—manganese deficiency
Brittle tissue	Leaves, petioles, stems may lack flexibility, break off easily when touched—calcium or boron deficiency
Soft tissue	Leaves very soft, easily damaged—nitrogen excess
Dieback	Leaves or growing point dies rapidly and dries out—boron or calcium deficiencies
Stunting	Plant shorter than normal
Spindly	Growth of stem and leaf petioles very thin and succulent

When observing a disorder, determine what plant part or organ is affected. Does it occur on the lower older leaves or on the upper younger leaves? Are the symptoms on the stem, fruit, flowers, and/or growing point of the plant? What is the appearance of the whole plant? Is it dwarfed, deformed, or branched excessively? What is the nature of the ailment? Is the tissue chlorotic (yellow), necrotic (brown), or deformed? Then, describe the color pattern and location of this chlorosis, necrosis, or deformation using the terms given in Table 2.3.

After the symptoms have been observed closely and described, it should be determined whether the disorder may be caused by something other than a nutritional imbalance. Other possible disorders to check include insect damage, parasitic diseases, pesticide damage, pollution damage, water stress, and light and temperature injury. Pesticide damage may cause burning if greater than the recommended dosages are used on the plants. Also, the use of herbicides such as 2,4-D near a greenhouse may cause deformation of plant leaves, closely resembling the symptoms of tobacco mosaic virus (TMV). Pollution damage may cause burning or bleaching of leaf tissue or a stippled effect (pinpoint-sized chlorotic spots) on leaves. Water stress, either lack or excess of water, will cause wilting (loss of turgidity) of leaves. Excessive sunlight or temperature may burn and dry leaf tissue, particularly on the margins.

Once the above factors have been checked and eliminated as potential causes, a nutritional disorder would be suspected. Generally, in hydroponics, nutritional disorders will appear on all plants at the same time and progress to others. The next step is to identify the nutrient disorder(s) by the use of a “key” (Table 2.4). Deficiency and toxicity symptoms for all the essential elements are given in Table 2.5. These two tables describe symptoms for most plants. Since different plant species will express various symptoms to a lesser or greater degree than others, Table 2.6 includes specific symptoms and remedies for tomatoes and cucumbers.

For further study of nutritional disorders, refer to Roorda van Eysinga and Smilde (1980). Sprague (1964) published a review of symptoms in plants due to mineral deficiencies and toxicities.

2.5.3 USE OF A KEY

The key presented here is a dichotomous table. A decision must be made at each alternative route, and finally a single explanation is given at the end. The key to nutritional disorders is based on symptoms observed on the plant, hence the importance of accurate symptom description. The key (Table 2.4) is for use in determining mineral deficiencies only, not toxicities.

The first decision concerns effects on older leaves (A) versus effects on upper younger leaves (AA). Once this choice is made, a series of choices follows. The next step is (B) versus (BB) under the previous choice of (A) or (AA). Then, (C) versus (CC), (D) versus (DD), and so on. For example, use the key to find the following symptoms: The young (upper) leaves of a plant are chlorotic, the veins green, and no dead spots are visible. The terminal bud is alive and not wilted. The older (lower) leaves show no symptoms. The terminal growing area is somewhat spindly, and there is some abortion of flowers. Since the upper leaves are affected, the first choice is (AA). The terminal bud is alive; therefore, the next choice is (BB). The next decision is (C) versus (CC). Since chlorosis is present, but no wilting, the correct choice would be (CC). The alternative of (D) or (DD) can be made on the basis of the lack of dead spots. The proper choice is (DD). The choice between sulfur (E) versus iron (EE) is a little difficult. In the case of sulfur, the interveinal tissue is light green, not the bright yellow that appears with iron deficiency. The spindly stalks and flower abortion also indicate iron over sulfur deficiency. As a result, the final choice is iron deficiency.

TABLE 2.4
A Key to Mineral Deficiency Symptoms

Symptoms	Deficient Element
A. Older or lower leaves affected	
B. General chlorosis and/or drying of lower leaves, retarded growth	
C. Chlorosis progresses from light green to yellow, from older leaves up to new growth. Growth is restricted, spindly, loss of older leaves	Nitrogen
CC. Leaves remain dark green, growth restricted, and distinctive purple coloration of undersides of leaves. Lower leaves dry. Root growth is restricted. Fruit-set delayed	Phosphorous
BB. Localized mottling or chlorosis with or without dead spots, no drying of lower leaves	
C. Interveinal chlorosis, mottled effect with green veins. Margins curl upward, necrotic spots, stalks slender	Magnesium
CC. Mottled or chlorotic leaves with spots of dead tissue	
D. Small dead spots at tips and between veins. Margins cup downward with brown spots. Growth is restricted, slender stalks. Roots poorly developed	Potassium
DD. Spots generalized, rapidly enlarging to include veins, leaves thick, stalks with shortened internodes. Young leaves small, interveinal chlorosis, mottled, curl downward	Zinc
E. Mottling of older leaves with veins remaining light green. Leaf margins become necrotic, may curl upward, necrotic spots of leaf tips and margins. Symptoms spread to younger leaves as deficiency progresses	Molybdenum
AA. Symptoms appear first in young leaves—terminal growth	
B. Growing tip distorted, young leaves at tips chlorotic, with necrotic spots expanding to browning of leaf margins and dieback	
C. Brittle tissue not present in growing tips, young leaves chlorotic, old leaves remain green, stems thick and woody, growing tip necrotic followed by dieback, blossom-end rot of fruit (especially tomatoes)	Calcium
CC. Growing tip—leaves and petioles—light green to yellow, brittle tissue, often deformed or curled. Rosetting of terminal growth because of shortening of internodes. Terminal bud dies, new growth may form at lower leaf axils, but these suckers (especially tomatoes) show similar symptoms of chlorosis, necrosis, browning, and brittleness. Internal browning, open locules, blotchy ripening of tomato fruit	Boron
BB. Growing tip alive, not distorted, wilting or chlorosis with or without dead spots, veins light or dark green	
C. Young leaves wilt, chlorosis, necrosis, retarded growth, lodging of growing tip	Copper
CC. Young leaves not wilted, chlorosis with or without necrosis and dead spots	
D. Interveinal chlorosis, veins remain green to give checkered pattern. Chlorotic areas become brown to later form necrotic spots of dead tissue	Manganese
DD. Interveinal dead spots not present, chlorosis of tissue may or may not involve veins	
E. Leaves uniformly light green becoming yellow, veins not green, poor, spindly growth, hard and woody stems	Sulfur
EE. Tissue between veins yellows, veins green, eventually veins become chlorotic. Yellow interveinal tissue becomes white, but no necrosis. Stems slender, short. Flowers abort and fall off, tomato flower clusters are small, thin stemmed	Iron

TABLE 2.5
Deficiency and Toxicity Symptoms for Essential Elements

1. Nitrogen
   Deficiency symptoms: Growth is restricted, and plants are generally yellow (chlorotic) from lack of chlorophyll, especially older leaves. Younger leaves remain green longer. Stems, petioles, and lower leaf surfaces of corn and tomato can turn purple
   Toxicity symptoms: Plants usually dark green in color with abundant foliage but usually with a restricted root system. Potatoes form only small tubers, and flowering and seed production can be retarded
2. Phosphorus
   Deficiency symptoms: Plants are stunted and often a dark green color. Anthocyanin pigments may accumulate. Deficiency symptoms occur first in more mature leaves. Plant maturity is often delayed
   Toxicity symptoms: No primary symptoms yet noted. Sometimes copper and zinc deficiency occurs in the presence of excess phosphorus
3. Potassium
   Deficiency symptoms: Symptoms first visible on older leaves. In dicots, these leaves are initially chlorotic but soon scattered dark necrotic lesions (dead areas) develop. In many monocots, the tips and margins of the leaves die first. Potassium-deficient corn develops weak stalks and is easily lodged
   Toxicity symptoms: Usually not excessively absorbed by plants. Oranges develop coarse fruit at high potassium levels. Excess potassium may lead to magnesium deficiency and possible manganese, zinc, or iron deficiency
4. Sulfur
   Deficiency symptoms: Not often encountered. Generally yellowing of leaves, usually first visible in younger leaves
   Toxicity symptoms: Reduction in growth and leaf size. Leaf symptoms often absent or poorly defined. Sometimes interveinal yellowing or leaf burning
5. Magnesium
   Deficiency symptoms: Interveinal chlorosis, which first develops on the older leaves. The chlorosis may start at leaf margins or tip and progress inward interveinally
   Toxicity symptoms: Very little information available on visual symptoms
6. Calcium
   Deficiency symptoms: Bud development is inhibited, and root tips often die. Young leaves are affected before old leaves and become distorted and small with irregular margins and spotted or necrotic areas
   Toxicity symptoms: No consistent visible symptoms. Usually associated with excess carbonate
7. Iron
   Deficiency symptoms: Pronounced interveinal chlorosis similar to that caused by magnesium deficiency but on the younger leaves
   Toxicity symptoms: Not often evident in natural conditions. Has been observed after the application of sprays where it appears as necrotic spots
8. Chlorine
   Deficiency symptoms: Wilted leaves that become chlorotic and necrotic, eventually attaining a bronze color. Roots become stunted and thickened near tips
   Toxicity symptoms: Burning or firing of leaf tip or margins. Bronzing, yellowing, and leaf abscission and sometimes chlorosis. Reduced leaf size and lower growth rate

TABLE 2.5 (continued)
Deficiency and Toxicity Symptoms for Essential Elements

9. Manganese

   Deficiency symptoms: Initial symptoms are often interveinal chlorosis on younger or older leaves depending on the species. Necrotic lesions and leaf shedding can develop later. Disorganization of chloroplast lamellae

   Toxicity symptoms: Sometimes chlorosis, uneven chlorophyll distribution, and iron deficiency (pineapple). Reduction in growth

10. Boron

    Deficiency symptoms: Symptoms vary with species. Stem and root apical meristems often die. Root tips often become swollen and discolored. Internal tissues sometimes disintegrate (or discolor) (e.g., "heart rot" of beets). Leaves show various symptoms including thickening, brittleness, curling, wilting, and chlorotic spotting

    Toxicity symptoms: Yellowing of leaf tip followed by progressive necrosis of the leaf beginning at tip or margins and proceeding toward midrib

11. Zinc

    Deficiency symptoms: Reduction in internode length and leaf size. Leaf margins are often distorted or puckered. Sometimes interveinal chlorosis

    Toxicity symptoms: Excess zinc commonly produces iron chlorosis in plants

12. Copper

    Deficiency symptoms: Natural deficiency is rare. Young leaves often become dark green and twisted or misshapen, often with necrotic spots

    Toxicity symptoms: Reduced growth followed by symptoms of iron chlorosis, stunting, reduced branching, thickening, and abnormal darkening of rootlets

13. Molybdenum

    Deficiency symptoms: Often interveinal chlorosis developing first on older or midstem leaves, then progressing to the youngest. Sometimes leaf marginal scorching or cupping

    Toxicity symptoms: Rarely observed. Tomato leaves turn golden yellow

TABLE 2.6
Summary of Mineral Deficiencies in Tomatoes and Cucumbers and Remedies

Mobile Elements (First Symptoms on Older Leaves)

1. Nitrogen

Tomatoes	*Cucumbers*
Spindly plant	Stunted growth
Lower leaves—yellowish green	Lower leaves—yellowish green
Severe cases—entire plant pale green	Severe cases—entire plant pale green
Major veins—purple color	Younger leaves stop growing
Small fruit	Fruit—short, thick, light green, spiny

Remedies

(i) Use a foliar spray of 0.25%–0.5% solution of urea
(ii) Add calcium nitrate or potassium nitrate to the nutrient solution

continued

TABLE 2.6 (continued)
Summary of Mineral Deficiencies in Tomatoes and Cucumbers and Remedies

2. Phosphorus

Tomatoes	*Cucumbers*
Shoot growth restricted, thin stem	Stunted
Severe cases—leaves small, stiff, curved downward	Severe cases—young leaves small, stiff, dark green
Leaf upper sides—bluish green	Older leaves and cotyledons—large water-soaked spots including both veins and interveinal areas
Leaf undersides—including veins—purple	Affected leaves fade, spots turn brown and desiccate, shrivel—except for petiole
Older leaves—yellow with scattered purple dry spots—premature leaf drop	

Remedies

Add monopotassium phosphate to the nutrient solution

3. Potassium

Tomatoes	*Cucumbers*
Older leaves—leaflets scorched, curled margins, interveinal chlorosis, small dry spots	Older leaves—discolored yellowish green at margins, later turn brown and dry
Middle leaves—interveinal chlorosis with small dead spots	Plant growth—stunted, short internodes, small leaves
Plant growth—restricted, leaves remain small	Later stages—interveinal and marginal chlorosis extends to center of leaf, also progresses up plant, leaf margins desiccate, extensive necrosis, larger veins remain green
Later stages—chlorosis and necrosis spreads over large area of leaves, also up plant; leaflets die back	
Fruit—blotchy, uneven ripening, greenish areas	

Remedies

(i) Foliar spray of 2% potassium sulfate
(ii) Add potassium sulfate or if no sodium chloride present in water, can add potassium chloride to the nutrient solution

4. Magnesium

Tomatoes	*Cucumbers*
Older leaves—marginal chlorosis progressing inward as interveinal chlorosis, necrotic spots in chlorotic areas	Older leaves—interveinal chlorosis from leaf margins inward, necrotic spots develop
Small veins—not green	Small veins—not green
Severe starvation—older leaves die, whole plant turns yellow, fruit production reduced	Severe starvation—symptoms progress from older to younger leaves, entire plant yellows, older leaves shrivel and die

Remedies

(i) Foliar spray—high-volume spray with 2% magnesium sulfate or low-volume spray with 10% magnesium sulfate
(ii) Add magnesium sulfate to the nutrient solution

5. Zinc

Tomatoes	*Cucumbers*
Older leaves and terminal leaves—smaller than normal	Older leaves—interveinal mottling, symptoms progress from older to younger leaves, no necrosis
Little chlorosis, but irregular shriveled brown spots develop, especially on petiolules (small petioles of leaflets) and on and between veins of leaflets	Internodes—at top of plant stop growing, leading to upper leaves being closely spaced, giving bushy appearance

TABLE 2.6 (continued)
Summary of Mineral Deficiencies in Tomatoes and Cucumbers and Remedies

Tomatoes	*Cucumbers*
Petioles—curl downward, complete leaves coil up	
Severe starvation—rapid necrosis, entire foliage withers	

Remedies

(i) Foliar spray with 0.1%–0.5% solution of zinc sulfate
(ii) Add zinc sulfate to the nutrient solution

Immobile Elements (First Symptoms on Younger Leaves)

1. Calcium

Tomatoes	*Cucumbers*
Upper leaves—marginal yellowing, undersides turn purple-brown color especially on margins, leaflets remain tiny and deformed, margins curl up	Upper leaves—white spots near edges and between veins, marginal interveinal chlorosis progresses inward
Progression to later stages—leaf tips and margins wither, curled petioles die back Growing point dies	Youngest leaves (growing point region)—remain small, edges deeply incised, curl upward, later shrivel from edges inward, and growing point dies
Older leaves—finally, chlorosis and necrotic spots form	Plant growth—stunted, short internodes, especially near apex
Fruit—blossom-end rot (leather-like decay at blossom ends of fruit)	Buds—abort, finally plant dies back from apex Older leaves—curve downward

Remedies

(i) Foliar spray in acute cases with 0.75%–1.0% calcium nitrate solution. Can also use 0.4% calcium chloride
(ii) Add calcium nitrate to the nutrient solution, or calcium chloride if you do not want to increase nitrogen level, but be sure there is little, if any, sodium chloride in the nutrient solution if calcium chloride is used

2. Sulfur

Tomatoes	*Cucumbers*
Upper leaves—stiff, curl downward, eventually large irregular necrotic spots appear, leaves become yellow	Upper leaves—remain small, bend downward, pale green to yellow, margins markedly serrate Plant growth—restricted
Stem, veins, petioles—purple	Older leaves—very little yellowing
Older leaves, leaflets—necrosis at tips and margins, small purple spots between veins	

Remedies

Add any sulfate to the nutrient solution. Potassium sulfate would be safest since the plants require high levels of potassium

Note: Sulfate deficiency rarely occurs since sufficient amounts are added by use of potassium, magnesium, and other sulfate salts in the normal nutrient formulation

continued

TABLE 2.6 (continued)
Summary of Mineral Deficiencies in Tomatoes and Cucumbers and Remedies

3. Iron

Tomatoes	*Cucumbers*
Terminal leaves—chlorosis starts at margins and spreads through the entire leaf, initially smallest veins remain green, giving reticulate pattern of green veins on yellow leaf tissues; leaf eventually turns completely pale yellow, no necrosis Progression—symptoms start from terminal leaves and work down to older leaves Growth—stunted, spindly, leaves smaller than normal Flowers—abortion	Young leaves—fine pattern of green veins with yellow interveinal tissue, later chlorosis spreads to veins and entire leaves turn lemon-yellow; some necrosis may develop on margins of leaves Progression—from top downward Growth—stunted, spindly Axillary shoots and fruits—also turn lemon-yellow

Remedies

(i) Foliar spray with 0.02%–0.05% solution of iron chelate (FeEDTA) every 3–4 d
(ii) Add iron chelate to the nutrient solution

4. Boron

Tomatoes	*Cucumbers*
Growing point—shoot growth restricted, leads to withering and dying of growing point Upper leaves—interveinal chlorosis, mottling of leaflets, remain small, curl inward, deformed, smallest leaflets turn brown and die Middle leaves—yellow-orange tints, veins yellow or purple Older leaves—yellowish green Lateral shoots—growing points die Petioles—very brittle, break off easily, clogged vascular tissue	Apex—growing point plus youngest unexpanded leaves curl up and die Axillary shoots—wither and die Older leaves—cupped upward beginning along margins, stiff, interveinal mottling Shoot tip—stops growing, leads to stunting

Remedies

(i) Apply a foliar spray of 0.1%–0.25% of solution of borax as soon as detected
(ii) Add borax to the nutrient solution

5. Copper

Tomatoes	*Cucumbers*
Middle and younger leaves—margins curl into a tube toward the midribs, no chlorosis or necrosis, bluish green color, terminal leaves small, stiff, and folded up Petioles—bend downward, directing opposite tubular leaflets toward each other Stem growth stunted Progression—later stages get necrotic spots adjacent to and on midribs and larger veins	Young leaves—remain small Plant growth—restricted, short internodes, bushy plant Older leaves—interveinal chlorosis in blotches Progression—leaves turn dull green to bronze, necrosis, entire leaf withers, chlorosis spreads from older to younger leaves

TABLE 2.6 (continued)
Summary of Mineral Deficiencies in Tomatoes and Cucumbers and Remedies

Remedies

(i) Foliar spray with 0.1%–0.2% solution of copper sulfate to which 0.5% hydrated lime has been added
(ii) Add copper sulfate to the nutrient solution

6. Manganese

Tomatoes	*Cucumbers*
Middle and older leaves—turn pale, later younger leaves also, characteristic checkered pattern of green veins and yellowish interveinal areas, later stages get small necrotic spots in pale areas, chlorosis less severe than in iron deficiency, also chlorosis is not confined to younger leaves as is the case with iron	Terminal or young leaves—yellowish interveinal mottling, at first even the small veins remain green, giving a reticular green pattern on a yellow background Progression—later, all except main veins turn yellow with sunken necrotic spots between the veins Shoots—stunted, new leaves remain small Older leaves—turn palest and die first

Remedies

(i) Foliar spray using high-volume spray of 0.1% or low-volume spray of 1% solution of manganese sulfate
(ii) Add manganese sulfate to the nutrient solution

7. Molybdenum

Tomatoes	*Cucumbers*
All leaves—leaflets show a pale green to yellowish interveinal mottling, margins curl upward to form a spout, smallest veins do not remain green, necrosis starts in the yellow areas, at the margins of the top leaflets and finally includes entire composite leaves that shrivel Progression—from the older to the younger leaves, but the cotyledons stay green for a long time	Older leaves—fade, particularly between veins, later leaves turn pale green, finally yellow and die Progression—from older leaves up to young leaves, youngest leaves remain green Plant growth—normal, but flowers are small

Remedies

(i) Foliar spray with 0.07%–0.1% solution of ammonium or sodium molybdate
(ii) Add ammonium or sodium molybdate to the nutrient solution

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3 Nutrient Solution

3.1 INORGANIC SALTS (FERTILIZERS)

In hydroponics, all essential elements are supplied to plants by dissolving fertilizer salts in water to make up the nutrient solution. The choice of salts to be used depends on a number of factors. The relative proportion of ions that a compound will supply must be compared with that required in the nutrient formulation. For example, one molecule of potassium nitrate (KNO_3) will yield one ion of potassium (K^+) and one of nitrate (NO_3^-), whereas one molecule of calcium nitrate ($Ca(NO_3)_2$) will yield one ion of calcium (Ca^{2+}) and two ions of nitrate $2(NO_3^-)$. Therefore, if a minimum number of cations is required while supplying sufficient nitrate (anions) then calcium nitrate should be used; that is, half as much calcium nitrate as potassium nitrate would be required to satisfy the needs of the nitrate anion.

The various fertilizer salts that can be used for the nutrient solution have different solubilities (Appendix 4). Solubility is a measure of the concentration of the salt that will remain in solution when dissolved in water. If a salt has a low solubility, only small amounts of it will dissolve in water. In hydroponics, fertilizer salts having high solubility must be used since they must remain in solution to be available to the plants. For example, calcium may be supplied by either calcium nitrate or calcium sulfate. Calcium sulfate is cheaper, but its solubility is very low. Therefore, calcium nitrate should be used to supply the entire calcium requirement.

The cost of a particular fertilizer must be considered in deciding on its use. In general, a greenhouse grade should be used. The cost is somewhat greater than that of a standard grade, but the purity and solubility will be greater. A poor grade will contain a large amount of inert carriers (clay, silt particles), which can tie up nutrients and plug feeder lines. Regular-grade calcium nitrate is bulk shipped to North America and packaged in this continent. For bulk shipping, it is coated with a greasy plasticizer to prevent it from accumulating water as it is hygroscopic (attracts water). Unfortunately, for use in nutrient solutions, this greasy coating creates a thick scum that floats on the solution surface, plugs irrigation lines, and makes cleaning of tanks and equipment difficult. To avoid this problem, the special grade for greenhouse nutrient solutions called “Greenhouse Grade” should be used. It is packaged in a green and white bag, not the blue and red or red bags of the regular grades (“Viking Ship” brand). This is now called “YaraLiva” CALCINIT™ Greenhouse Grade, 15.5-0-0. The brand is now “Yara” with the Viking ship logo above.

The availability of nitrate versus ammonium compounds to plants is important in promoting either vegetative or reproductive growth. Plants can absorb both the cationic ammonium ion (NH_4^+) and the anion nitrate (NO_3^-). Ammonium, once absorbed, can immediately serve in the synthesis of amino acids and other compounds containing reduced nitrogen. Absorption of ammonium can therefore cause excessive vegetative growth, particularly under poor light conditions. Nitrate nitrogen, on the other hand, must be reduced before it is assimilated; therefore, vegetative growth will be held back. Ammonium salts could be used under bright summer conditions when photosynthetic rates are high or if nitrogen deficiency occurs and a rapid source of nitrogen is needed. In all other cases, nitrate salts should be used.

A summary of some salts that could be used for a hydroponic nutrient solution is given in Table 3.1. The particular choice of salt will depend on the above-mentioned factors and market availability. If a dry premix is to be used, such as in sawdust, peat, or vermiculite media, some of the more insoluble salts could be used, whereas if a nutrient solution is to be made up in advance, the more soluble compounds should be used (see footnote in Table 3.1). Potassium chloride and calcium chloride should be used only to correct potassium and calcium deficiencies, respectively. These, however, can be used only if insignificant amounts of sodium chloride (<50–100 ppm) are present in the nutrient solution. If chlorides are added in the presence of sodium, poisoning of the plants will result.

The use of chelates (of iron, manganese, and zinc) is highly recommended since they remain in solution and are readily available to plants even under pH shifts. A chelated salt is one having a soluble organic component to which the mineral element can adhere until uptake by the plant roots occurs. The organic component is ethylenediaminetetraacetic acid (EDTA). EDTA has a high affinity for calcium ions and is thus a poor chelating agent for calcareous media (limestone, coral sand). In this case, it should be replaced with ethylenediamine dihydroxyphenylacetic acid (EDDHA). Iron can be supplied from the iron salt of sodium ferric diethylenetriamine pentaacetate (DTPA). This salt is abbreviated Fe-DP and has 7% iron. A good make is “Sprint 330” from “Becker Underwood,” which has 10% iron chelated to DTPA.

3.2 RECOMMENDED COMPOUNDS FOR COMPLETE NUTRIENT SOLUTIONS

Calcium nitrate that provides both calcium and nitrate nitrogen should be used. Any additional nitrogen required should be provided by potassium nitrate, which also provides potassium. All phosphorus may be obtained from monopotassium phosphate, which also provides some potassium. The remaining potassium requirement can be obtained from potassium sulfate, which also supplies some sulfur. Additional sulfur comes from other sulfates such as magnesium sulfate, which supplies the magnesium needs.

Micronutrients may be obtained from commercial premixes. While these are relatively expensive, they save the substantial labor of weighing the individual compounds contained in the mix.

Hobby growers may wish to use premixes for the macronutrients, but commercial growers should use the basic compounds listed in Table 3.1. This is because it is very difficult to get a homogeneous mixture of fertilizers when hundreds of pounds of individual compounds are blended with a mechanical mixer. Many of the compounds are in powder or fine grain form, and often lumpy, which do not mix evenly mechanically. Experience with such premixes has revealed shortages in magnesium, almost always a shortage of iron and, often, excesses of manganese. In addition, premixes do not offer flexibility in manipulating a nutrient formulation, which is necessary during different stages of plant growth and under changing sunlight hours and day length. This ability to make changes in the nutrient formulation is imperative in the optimization of crop yields.

TABLE 3.1
Summary of Fertilizer Salts for Use in Hydroponics

Chemical Formula	Chemical Name	Molecular Weight	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
			A. Macroelements			
[a]KNO_3	Potassium nitrate (saltpeter)	101.1	K^+, NO_3^-	1:4	Low	Highly soluble, high purity
[a]$Ca(NO_3)_2$	Calcium nitrate	164.1	Ca^{2+}, $2(NO_3^-)$	1:1	Low–medium	Highly soluble; use Greenhouse Grade
$(NH_4)_2SO_4$	Ammonium sulfate	132.2	$2(NH_4^+)$, SO_4^{2-}	1:2	Medium	These ammonium compounds should be used only under very good light conditions or to correct N-deficiencies
$NH_4H_2PO_4$	Ammonium dihydrogen phosphate	115.0	NH_4^+, $H_2PO_4^-$	1:4	Medium	
NH_4NO_3	Ammonium nitrate	80.05	NH_4^+, NO_3^-	1:1	Medium	
$(NH_4)_2HPO_4$	Ammonium monohydrogen phosphate	132.1	$2(NH_4^+)$, HPO_4^{2-}	1:2	Medium	
[a]KH_2PO_4	Monopotassium phosphate	136.1	K^+, $H_2PO_4^-$	1:3	Very costly	An excellent salt, highly soluble and pure, but costly
KCl	Potassium chloride (muriate of potash)	74.55	K^+, Cl^-	1:3	Costly	Should only be used for K-deficiencies and when no sodium chloride is present in nutrient solution
[a]K_2SO_4	Potassium sulfate	174.3	$2K^+$, SO_4^{2-}	1:15	Low	Has low solubility; now soluble grades available
$Ca(H_2PO_4)_2$	Monocalcium phosphate	252.1	Ca^{2+}, $2(H_2PO_4^-)$	1:60	Low	Very difficult to obtain a soluble grade
$CaH_4(PO_4)_2$	Triple super phosphate	Variable	Ca^{2+}, $2(PO_4^{2-})$	1:300	Low	Very low solubility, good for dry premixes, not for nutrient solutions

continued

TABLE 3.1 (continued)
Summary of Fertilizer Salts for Use in Hydroponics

Chemical Formula	Chemical Name	Molecular Weight	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
[a]$MgSO_4 \cdot 7H_2O$	Magnesium sulfate (epsom salts)	246.5	Mg^{2+}, SO_4^{2-}	1:2	Low	Excellent, cheap, highly soluble, pure
$CaCl_2 \cdot 2H_2O$	Calcium chloride	147.0	Ca^{2+}, $2Cl^-$	1:1	Expensive	Highly soluble, good to overcome Ca-deficiencies, but used only if no NaCl is present in nutrient solution
$CaSO_4 \cdot 2H_2O$	Calcium sulfate (gypsum)	172.2	Ca^{2+}, SO_4^{2-}	1:500	Low	Very insoluble, cannot be used for nutrient solutions
H_3PO_4	Phosphoric acid (orthophosphoric acid)	98.0	PO_4^{3-}	Concentrated acid solution	Expensive	Good use in correction of P-deficiencies
			B. Microelements			
$FeSO_4 \cdot 7H_2O$	Ferrous sulfate (green vitriol)	278.0	Fe^{2+}, SO_4^{2-}	1:4	—	—
$FeCl_3 \cdot 6H_2O$	Ferric chloride	270.3	Fe^{3+}, $3Cl^-$	1:2	—	—
[a]FeDTPA	Iron chelate (sprint 330) (10% iron)	468.15	Fe^{2+}	Highly soluble	Expensive	Best source of ion; dissolve in hot water
[a]FeEDTA	Iron chelate (sequestrene) (10.5% iron)	382.1	Fe^{2+}	Highly soluble	Expensive	Good source of iron; dissolve in hot water
[a]H_3BO_3	Boric acid	61.8	B^{3+}	1:20	Expensive	Best source of boron; dissolve in hot water
$Na_2B_8O_{13} \cdot 4H_2O$	Disodium octaborate tetra hydrate (solubor)	412.52	B^{3+}	Very soluble	Inexpensive	—
$Na_2B_4O_7 \cdot 10H_2O$	Sodium tetraborate (borax)	381.4	B^{3+}	1:25	—	—
[a]$CuSO_4 \cdot 5H_2O$	Copper sulfate (bluestone)	249.7	Cu^{2+}, SO_4^{2-}	1:5	Inexpensive	—
[a]$MnSO_4 \cdot 4H_2O$	Manganese sulfate	223.1	Mn^{2+}, SO_4^{2-}	1:2	Inexpensive	—

TABLE 3.1 (continued)
Summary of Fertilizer Salts for Use in Hydroponics

Chemical Formula	Chemical Name	Molecular Weight	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
$MnCl_2 \cdot 4H_2O$	Manganese chloride	197.9	Mn^{2+}, $2Cl^-$	1:2	Inexpensive	—
[a]$ZnSO_4 \cdot 7H_2O$	Zinc sulfate	287.6	Zn^{2+}, SO_4^{2-}	1:3	Inexpensive	—
$ZnCl_2$	Zinc chloride	136.3	Zn^{2+}, $2Cl^-$	1:1.5	Inexpensive	—
$(NH_4)_6Mo_7O_{24}$	Ammonium molybdate	1163.8	NH_4^+, Mo^{6+}	1:2.3 Highly soluble	Moderately expensive	—
Na_2MoO_4	Sodium molybdate	205.92	$2Na^+$, Mo^{6+}	Highly soluble	Moderately expensive	—
[a]ZnEDTA	Zinc chelate	431.6	Zn^{2+}	Highly soluble	Expensive	—
[a]MnEDTA	Manganese chelate	381.2	Mn^{2+}	Highly soluble	Expensive	—

[a] These more soluble compounds should be used for preparing nutrient solutions.

3.3 FERTILIZER CHEMICAL ANALYSES

The amounts of available nitrogen, phosphorus, and potassium are given on fertilizer bags as the percentage of nitrogen (N), phosphoric anhydride (P_2O_5), and potassium oxide (K_2O). It has traditionally been expressed in these terms, not in percentage of N, P, or K alone. For example, potassium nitrate is given as 13-0-44, indicating 13% N, 0% P_2O_5, and 44% K_2O.

Nutrient formulations for hydroponics express nitrogen as N, NH_4^+, or NO_3^-; phosphorus as P or PO_4^{3-}, not P_2O_5; and potassium as K^+, not K_2O. Therefore, it is necessary to convert N to NO_3^-, P_2O_5 to P or PO_4^{3-}, and K_2O to K^+ or vice versa in each case. Conversions of this nature can be made by calculating the fraction of each element within its compound source. Table 3.2 lists conversion factors to determine the fraction of an element within a compound and vice versa. It was derived by the use of atomic and molecular weights as follows: the fraction of N in NO_3^- is the atomic weight of nitrogen (14) divided by the molecular weight of nitrate (62), which is 14/62 = 0.226. In Table 3.2, this factor is listed in the second line under the column conversion factor B to A. This is because we have nitrate and want to find the amount of nitrogen in it. To determine the amount of nitrate needed for a unit of nitrogen, the reciprocal (inverse) of the fraction is used as the following ratio is applied and solved for “*x*.”

$$\begin{array}{cc} N & NO_3 \\ 1 & x \\ 14 & 62 \end{array}$$

Cross multiplying, we get

$$14x = 62$$

TABLE 3.2
Conversion Factors for Fertilizer Salts

		Conversion Factor	
Column A[a]	**Column B[a]**	**A to B**	**B to A**
Nitrogen (N)	Ammonia (NH_3)	1.216	0.822
	Nitrate (NO_3)	4.429	0.226
	Potassium nitrate (KNO_3)	7.221	0.1385
	Calcium nitrate ($Ca(NO_3)_2$)	5.861	0.171
	Ammonium sulfate ($(NH_4)_2SO_4$)	4.721	0.212
	Ammonium nitrate (NH_4NO_3)	2.857	0.350
	Diammonium phosphate ($(NH_4)_2HPO_4$)	4.717	0.212
Phosphorus (P)	Phosphoric anhydride (P_2O_5)	2.292	0.436
	Phosphate (PO_4)	3.066	0.326
	Monopotassium phosphate (KH_2PO_4)	4.394	0.228
	Diammonium phosphate ($(NH_4)_2HPO_4$)	4.255	0.235
	Phosphoric acid (H_3PO_4)	3.164	0.316
Potassium (K)	Potash (K_2O)	1.205	0.830
	Potassium nitrate (KNO_3)	2.586	0.387
	Monopotassium phosphate (KH_2PO_4)	3.481	0.287
	Potassium chloride (KCl)	1.907	0.524
	Potassium sulfate (K_2SO_4)	2.229	0.449
Calcium (Ca)	Calcium oxide (CaO)	1.399	0.715
	Calcium nitrate ($Ca(NO_3)_2$)	4.094	0.244
	Calcium chloride ($CaCl_2{\cdot}2H_2O$)	3.668	0.273
	Calcium sulfate ($CaSO_4{\cdot}2H_2O$)	4.296	0.233
Magnesium (Mg)	Magnesium oxide (MgO)	1.658	0.603
	Magnesium sulfate ($MgSO_4{\cdot}7H_2O$)	10.14	0.0986
Sulfur (S)	Sulfuric acid (H_2SO_4)	3.059	0.327
	Ammonium sulfate ($(NH_4)_2SO_4$)	4.124	0.242
	Potassium sulfate (K_2SO_4)	5.437	0.184
	Magnesium sulfate ($MgSO_4{\cdot}7H_2O$)	7.689	0.130
	Calcium sulfate ($CaSO_4{\cdot}2H_2O$)	5.371	0.186
Iron (Fe)	Ferrous sulfate ($FeSO_4{\cdot}7H_2O$)	4.978	0.201
	Iron chelate (10% iron) (FeEDTA)/(FeDTPA)	10.00	0.100
Boron (B)	Boric acid (H_3BO_3)	5.717	0.175
	Sodium tetraborate (Borax) ($Na_2B_4O_7{\cdot}10H_2O$)	8.820	0.113
	Disodium octaborate (Solubor) ($Na_2B_8O_{13}{\cdot}4H_2O$)	4.770	0.210
Copper (Cu)	Copper sulfate ($CuSO_4{\cdot}5H_2O$)	3.930	0.254
Manganese (Mn)	Manganese sulfate ($MnSO_4{\cdot}4H_2O$)	4.061	0.246
	Manganese chloride ($MnCl_2{\cdot}4H_2O$)	3.602	0.278
	Manganese chelate (5% liquid) ($Mn(NH_4)_2EDTA$)	20.00	0.050
Zinc (Zn)	Zinc sulfate ($ZnSO_4{\cdot}7H_2O$)	4.400	0.227
	Zinc chloride ($ZnCl_2$)	2.085	0.480
	Zinc chelate (14% powder) (ZnEDTA)	7.143	0.140
	Zinc chelate (9% liquid) (ZnEDTA)	11.11	0.090

TABLE 3.2 (continued)
Conversion Factors for Fertilizer Salts

		Conversion Factor	
Column A[a]	**Column B**[a]	**A to B**	**B to A**
Molybdenum (Mo)	Ammonium molybdate ($(NH_4)_6Mo_7O_{24}$)	1.733	0.577
	Sodium molybdate (Na_2MoO_4)	2.146	0.466

[a] To convert from an element (column A) to the compound supplying it (column B), use conversion factor A to B. To determine amounts of an element (column A) present in a compound (column B), multiply by factor B to A.
These factors are derived from the fraction of an element present in a compound based on the atomic weight of the element and molecular weight of the compound.

Therefore,

$$x = \frac{62}{14} = 4.429$$

This is the conversion factor A to B in the second line of Table 3.2. Understanding this concept for the derivation of these factors will enable one to calculate other factors, should compounds other than those appearing in Table 3.2 be used.

3.4 FERTILIZER IMPURITIES

Most fertilizer salts are not 100% pure. They often contain inert “carriers” such as clay, silt, and sand particles, which do not supply ions. Therefore, the percentage purity or a guaranteed analysis is often given on the fertilizer bag. The percentage purities of some common fertilizers are given in Table 3.3. These impurities must be taken into consideration when calculating the fertilizer requirements for a particular nutrient formulation.

Many fertilizers have synonyms or common names. A list of these common names is given in Table 3.4.

3.5 NUTRIENT FORMULATIONS

Nutrient formulations are usually given in parts per million (ppm) concentrations of each essential element. One part per million is one part of one item in 1 million parts of another. It may be a weight measure, for example, 1 μg/g, a weight–volume measure, for example, 1 mg/L, or a volume–volume measure, for example, 1 μL/L. Proofs for these are as follows:

$$1\ \mu g/g = \frac{1/1{,}000{,}000\ g}{1\ g} = \frac{1}{1{,}000{,}000}\ g$$

$$1\ \mu L/L = \frac{1/1{,}000{,}000\ L}{1\ L} = \frac{1}{1{,}000{,}000}\ L$$

TABLE 3.3
Percentage Purities of Commercial Fertilizers

Salt	Purity (%)
Ammonium phosphate ($NH_4H_2PO_4$) (food grade)	98
Ammonium sulfate ($(NH_4)_2SO_4$)	94
Ammonium nitrate, pure (NH_4NO_3)	98
Calcium nitrate ($Ca(NO_3)_2$)	90
Calcium chloride ($CaCl_2{\cdot}2H_2O$)	77
Calcium sulfate ($CaSO_4$) (Gypsum)	70
Monocalcium phosphate ($Ca(H_2PO_4)_2$) (food grade)	92
Monopotassium phosphate (KH_2PO_4)	98
Magnesium sulfate ($MgSO_4{\cdot}7H_2O$)	98
Potassium nitrate (KNO_3)	95
Potassium sulfate (K_2SO_4)	90
Potassium chloride (KCl)	95

The purity is calculated on the basis of the designated formula. Water of crystallization is not considered as impurity. Always check the percentage purity on the bag as it varies with different manufacturers.
Note that in Table 3.2, the water of crystallization has been accounted for in the calculations of the conversion factors.

1 mg/L:

$$1\text{ mg} = \frac{1}{1{,}000}\text{ g},\quad 1\text{ L} = 1{,}000\text{ mL}$$

Therefore,

$$1\text{ mg/L} = \frac{1/1{,}000\text{ g}}{1{,}000\text{ mL H}_2\text{O}} = \frac{1}{1{,}000{,}000}\text{ g}\qquad\text{since 1 mL of H}_2\text{O weighs 1 g}$$

3.5.1 ATOMIC AND MOLECULAR WEIGHTS

Atomic and molecular weights of elements and compounds, respectively, must be used in calculating nutrient formulation concentration requirements. Atomic weights indicate the relative weights of different atoms, that is, how the weight of one atom compares with that of another. Tables of atomic weights for every atom have been drawn up by establishing a relative scale of atomic weights. In doing so, one element is chosen as the standard and all other elements are compared with it. Oxygen (O) has been assigned an atomic weight of exactly 16, and all other elements are related to it. Table 3.5 lists the atomic weights of elements commonly used in hydroponics.

When a number of atoms combine, they form a molecule, which is expressed using a molecular formula. For example, water is represented as H_2O and consists of two atoms of hydrogen (H) and one atom of oxygen (O). The weight of any compound is the molecular

TABLE 3.4
Chemical Names and Synonyms of Compounds Generally Used in Nutrient Solutions

Chemical Name	Synonyms or Common Name
Potassium nitrate (KNO_3)	Saltpeter
Sodium nitrate ($NaNO_3$)	Chile saltpeter; niter; Chile niter
Ammonium acid phosphate ($NH_4H_2PO_4$)	Ammonium biphosphate; ammonium dihydrogenphosphate; monobasic ammonium phosphate
Urea ($CO(NH_2)_2$)	Carbamide; carbonyldiamide
Potassium sulfate (K_2SO_4)	Sulfate of potash
Potassium acid phosphate (KH_2PO_4)	Potassium biphosphate; potassium dihydrogen phosphate; monobasic potassium phosphate
Potassium chloride (KCl)	Muriate of potash; chloride of potash
Monocalcium phosphate ($Ca(H_2PO_4)_2H_2O$)	Calcium “superphosphate” (usually 20% pure); calcium “treble superphosphate” (usually 75% pure); calcium biphosphate; calcium acid phosphate
Phosphoric acid (H_3PO_4)	Commercial technical grade is 70%–75% H_3PO_4
Calcium sulfate ($CaSO_4{\cdot}2H_2O$)	Gypsum
Calcium chloride ($CaCl_2{\cdot}2H_2O$)	Calcium chloride dihydrate. Also available as hexahydrate ($CaCl_2{\cdot}6H_2O$)
Magnesium sulfate ($MgSO_4{\cdot}7H_2O$)	Epsom salts
Ferrous sulfate ($FeSO_4{\cdot}7H_2O$)	Green vitriol; iron vitriol
Zinc sulfate ($ZnSO_4{\cdot}7H_2O$)	White or zinc vitriol
Boric acid (H_3BO_3)	Boracic acid; orthoboric acid
Copper sulfate ($CuSO_4{\cdot}5H_2O$)	Cupric sulfate; Bluestone

Source: Adapted from Withrow, R.B. and A.P. Withrow, *Nutriculture*, Purdue University Agricultural Experiment Station Publication. S.C. 328, Lafayette, IN, 1948.

weight, which is simply the sum of the weights of the atoms in the molecule. The molecular weight of water is 18 (there are two atoms of hydrogen, each having atomic weight of 1.00, and one atom of oxygen having an atomic weight of 16.0). Molecular weights of commonly used fertilizers for hydroponics are given in Table 3.1. The atomic weights of all known elements are given in tables and periodic charts of chemistry texts.

The following examples will clarify the use of atomic and molecular weights in nutrient formulation calculations:

Calcium nitrate—$Ca(NO_3)_2$

Atomic Weight	Molecular Weight
Ca = 40.08	Ca = 40.08
N = 14.008	2N = 28.016
O = 16.00	6O = 96.0
	Total = 164.096

Note: There are two nitrogen atoms and six oxygen atoms in calcium nitrate.

TABLE 3.5
Atomic Weights of Elements Commonly Used in Hydroponics

Name	Symbol	Atomic Weight
Aluminum	Al	26.98
Boron	B	10.81
Calcium	Ca	40.08
Carbon	C	12.01
Chlorine	Cl	35.45
Copper	Cu	63.54
Hydrogen	H	1.008
Iron	Fe	55.85
Magnesium	Mg	24.31
Manganese	Mn	54.94
Molybdenum	Mo	95.94
Nitrogen	N	14.01
Oxygen	O	16.00
Phosphorus	P	30.97
Potassium	K	39.10
Selenium	Se	78.96
Silicon	Si	28.09
Sodium	Na	22.99
Sulfur	S	32.06
Zinc	Zn	65.37

3.5.2 CALCULATIONS OF NUTRIENT FORMULATIONS

If a nutrient formulation calls for 200 ppm of calcium (200 mg/L), we need 200 mg of calcium in every liter of water. In 164 mg of $Ca(NO_3)_2$ we have 40 mg of Ca [using the atomic and molecular weights to determine the fraction of calcium in calcium nitrate—assuming 100% purity of $Ca(NO_3)_2$]. The first step is to calculate how much $Ca(NO_3)_2$ is required to obtain 200 mg of Ca. This is done by setting up a ratio as follows:

$$164 \text{ mg } Ca(NO_3)_2 \text{ yields } 40 \text{ mg Ca}$$
$$x \text{ mg } Ca(NO_3)_2 \text{ yields } 200 \text{ mg Ca}$$
$$\text{Ratio of } Ca/Ca(NO_3)_2 \text{ is given by } \frac{40}{164} = \frac{200}{x}$$

Solving for x:

$$40x = 200 \times 164 \text{ (cross multiply)}$$
$$x = 200 \times \frac{164}{40} = 820$$

Therefore, 820 mg of $Ca(NO_3)_2$ will yield 200 mg of Ca. If the 820 mg of $Ca(NO_3)_2$ is dissolved in 1 L of water, the resultant solution will have a concentration of 200 ppm (200 mg/L) of Ca. This assumes, however, that the $Ca(NO_3)_2$ is 100% pure. If it is not—which is usually the case—it will be necessary to add more to compensate for the impurity. For example, if the $Ca(NO_3)_2$ is 90% pure, it will be necessary to add

$$\frac{100}{90} \times 820 = 911\ \text{mg Ca}\,(\text{NO}_3)_2$$

Hence, 911 mg $Ca(NO_3)_2$ in 1 L of water will give 200 ppm of Ca.

Of course, in most cases a volume of nutrient solution larger than 1 L will be required. The second step, then, is to calculate the amount of fertilizer required for a given volume of nutrients.

Initially, calculate the amount of a compound needed using the metric system of milligrams per liter, then convert to pounds per gallon, if necessary. First, convert the volume of the nutrient tank in gallons to liters. To do this, be aware that there is the following difference between imperial gallons (British system) and US gallons:

$$\begin{aligned} \text{1 US gallon (gal)} &= 3.785\ \text{L} \\ \text{1 Imperial gallon (gal)} &= 4.5459\ \text{L} \\ \text{Hence, 100 US gal} &= 378.5\ \text{L} \\ \text{100 Imperial gal} &= 454.6\ \text{L} \end{aligned}$$

The solution to the following problem will demonstrate the use of these conversions. Assume that a 200-ppm concentration of Ca is required in a 300-US-gal nutrient tank.

$$\text{300 US gal} = 300 \times 3.785\ \text{L} = 1{,}135.5\ \text{L}$$

If 911 mg $Ca(NO_3)_2$ is required per liter of water, the amount needed for 300 US gal would be

$$911\ \text{mg} \times 1{,}135.5\ \text{L} = 1{,}034{,}440\ \text{mg}$$

To convert to grams, divide by 1,000 as 1,000 mg = 1 g

$$\frac{1{,}034{,}440\ \text{mg}}{1{,}000\ \text{mg}} = 1{,}034.4\ \text{g}$$

Now, convert to kilograms by dividing by 1,000 as 1,000 g = 1 kg

$$\frac{1{,}034.4\ \text{g}}{1{,}000\ \text{g}} = 1.034\ \text{kg}$$

To calculate in pounds, use either 1 lb = 454 g or 1 kg = 2.2046 lb
Therefore,

$$\frac{1{,}034.4\ \text{g}}{454\ \text{g}} = 2.278\ \text{lb} = 2.28\ \text{lb}$$

or

$$1.034\ \text{kg} \times 2.2046 = 2.28\ \text{lb}$$

Then, convert the fraction of pounds to ounces using 1 lb = 16 oz.

$$2\ \text{lb} + (0.28\ \text{lb} \times 16 = 4.5\ \text{oz}) \qquad \text{That is, 2 lb 4.5 oz.}$$

While this conversion to pounds is precise enough for larger weights, anything under a pound should be weighed in grams for more accuracy. A suitable gram scale for most weighting under 1 lb is a triple-beam balance that is accurate to 0.1 g.

If the compound used contains more than one essential element—this is the usual case—the third step is to determine how much of each of the other elements was added when satisfying the needs of the first essential element. Calcium nitrate contains both calcium and nitrogen. Therefore, the third step is to calculate the amount of nitrogen added while satisfying the calcium needs.

This should be done using the ppm concept so that adjustments can be made for this element. The calculation is done using the fraction of nitrogen in calcium nitrate and multiplying the amount of calcium nitrate used by this fraction. The weight of calcium nitrate before adjustments for impurities should be used, that is, 820 mg not 911 mg, as follows:

$$\frac{2(14)}{164} \times 820\ \text{mg/L} = 140\ \text{mg/L (ppm)}$$

In summary, 820 mg/L of calcium nitrate will yield 200 mg/L of calcium and 140 mg/L of nitrogen (assuming 100% purity). Further, using the example for a 300-US-gal tank, 2 lb 4.5 oz (1,034 g) of calcium nitrate provides 200 ppm of calcium and 140 ppm of nitrogen in the tank of solution.

Using the conversion factors in Table 3.2, the calculations may be simplified. The atomic and molecular weights and their fractions need not be used, as that is how the conversion factors of Table 3.2 were derived as explained earlier.

Going back to step one to determine the amount of calcium nitrate needed to supply 200 ppm (mg/L) of calcium, use the conversion factor in Table 3.2. We want 200 ppm of Ca from the source $Ca(NO_3)_2$. Use the factor A to B of 4.094.

$$200 \times 4.094 = 819\ \text{mg/L of}\ Ca(NO_3)_2$$

Note that there is a slight difference between this value and the previous one (819 mg/L vs. 820 mg/L). This small difference is insignificant for our purposes.

Similarly, the amount of nitrogen in 819 mg/L of calcium nitrate may be calculated using conversion factor B to A of 0.171 in Table 3.2:

$$0.171 \times 819\ \text{mg/L} = 140\ \text{mg/L (ppm) of N}$$

The fourth step is to calculate the additional amount of the second element needed from another source. For example, if the nutrient formulation asked for 150 ppm of N, the additional requirement would be

$$150 - 140 = 10\ \text{ppm of N}$$

This could be obtained from KNO_3. Then the amount of KNO_3 needed to supply 10 ppm of N using the conversion factor A to B of 7.221 in Table 3.2 would be

$$7.221 \times 10 = 72.21 \text{ mg/L of } KNO_3$$

Since KNO_3 also contains potassium (K), we must calculate the amount present using conversion factor B to A of 0.387 (Table 3.2):

$$0.387 \times 72.21 \text{ mg/L} = 28 \text{ mg/L (ppm) of K}$$

To determine the amount of KNO_3 needed for a 300-US-gal nutrient tank to provide 10 ppm of N, the following calculations must be done:

1. Adjust for impurity from Table 3.3 (95% pure):

$$\frac{100}{95} \times 72.21 \text{ mg/L} = 76 \text{ mg/L}$$

2. The volume of a 300-US-gal tank is obtained as

$$300 \times 3.785 \text{ L} = 1{,}135.5 \text{ L}$$

3. Therefore, the amount of KNO_3 needed is given by

$$1{,}135.5 \text{ L} \times \frac{76 \text{ mg}}{1{,}000 \text{ mg}} = 86.3 \text{ g}$$

This weight may be kept in grams as it is under 1 lb, or it may be converted to ounces.

4. Since 1 oz = 28.35 g

$$\frac{86.3 \text{ g}}{28.35 \text{ g}} = 3.0 \text{ oz}$$

Note that measurements in grams are more accurate than those in ounces.

These calculations may be continued for all the essential elements. The types and quantities of the various fertilizer salts must be manipulated until the desired formulation is achieved.

In some cases a problem may arise if the requirements of one element are satisfied by the use of a compound that contains two or more essential elements, but the concentration of another element exceeds the level required.

For instance, if the nutrient formulation called for 300 ppm Ca and 150 ppm N, the calcium supplied by calcium nitrate can be calculated as follows:

1. Weight of $Ca(NO_3)_2$ needed (use Table 3.2 conversion factors):

$$300 \text{ ppm (mg/L)} \times 4.094 = 1{,}228 \text{ mg/L}$$

2. Amount of N added:

$$1{,}228\ \text{mg/L} \times 0.171 = 210\ \text{mg/L (ppm) N}$$

This gives an excess of 60 ppm of N over the recommended 150 ppm N given in the formulation. Therefore, the level of N will govern the amount of $Ca(NO_3)_2$ that can be used as a source of Ca. The previous steps must be recalculated using the limit of 150 ppm N:

1. Weight of $Ca(NO_3)_2$ needed (use factors of Table 3.2):

$$150\ \text{ppm (mg/L)} \times 5.861 = 879\ \text{mg/L}$$

2. Amount of Ca added:

$$879\ \text{mg/L} \times 0.244 = 214\ \text{mg/L (ppm) Ca}$$

   If the recommended level of Ca is 300 ppm, then (300 − 214) = 86 ppm Ca must be supplied from sources other than $Ca(NO_3)_2$. Since calcium sulfate ($CaSO_4$) is very insoluble, the only alternative is to use calcium chloride ($CaCl_2{\cdot}2H_2O$). Note the water of crystallization in calcium chloride. This has been taken into account in calculating the conversion factors in Table 3.2.

3. Weight of $CaCl_2{\cdot}2H_2O$ needed:

$$86\ \text{ppm (mg/L)} \times 3.668 = 315\ \text{mg/L}$$

4. Amount of Cl added (Table 3.2 has no factor for the conversion from calcium chloride to chlorine, so the atomic weight fraction must be used):

$$\frac{\text{Atomic weight of chlorine}}{\text{Molecular weight of calcium chloride}} \times 315\ \text{mg/L}$$

$$\frac{2(35.5)}{147} \times 315 = 152\ \text{mg/L (ppm) Cl}$$

This level of chloride is tolerable to the plants as long as the level of sodium in the raw water and other fertilizers used does not exceed 100–150 ppm.

Once the weight for each compound in the nutrient formulation has been determined for a given tank volume, changes can be easily calculated by use of ratios. These changes using ratios allow you to adjust tank volumes or concentrations for any of the elements. For example, to calculate the amount of calcium nitrate needed to provide 200 ppm Ca in a 500-US-gal tank, instead of the original 300-US-gal tank used in the example earlier, simply use the ratio:

$$\frac{500\ \text{US gal}}{300\ \text{US gal}} \times 1{,}034.4\ \text{g of } Ca(NO_3)_2 = 1{,}724\ \text{g of } Ca(NO_3)_2$$

or

$$\begin{aligned}\frac{500}{300}\times 2.28\ \text{lb} &= 3.8\ \text{lb}\\ &= 3\ \text{lb} + (0.8\ \text{lb}\times 16\ \text{oz})\\ &= 3\ \text{lb}\ 12.8\ \text{oz of Ca(NO}_3)_2\end{aligned}$$

Often it is necessary to change the levels of individual elements during weather changes, plant growth stages, or the presence of deficiencies or toxicities revealed by symptoms on the plants and/or nutrient and tissue analyses. For example, to change the concentration of Ca from 200 to 175 ppm in the same tank volume (300 US gal),

$$\frac{175\ \text{ppm Ca}}{200\ \text{ppm Ca}}\times 1{,}034.4\ \text{g} = 905\ \text{g of calcium nitrate}$$

or

$$\frac{175}{200}\times 2.28\ \text{lb} = 1.995\ \text{lb; round off to 2.0 lb}$$

Remember, this also affects the level of the other elements in compounds containing more than one essential element. The change in the nitrogen level is

$$\frac{175}{200}\times 140\ \text{ppm N} = 122.5\ \text{ppm N}$$

3.5.3 CALCULATIONS FOR CHEMICAL SUBSTITUTIONS FOR FERTILIZERS

In some areas of the world a number of basic fertilizers required may not be available. In that case, it becomes necessary to substitute other chemicals that are available to provide the needed amount of essential elements. Calculations for such substitutions are as follows:

1. Substitute potassium hydroxide (KOH) and phosphoric acid (H_3PO_4) for diammonium phosphate ($(NH_4)_2HPO_4$) or monopotassium phosphate (KH_2PO_4) to supply phosphorus (P) and some potassium (K).
   Note that KOH must be used to neutralize the strong acidity of H_3PO_4.
   The reaction is as follows:

$$\begin{aligned}H_3PO_4 + KOH &\rightarrow K^+ + OH^- + 3H^+ + PO_4^{3-}\\ &\rightarrow K^+ + PO_4^{3-} + H_2O + 2H^+\end{aligned}$$

$$\text{Molecular weight of } H_3PO_4 = M_{H_3PO_4} = 97.99$$

   Need: 60 ppm of P from H_3PO_4:

$$60\times 3.164\ \text{(from Table 3.2)} = 189.8\ \text{mg/L}$$

The neutralization reaction is given as follows:

$$\begin{array}{ccc} 189.8 & & x \\ H_3PO_4 & + & KOH \\ 97.99 & & 56.108 \end{array}$$

Solving for x,

$$x = \frac{189.8 \times 56.108}{97.99} = 108.7 \text{ mg/L}$$

Hence,

$$\text{Amount of K} = \frac{39.1}{56.108} \times 108.7 = 0.6969 \times 108.7 = 75.7 \text{ mg/L}$$

However, phosphoric acid is a liquid; therefore, the weight required must be converted to volume measure. To do this, the specific gravity or density (D) must be used. Density is the ratio of weight to volume ($D = W/V$). Density of phosphoric acid is 1.834 (Appendix 4).
Volume can be obtained by

$$D = \frac{W}{V} \text{ or } V = \frac{W}{D}, \text{ that is, } V = \frac{189.8}{1.834} = 103.5 \ \mu\text{L/L}$$

2. Substitute nitric acid (HNO_3) and calcium carbonate ($CaCO_3$) for calcium nitrate $Ca(NO_3)_2 \cdot 4H_2O$ to supply calcium (Ca) and nitrogen (N). Note that $CaCO_3$ must be used to neutralize the strong acid of HNO_3. Add nitric acid to the calcium carbonate until all the solid just dissolves. Dilute nitric acid may be used; it will just take more time to dissolve the calcium carbonate. The reaction is as follows:

$$\begin{aligned} CaCO_3 + 2H_2O &\rightarrow Ca^{2+} + NO_3^{-} + H^{+} + CO_3^{2-} \\ &\rightarrow Ca^{2+} + NO_3^{-} + HCO_3^{-} \\ CaCO_3 = M_{CaCO_3} &= 100.1 \end{aligned}$$

Need: 150 ppm of Ca from $CaCO_3$:

$$150 \times \frac{100.1}{40.08} = 374.6 \text{ mg/L}$$
$$2HNO_3 = M_{HNO_3} = 63.016 \times 2 = 126.03$$

The reaction is given by

$$\begin{array}{ccc} 100.1 & & 126.03 \\ CaCO_3 & + & 2HNO_3 \\ 374.6 & & x \end{array}$$

Solving for x,

$$x = \frac{374.6 \times 126.03}{100.1} = 471.6\ \text{mg/L}$$

Hence,

$$\text{Amount of N} = 471.6 \times \frac{14}{63.016} = 104\ \text{mg/L}$$

Since HNO_3 is a liquid, the amount must be converted to volume measure:

$$D = 1.5027$$
$$D = \frac{W}{V} \text{ or } V = \frac{W}{D} = \frac{471.6}{1.5027} = 313.8\ \mu\text{L/L}$$

Often, HNO_3 is not 100% pure; therefore, it must be adjusted for the percentage purity.

In summary, 375 mg/L of $CaCO_3$ and 314 μL/L of HNO_3 will provide 150 ppm Ca and 104 ppm N.

3. Substitute nitric acid (HNO_3) and potassium hydroxide (KOH) for potassium nitrate (KNO_3). Note that KOH must be used to neutralize the strong acidity of HNO_3. The reaction is as follows:

$$KOH + HNO_3 \rightarrow K^+ + NO_3^- + H_2O$$

Amount of K needed in the formulation is 150 ppm. From KOH used with H_3PO_4 for P source, there is 76 ppm of K; therefore, there is still a need for

$$150 - 76 = 74\ \text{ppm K}$$

KOH:

$$74 \times \frac{56.108}{39.1} = 106\ \text{mg/L}$$

HNO_3:

$$\begin{array}{ccc} 56.108 & & 63.016 \\ \text{KOH} & + & \text{HNO}_3 \\ 106 & & x \end{array}$$

$$x = \frac{106 \times 63.016}{56.108} = 119\ \text{mg/L}$$

$$\text{Amount of N} = 119 \times \frac{14}{63.016} = 26.4\ \text{mg/L}$$

Since HNO_3 is a liquid, the amount must be converted to volume measure:

$$D = 1.5027$$

$$D = \frac{W}{V} \text{ or } V = \frac{W}{D} = \frac{119.0}{1.5027} = 79.2\ \mu\text{L/L}$$

That is, 106 mg/L of KOH and 79.2 μL/L of HNO_3 will provide 74 ppm of K and 26 ppm of N.

4. To make FeEDTA chelate:
   The objective is to make a 200-kg stock solution containing 10,000 mg/L (ppm) (1% iron) of chelated iron.
   - (i) Dissolve 10.4 kg EDTA (acid) in a solution of 16 kg of KOH in 114 L of water. Adjust the weight of KOH used accordingly if the KOH is not 100% pure. Do not add all of the KOH to the solution initially in order to maintain the pH at 5.5. Should the pH exceed 5.5, reduce it by addition of a 10% nitric acid (HNO_3) solution. If the pH is substantially less than 5.5, add KOH dissolved in water to the solution, slowly stirring until the pH reaches 5.5.
   - (ii) Separately dissolve 10 kg of ferrous sulfate ($FeSO_4$) in 64 L of hot water. Slowly add the ferrous sulfate solution, while stirring, to the EDTA/KOH solution of pH 5.5. If the pH goes below 5.0, add some of the KOH solution while stirring vigorously. With each addition of KOH solution, precipitation of ferrous hydroxide ($Fe(OH)_2$) will occur. As the pH adjusts itself, this will redissolve, but the redissolution will become slower as the pH of the stock solution rises closer to 5.5.
   - (iii) After all of the ferrous sulfate and KOH solution have been added to the EDTA/KOH solution, weigh the final solution and adjust the volume with addition of water until a final solution weight of 200 kg is achieved.

   Example:
   To obtain 5 ppm of iron in 30,000 L of water:
   - (i) The stock solution contains 10,000 mg/L of iron.
   - (ii) We need 5 mg/L (ppm) of iron in the nutrient solution.
   - (iii) Therefore, in 30,000 L of water we need 30,000 × 5 = 150,000 mg or 150 g of iron.

(iv) Hence, if the FeEDTA stock solution contains 10,000 mg/L or 10 g/L of iron, we need

For 150 g of iron: 150/10 = 15 L of FeEDTA stock solution

Note: The density of a compound should be obtained from the manufacturer as variations will occur among sources. A general table of solubilities and densities is given in Appendix 4.

3.5.4 NUTRIENT FORMULATION ADJUSTMENTS

Since the nutrient formulation will have to be adjusted frequently during the growing of any crop, it is necessary to understand the calculations and manipulations outlined in Section 3.5.3. Many claims have been made as to the derivation of "optimum formulations" for a particular crop. Too often, however, these claims are not substantiated and cannot be supported since the optimum formulation depends on too many variables, which cannot be controlled. An optimum formulation would depend on the following variables:

1. Plant species and variety
2. Stage of plant growth
3. Part of the plant representing the harvested crop (root, stem, leaf, fruit)
4. Season of year—day length
5. Weather—temperature, light intensity, sunshine hours

Different varieties and plant species have different nutrient requirements, particularly nitrogen, phosphorus, and potassium. For example, lettuce and other leafy vegetables can be given higher rates of nitrogen than tomatoes or cucumbers. The latter two require higher amounts of phosphorus, potassium, and calcium than do leafy plants.

Ulises Durany (1982) states that the nitrogen (N) level should remain lower (N = 80–90 ppm) for species that produce fruits than those that produce leaves (N = 140 ppm). For species that are grown for roots, potassium (K) should be higher (K = 300 ppm). For lettuce, on the other hand, relatively low levels of potassium (K = 150 ppm) favor the closing of the heads and therefore result in greater weights.

The proportions among the various elements must vary according to the species of plant, the growth cycle and development of the plant, and the climatic conditions, particularly light intensity and duration. When high K:N ratios of a nutrient formulation are used on tomatoes and peppers, the upper part of the plants will have shorter and smaller leaves. In some varieties of tomatoes this can cause green shoulder and sunscald and possibly make the fruit more susceptible to blossom-end rot (BER).

In peppers, reduction in leaf growth in the top of the plant will make the fruit very prone to sunscald. That is, the fruit is exposed to direct sunlight at the top of the plant without sufficient shading from the upper leaves and results in the fruit heating up to temperatures that cause burning. Temperatures in excess of 38°C (100°F) have been reported in tomatoes at the top of the plant without any shading from leaves above. The developing fruit of peppers are particularly affected by high light intensity at the top of the plant. Keeping the plants in a more vegetative state to develop a large canopy will protect the fruit from direct sunlight.

Automatic shading systems to reduce direct sunlight by 35%–40% will assist in reducing sunscald, but still, the plants need to be vigorous at the top to overcome this effect on the fruit and subsequent loss of production.

Nutrient formulations are generally composed of several different levels to be used at the different stages of plant growth. Formulations for tomatoes, cucumbers, and peppers usually consist of three levels—A, B, and C. These levels apply mainly to the macroelements, with some small adjustments to the microelements. In the past, the three levels were somewhat simplified to formulation A being approximately one-third of C, and B being two-thirds of C. However, at present, with more experience with these greenhouse crops, more specific adjustments are made to the macroelements and not necessarily in this simplified ratio. These adjustments will vary with location, climate, and growing method (hydroponic system).

For tomatoes grown in greenhouses in northern temperate climates, the formulations are divided into seeding and early seedling development (phase I), planting into the growing system and early growth (phase II), and production, training, and pruning (phase III). This would be similar for peppers.

In cucumbers, formulations are partitioned into three distinct phases based on fruit development and its location. Phase I is the period from seeding until the first cucumber develops to 4–5 in. at the 7th to 8th node or up to the 10th node, which depends on light conditions to permit the plant to grow large lower leaves. Phase II is during the production of five to six stem fruits. Phase III is after harvesting all the stem fruits and when fruit development on the laterals begins and thereafter.

Some typical nutrient formulations derived over the years by various researchers and commercial growers are given in Table 3.6.

Leafy vegetables may use a two-level formulation. The first level (about half of the final level) is used until the plants are about 3–4 wk old, and the second (full strength) level thereafter.

In general, plants harvested for their leaves can tolerate higher N levels since nitrogen promotes vegetative growth. However, plants grown for fruit production should have lower N and higher P, K, and Ca levels. Under high light conditions, plants will use more nitrogen than under poor light.

High potassium (K) levels during the fall and early winter will improve fruit quality. This potassium/nitrogen ratio (K:N) is more important and should be varied with the climate. During the longer sunny summer days, the plant needs more nitrogen and less potassium than during the shorter, darker winter days. It is common practice therefore to double the ratio of K:N during the winter. This will make for harder growth in winter than would take place on a summer formulation.

Ulises Durany (1982) recommends that for the development of tomatoes during the initial vegetative phase, the N:K proportion should be 1:5 (e.g., 80 ppm N : 400 ppm K); in the intermediate phase during blossoming and fruit-set, the N:K ratio should be 1:3 (e.g., 110 ppm N : 330 ppm K); and the mature stage with ripening fruit should have a N:K ratio of 1:1.5 (e.g., 140 ppm N : 210 ppm K). This can be achieved through the use of potassium nitrate and calcium nitrate with potassium sulfate.

Schwarz (1968) lists a number of ratios for N:P:K to be used during the summer and winter seasons for various crops grown in European, Mediterranean, and subtropical climates (Table 3.7).

3.6 NUTRIENT STOCK SOLUTIONS

3.6.1 Injector or Proportioner System

Fertilizer injection systems have become very popular with commercial growers since they save time by reducing the number of nutrient solution preparations. They also work well in the automation of nutrient solution adjustment using computer monitoring and injection of stock solutions. Therefore, more accurate, stabilized solutions can be maintained. Injector systems are used with both open and recirculating hydroponic designs. With solution and tissue analyses, appropriate adjustments in the formulation can be made by altering the settings on the injector heads.

A fertilizer injector or proportioner automatically makes up the nutrient solution by injecting preset amounts of concentrated stock solutions into the irrigation lines. In an "open" hydroponic system (nutrient solution is not recycled), a new nutrient solution is prepared automatically with each watering cycle (Figure 3.1). Changing of the nutrient solution is eliminated. Additional stock solutions are simply made up every week or so.

In earlier designs of adding stock solutions A and B to the irrigation system, a three-way valve was used to alternate the flow of stock solution A and stock solution B during irrigation cycles. Acid was added to stock solution A as needed to adjust the pH. If nitric acid was used, it could be divided over both stock solutions, whereas, phosphoric acid had to remain in the stock solution B. It is important that parts made of plastic are used, to prevent corrosion by the stock solutions and entrance into the nutrient solution of elements such as copper and zinc, which could result in toxic levels to the plants.

At present, most systems use a blending or mixing tank in which the irrigation water and fertilizers are mixed homogeneously. The blending tank may be part of a water "loop" piping of large diameter (4-in. diameter or more) (10 cm) or small pumps that inject the stock solutions into a mixing tank, from where it is pumped with another pump to the irrigation system. With the "loop" piping design the different stock solutions entering the main pipe should be installed at different angles so that as they flow into the irrigation water they will not immediately come into contact with each other to

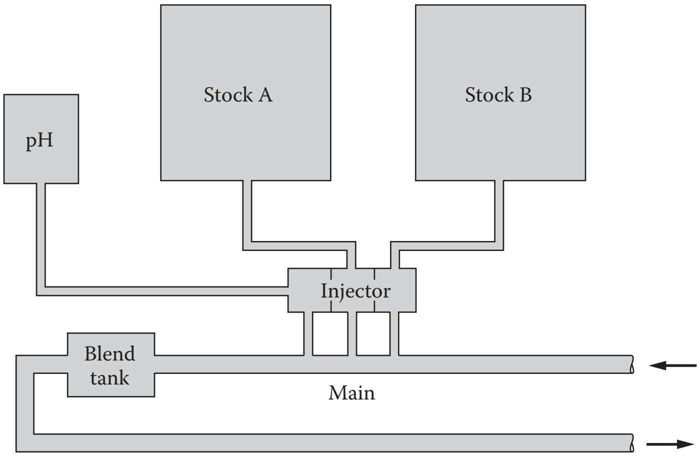

FIGURE 3.1 Layout of a basic injector system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

TABLE 3.6
Composition of Nutrient Solutions (ppm)

References		pH	Ca	Mg	Na	K	N as NH_4^+	N as NO_3^-	P as PO_4^{3-}	S as SO_4^{2-}	Cl	Fe	Mn	Cu	Zn	B	Mo
Knopp (1865)		—	244	24	—	168	—	206	57	32	—	[b]na	—	—	—	—	—
Shive (1915)		—	208	484	—	562	—	148	448	640	—	[b]na	—	—	—	—	—
Hoagland (1919)		6.8	200	99	12	284	—	158	44	125	18	[b]na	—	—	—	—	—
Jones & Shive (1921)		—	292	172	—	102	39	204	65	227	—	0.8	—	—	—	—	—
Rothamsted		6.2	116	48	—	593	—	139	117	157	17	8	0.25	—	—	0.2	—
Hoagland & Snyder (1933, 1938)		—	200	48	—	234	—	210	31	64	—	[b]na	0.1	0.014	0.01	0.1	0.016
Hoagland & Arnon (1938)		—	160	48	—	234	14	196	31	64	—	[a]0.6	0.5	0.02	0.05	0.5	0.01
Long Ashton Soln		5.5–6.0	134–300	36	30	130–295	—	140–284	41	48	3.5	5.6 or 2.8	0.55	0.064	0.065	0.5	0.05
Eaton (1931)		—	240	72	—	117	—	168	93	96	—	0.8	0.5	—	—	1	—
Shive & Robbins (1942)		—	60	53	92	117	—	56	46	70	107	[b]na	0.15	—	0.15	0.1	—
Robbins (1946)		—	200	48	—	195	—	196	31	64	—	0.5	0.25	0.02	0.25	0.25	0.01
White (1943)		4.8	50	72	70	65	—	47	4	140	31	1.0	1.67	0.005	0.59	0.26	0.001
Duclos (1957)		5–6	136	72	—	234	—	210	27	32	—	3	0.25	0.15	0.25	0.4	2.5
Tumanov (1960)		6–7	300 to 500	50	—	150	—	100 to 150	80–100	64	4	2	0.5	0.05	0.1	0.5	0.02
A. J. Abbott		6.5	210	50	—	200	—	150	60	147	—	5.6	0.55	0.064	0.065	0.5	0.05
E. B. Kidson		5.5	340	54	35	234	—	208	57	114	75	2	0.25	0.05	0.05	0.5	0.1
Purdue	A	—	200	96	—	390	28	70	63	607	—	2.0	0.3	0.02	0.05	0.5	—
(1948)	B	—	200	96	—	390	28	140	63	447	—	1.0	0.3	0.02	0.05	0.5	—
	C	—	120	96	—	390	14	224	63	64	—	1.0	0.3	0.02	0.05	0.5	—
Schwartz (Israel)		—	124	43	—	312	—	98	93	160	—	—	—	—	—	—	—
Schwartz (California)		—	160	48	—	234	15	196	31	64	—	—	—	—	—	—	—
Schwartz (New Jersey)		—	180	55	—	90	20	126	71	96	—	—	—	—	—	—	—
Schwartz (South Africa)		—	320	50	—	300	—	200	65	—	—	—	—	—	—	—	—
CDA	A	—	131	22	—	209	33	93	36.7	29.5	188	1.7	0.8	0.035	0.094	0.46	0.027
Saanichton	B	—	146	22	—	209	33	135	36.7	29.5	108	1.7	0.8	0.035	0.094	0.46	0.027
B.C. Canada	C	—	146	22	—	209	33	177	36.7	29.5	—	1.7	0.8	0.035	0.094	0.46	0.027

Dr. Pilgrim	C	—	272	54	—	400	—	143.4	93	237.5	—	—	—	—	—	—	—
Elizabeth	B	—	204	41	—	300	—	107.6	70	178	—	—	—	—	—	—	—
N.C., USA	A	—	136	27	—	200	—	71.7	46.5	119	—	—	—	—	—	—	—
Dr. H.M. Resh	C	—	197	44	—	400	30	145	65	197.5	—	2	0.5	0.03	0.05	0.5	0.02
Univ. of B.C	B	—	148	33	—	300	20	110	55	144.3	—	2	0.5	0.03	0.05	0.5	0.02
Vancouver Canada (1971)	A	—	98	22	—	200	10	80	40	83.2	—	2	0.5	0.03	0.05	0.5	0.02
Dr. H.M. Resh Tropical – Dry		—	250	36	—	200	53	177	60	129	—	5	0.5	0.03	0.05	0.5	0.02
Tropical – Wet Lettuce (1984)		—	150	50	—	150	32	115	50	52	—	5	0.5	0.03	0.05	0.5	0.02
Dr. H.M. Resh Lettuce Florida (1989) Calif. (1993)		—	200	40	—	210	25	165	50	113	—	5	0.5	0.1	0.1	0.5	0.05
Dr. H.M. Resh Cucumbers	I	—	100	20	—	175	3	128	27	26	—	2	0.8	0.07	0.1	0.3	0.03
Florida	II	—	220	40	—	350	7	267	55	53	—	3	0.8	0.07	0.1	0.3	0.03
(1990)	III	—	200	45	—	400	7	255	55	82	—	2	0.8	0.1	0.33	0.4	0.05
Dr. H.M. Resh Lettuce Anguilla, B.W.I. (2011)		—	200	50	[c]50–90	210	—	185 to 195	50	66	[c]65 to 253	5	0.5	0.15	0.15	0.3	0.05
Dr. H.M. Resh Tomato	A	—	240	50	—	201	—	169	49	119	—	2.5	0.58	0.15	0.4	0.3	0.03
Anguilla, B.W.I.	B	—	200	60	—	351	—	137	49	196	—	2.5	0.58	0.15	0.4	0.3	0.03
(2011)	C	—	214	50	—	379	—	177	49	145	—	2.5	0.58 to 0.6	0.15	0.3	0.3	0.05
Sonneveld & Straver Tomato	I	—	240	48	—	195	7	224	46.5	64	—	2.3	0.6	0.05	0.4	0.3	0.05
Netherlands	II	—	190	60	—	351	—	189	46.5	128	—	2.3	0.6	0.05	0.7	0.3	0.05
(1992)	III	—	170	48	—	341	18	192	38.7	120	—	2.3	0.6	0.05	0.3	0.3	0.05
Sonneveld & Straver Cucumber	I	—	185	33	—	270	18	190	39	90	—	2.3	0.6	0.05	0.4	0.4	0.05
Netherlands	II	—	210	33	—	345	18	246	39	65	—	2.3	0.6	0.05	0.4	0.4	0.05
(1992)	III	—	170	36	—	293	18	213	39	44	—	2.3	0.6	0.05	0.4	0.3	0.05

[a] Add three times weekly.

[b] na, information not available or indicated trace or as required.

[c] These were sodium and chloride levels in the raw water from sea water desalinated by reverse osmosis. These level variations were present in all formulations used in Anguilla, for lettuce, herbs, tomatoes, cucumbers, and peppers for the period 1999 through 2011.

TABLE 3.7
Ratios of N:P:K Recommended for Summer and Winter Seasons in Several Climatic Regions

Crop, Climate, Season		N	P	K
	Tomato (mature stage)			
Middle European climate	Summer	1	0.2–0.3	1.0–1.5
	Winter	1	0.3–0.5	2–4
Mediterranean and subtropical climate	Summer	1	0.2	1
	Winter	1	0.3	1.5–2.0
	Lettuce and other leafy vegetables			
	Summer	1	0.2	1
	Winter	2	0.3	2
	Ammonium:nitrate ratio (NH_4:NO_3)			
	Summer	1:3–4		
	Winter	1:4–8		

Source: Modified from Schwarz, M., *Guide to Commercial Hydroponics*, Israel University Press, Jerusalem, 1968, p. 32.

prevent precipitation of the fertilizers within the main irrigation pipe. The pH is adjusted in the mixing tank with an acid or base as needed. The electrical conductivity (EC) and pH are monitored and controlled by computer at the mixing tank, and additional EC and pH units are installed downstream in the main irrigation line to monitor the solution and signal an alarm if preset levels are exceeded or not reached. If the alarm is set by an excess of nutrients in the mixing tank, the injection system will automatically stop until corrected in order to prevent toxicity to the crop. Figure 3.2 shows A, B, and acid stock solutions with a mixing tank.

Injectors may also be used with recycle systems to automatically adjust the returning nutrient solution. Analysis of the returning solution indicates the modifications to be made to the stock solution to bring the nutrients to optimum levels before once again irrigating the plants. While nutrient solution analysis must be done by a laboratory to determine the levels of all essential elements, the general total salt levels can be determined by an EC meter. The EC meter and a pH meter act as sensors for the computer in monitoring the current status of the returning and outgoing solutions. The computer can then activate the injector to adjust the nutrient solution according to preset levels stored in the computer (Figure 3.3). The formulations of the nutrient stock solutions and the settings of the injector heads allow the operator to make changes in the outgoing nutrient solution to achieve optimum nutrient levels of each ion.

Some commercial growers are now taking the injection system to another level by using individual stock tanks for each fertilizer providing macroelements, trace elements, and pH adjustment. These are then dispensed individually into the mixing tank. This has a great advantage for closed hydroponic systems in that it enables the grower to selectively add given portions of each of the fertilizers and therefore make finer adjustments, almost on an individual element basis.

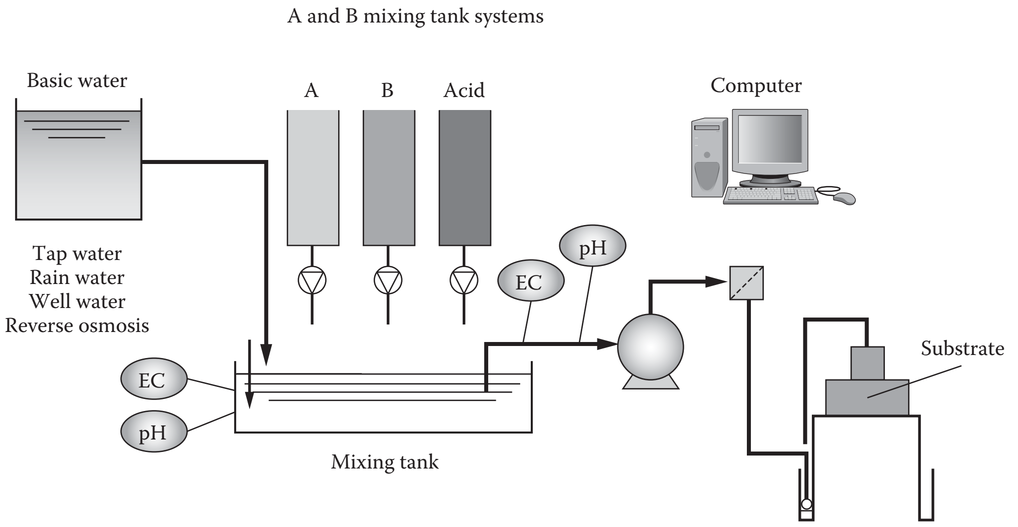

FIGURE 3.2 A, B, and acid stock mixing tank system. (Adapted from K. Welleman. *6th Curso Y Congreso Internacional de Hidroponia en Mexico.* Toluca, Mexico, April 17–19, 2008b. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

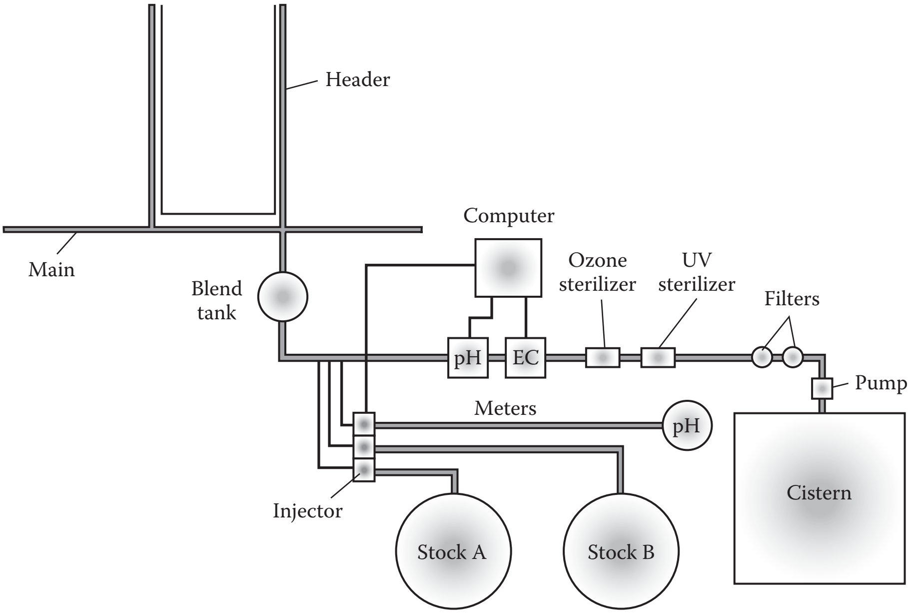

FIGURE 3.3 Layout of injector system for recirculating systems. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

The returning solution can be analyzed, and additions of the individual compounds can be made at different rates according to those elements being depleted in the nutrient solution. This can be computer activated, similar to the previous system using only two stock solutions. Such a multi-injection fertilizer system is shown in Figure 3.4.

There are a number of different manufacturers of injectors (Appendix 5). The choice of a particular make will depend on the volume of nutrient solution to be injected at any

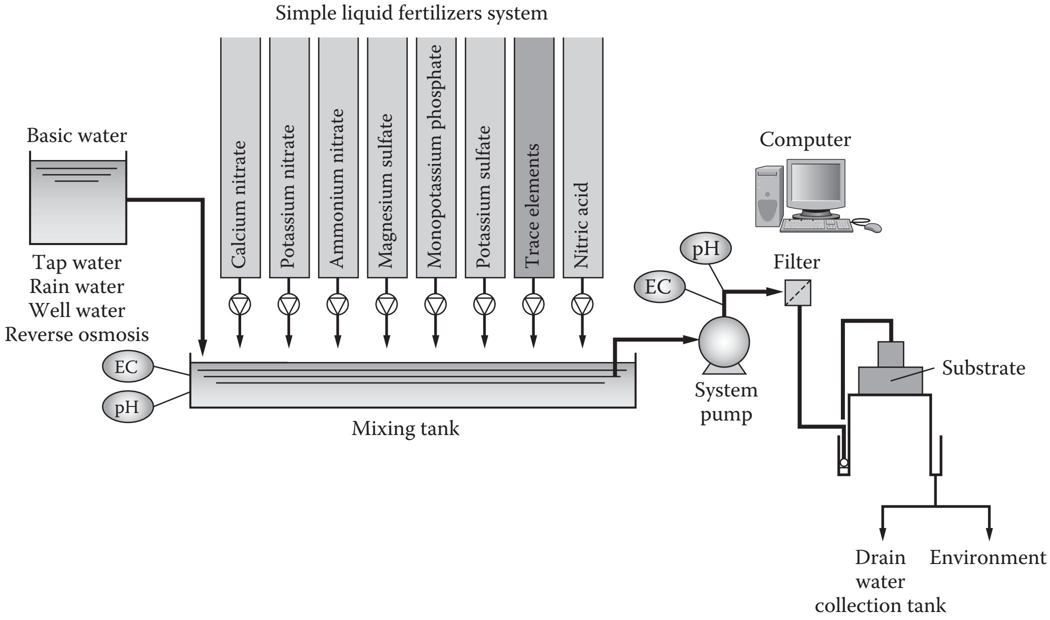

FIGURE 3.4 Individual stock mixing tank system. (Adapted from K. Welleman, The Netherlands. *6th Curso Y Congreso Internacional de Hidroponia en Mexico*. Toluca, Mexico, April 17–19, 2008b. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

given time in gallons per minute (gpm), the accuracy required for the system, the type of computer controller system, and the ability to expand the system. Some of the better makes of injectors allow addition of injector heads to expand the hydroponic system, making it unnecessary to purchase a new injector.

For example, a 3-acre (1.2-ha) hydroponic herb operation used an Anderson injector with five heads as shown in Figure 3.5. The system consisted of a 3-in. (7.6-cm)-diameter water main forming a loop with the injector, a blending tank, and a filter before going into the irrigation system of the hydroponic beds. The water flows from right to left in the system illustrated in Figure 3.6.

A paddle-wheel sensor upstream from the injector (Figure 3.5) monitors the flow of water. For every 4 gal (15 L) of water that passes, the sensor sends impulses to the controller (the gray box on the white panel in Figure 3.6).

The controller activates one stroke of the injector for every 4 gal (15 L) of water going through the main loop. A stroke occurs when the controller sends an electric current to the solenoid valve on the injector, opening the valve and allowing the pressure of the raw water to drive the diaphragms of the injector heads. The raw water passes through a 200-µm household filter before entering the solenoid to prevent any silt from damaging the valve. As the pressurized water (minimum of 15–20 psi or 103.5–138 kPa) enters the back of the diaphragm of each head, it pushes the diaphragm forward, causing the displacement of the stock solution in front of it. The stock solution flows to the main loop via tubing and a header. Backflow preventer valves on heads of the injector and on the inlets to the stock solution header on the main loop prevent dilution from backing up on the return stroke of the diaphragms (Figure 3.5). This injector has five heads: two for stock A, two for stock B, and a smaller acid head (on the left of Figure 3.5).

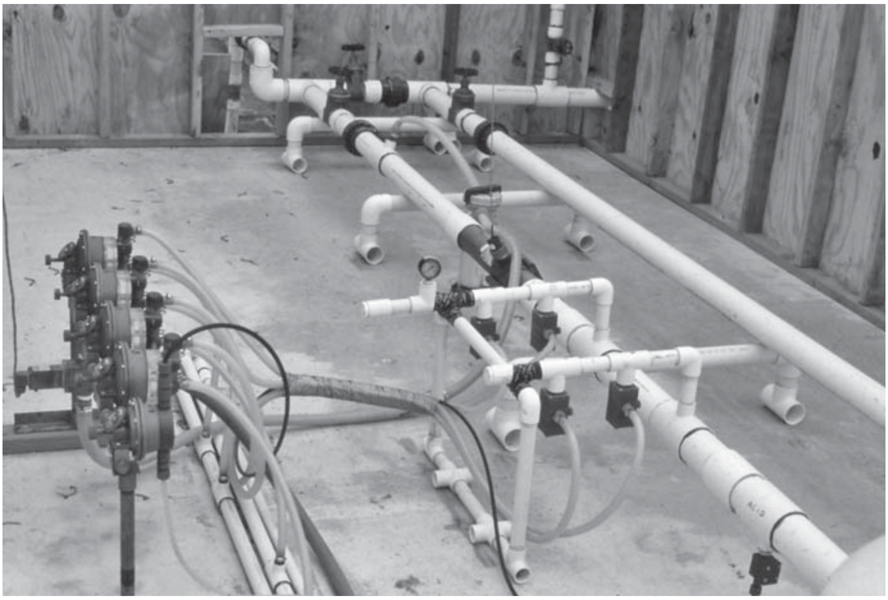

FIGURE 3.5 Anderson injector with five heads (on the left), paddle-wheel sensor on main line (gray area on pipe before inlet lines from injector). Water flows from back to front. (From California Watercress, Inc., Fillmore, CA. With permission.)

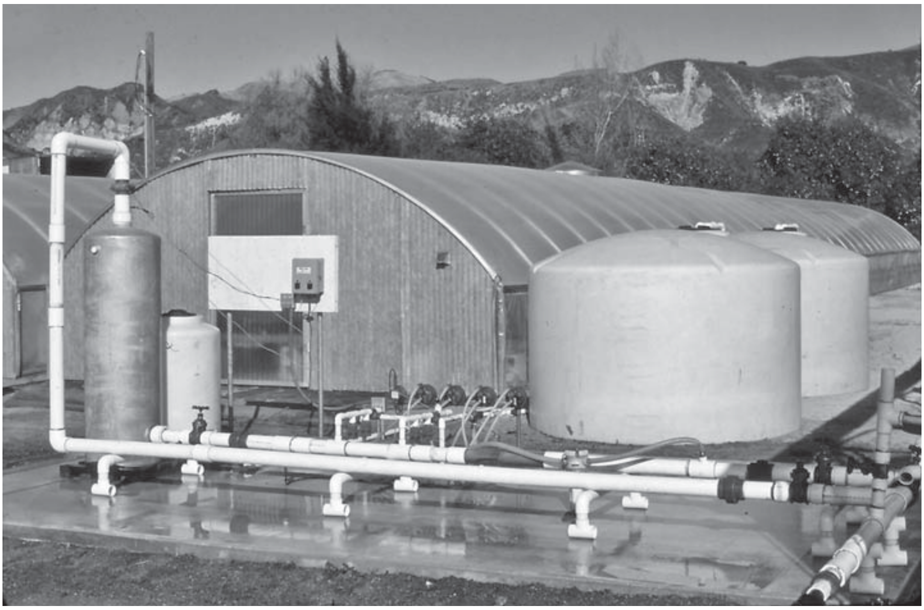

FIGURE 3.6 Stock tanks A and B. (From California Watercress, Inc., Fillmore, CA. With permission.)

Each stroke of the injector displaces 40 mL of stock solution per head at the “10” setting on the head dial. At optimum injector operation of 32 strokes per minute, the maximum flow through the system is 32 × 4 gal = 128 gal/min (484.5 L/min). The ratio of fertilizer stock to water achieved per head is 40 mL:15,142 mL (4 US gal), or 1:378. For two heads the ratio is 80 mL:15,142 mL, or 1:189. To obtain a 1:200 dilution, set the dial on each head of stocks A and B to 9.5. This setting gives 9.5/10 × 40 mL = 38 mL of 200× concentration stock solution. The ratio for the two heads of each stock solution is 76 mL:15,142 mL, or 1:200 (fertilizer to water).

For a larger system, the impulse setting from the paddle-wheel sensor is increased at the controller. For example, if the setting is increased to one stroke per 5 gal (19 L), optimum operation would allow a flow of 5 gal × 32 strokes/min = 160 gal/min (606 L/min). However, if a 1:200 proportion was still required, an additional injector head would have to be installed. Each head is only capable of displacing 40 mL of stock solution per stroke. The maximum dilution of a two-head injector on a 5 gal/stroke basis is 80 mL:18,927 mL (5 US gal), or 1:236.

Alternatively, the strength of the stock solutions could be increased above 236 times. Following these principles, the injector system can be expanded with additional heads to operate with higher volumes of water flow.

The entrance of stock solutions A and B into the main loop is separated by at least 18 in. (46 cm) so that adequate mixing with raw water occurs before they come in contact with each other. Another method to ensure that no precipitation occurs is to have the entrances of the separate stock solutions into the main loop positioned at different angles to each other. That is, the two entrances should not be in line with each other; one of them should be rotated about 90° from the other. As the water nutrient passes downstream, it is mixed further in an 80-gal (303-L) blending tank as shown in Figure 3.6. The acid enters the main loop several feet (60 cm) downstream from the stock solutions (small black tubing entering underneath the main loop in Figure 3.5).

The stock solutions and acid enter the injector heads with flexible tubing (Figure 3.5) from the header lines connected to the 1,500-gal (5,678-L) stock tanks A and B and a 30-gal (114-L) acid tank (Figure 3.6). The main loop carries the mixed solution from the blending tank to the hydroponic growing system (Figure 3.6). A 200-mesh filter installed downstream removes any particulate matter before the solution enters the drip irrigation system.

3.6.2 STOCK SOLUTIONS

Stock solutions are concentrated nutrient solutions. Depending on the ability of the injector, the stock solutions may be prepared at 50, 100, or 200 times the normal strength. A second factor that may limit the degree of concentration of the stock solution is fertilizer solubility. The least soluble fertilizer will be the limiting factor for the entire stock solution. When determining the strength of the stock solution, refer to the information on "Physical Constants of Inorganic Compounds" listed in Appendix 4.

Two separate stock solutions plus an acid solution must be prepared in individual tanks. These are generally called "stock A," "stock B," and "acid." The reason for separate solutions is that precipitation will occur among the sulfates and nitrates of some compounds if mixed together at high concentrations. For example, the sulfates of potassium sulfate or magnesium sulfate will precipitate with calcium from calcium nitrate.

Stock A may contain half the total potassium nitrate requirement and all of the calcium nitrate, ammonium nitrate, nitric acid (to lower the pH of the stock solution to under 5.0), and iron chelate requirement. Stock B would consist of the other half of potassium nitrate, all of potassium sulfate, monopotassium phosphate, phosphoric acid, magnesium sulfate, and the remaining micronutrients apart from iron. Acid stock solution is diluted to about 15%–20% of the concentrated liquid form available from suppliers. Care should always be exercised with such strong acids as they cause severe injury to humans. Always add acid to water, never water to acid.

Some of the acids used are nitric acid (HNO_3) (42%) (produces harmful vapors and burns the skin), sulfuric acid (H_2SO_4) (66%) (burns the skin and produces holes in clothing), phosphoric acid (H_3PO_4) (75%), and hydrochloric acid (HCl) (muriatic acid). With these strong acids, protective plastic/rubber gloves, apron, goggles, and an approved respirator should be worn. Particular care must be taken with nitric acid as it gives off toxic fumes when it comes in contact with the air.

To determine the upper limit of concentration for a stock solution, use the solubility products listed in Appendix 4. Solubility is given as the amount in grams of a specific fertilizer that may be dissolved in 100 mL of cold or hot water. Since the stock solution will probably not be heated, the values for cold water should be used. The following example demonstrates the use of these solubility factors.

Compound	**Solubility (g/100 mL Cold Water)**
Stock A	
Potassium nitrate[a]	13.3
Calcium nitrate	121.2
Ammonium nitrate	118.3
Nitric acid	No limit
Iron chelate	Very soluble
Stock B	
Potassium nitrate	13.3
Potassium sulfate[a]	12.0
Monopotassium phosphate (potassium dihydrogen phosphate)	33.0
Phosphoric acid	548
Magnesium sulfate	71

[a] These are the least soluble compounds and possibly the limiting ones, depending on the weights of each required. Although micronutrients will be included in stock solution B, they have not been included in this list of solubilities since they will be required in very small amounts, which will not exceed their solubilities at the 200× concentration.

To demonstrate the calculations of a stock solution, the following nutrient formulation will be used:

N: 200 ppm	P: 50 ppm	K: 300 ppm
Ca: 200 ppm	Mg: 40 ppm	Fe: 5 ppm
Mn: 0.8 ppm	Cu: 0.07 ppm	Zn: 0.1 ppm
B: 0.3 ppm	Mo: 0.03 ppm	

Assume that raw water contains 30 ppm of Ca and 20 ppm of Mg. The following are then the adjustments to the formulation:

1. The amount of Ca to be added will be 170 ppm (200–30).
2. The amount of Mg to be added is 20 ppm (40–20).

Using 1,200-US-gal tanks to store each stock solution and a 200× concentration of solution, the procedure is as follows:

1. Determine the amount of each compound to satisfy the macronutrients and adjust for impurities.
   Ca: 170 ppm (mg/L)
   (i) Weight of $Ca(NO_3)_2$ (use Table 3.2 conversion factors):

$$170 \times 4.094 = 696 \text{ mg/L}$$

   (ii) Adjust for impurity from Table 3.3 (90% pure):

$$\frac{100}{90} \times 696 = 773 \text{ mg/L}$$

2. Calculate the amount of the compound for the stock solution concentration (200× in this case).

$$200 \times 773 \text{ mg/L} = 154{,}600 \text{ mg/L or } 154.6 \text{ g/L} \qquad (1000 \text{ mg} = 1 \text{ g})$$

3. Compare this amount with the solubility given in grams per 100 mL of cold water.
   (i) Convert to grams per 100 mL:

$$154.6 \text{ g/L}$$

   That is, 154.6 g/1000 mL (since 1 L = 1000 mL) or 15.46 g/100 mL (divide by 10 to get 100 mL)
   (ii) Compare with the solubility:

$$15.46 \text{ g/100 mL versus } 121.2 \text{ g/100 mL}$$

   Therefore, this amount is well within the solubility limits of calcium nitrate.
4. Continue with the calculations for all macronutrient compounds.
   N: We require a total of 200 ppm from all sources. Assume that we wish to use some ammonium nitrate to supply 10 ppm of N from NH_4.
   (i) Amount of N in $Ca(NO_3)_2$ added:

$$696 \text{ mg/L of } Ca(NO_3)_2 \text{ (before adjustment for purity)}$$
$$696 \text{ mg/L} \times 0.171 \text{ (Table 3.2 factor)} = 119 \text{ mg/L (ppm)}$$

   (ii) Balance needed from sources other than calcium nitrate:

$$200 - 119 = 81 \text{ ppm (mg/L)}$$

   (iii) Amount of NH_4NO_3 needed to obtain 10 ppm of N from NH_4 and 10 ppm of N from NO_3 (i.e., a total of 20 ppm N from NH_4NO_3 source):

$$20 \text{ mg/L} \times 2.857 \text{ (Table 3.2 factor)} = 57 \text{ mg/L}$$

(iv) Adjust for purity (Table 3.3—98%):

$$\frac{100}{98} \times 57 \text{ mg/L} = 58 \text{ mg/L}$$

(v) For 200× concentration:

$$200 \times 58 \text{ mg/L} = 11{,}600 \text{ mg/L or } 11.6 \text{ g/L}$$

(vi) Express in grams per 100 mL and compare with solubility:

11.6 g/L = 1.16 g/100 mL (divide by 10 as 1 L = 1000 mL)
1.16 g/100 mL versus 118.3 g/100 mL

Therefore, the level of ammonium nitrate is within the solubility range.

(vii) Balance of N required from sources other than calcium nitrate and ammonium nitrate:

$$200 - (119 + 20) = 61 \text{ ppm (mg/L)}$$

(viii) Final source of N is from KNO_3:

61 mg/L × 7.221 (Table 3.2 factor) = 440.5 mg/L

(ix) Adjust for purity (Table 3.3—95%):

$$\frac{100}{95} \times 440.5 \text{ mg/L} = 464 \text{ mg/L}$$

(x) For 200× concentration:

$$200 \times 464 \text{ mg/L} = 92{,}800 \text{ mg/L or } 92.8 \text{ g/L}$$

(xi) Express in g/100 mL and compare with solubility:

92.8 g/L = 9.28 g/100 mL
9.28 g/100 mL versus 13.3 g/100 mL

This is within the solubility limit. Note that half of the potassium nitrate is added to stock A and the other half to stock B.
Therefore, 9.28/2 = 4.64 g/100 mL concentration is actually added to each tank. Often, a higher level of potassium nitrate is used, and therefore, splitting it between the two stock solutions keeps within the solubility limit.

K: 300 ppm (mg/L)

(i) Amount of K in KNO_3 used:

440.5 mg/L × 0.387 (Table 3.2 factor) = 170.5 mg/L

(ii) Balance of K needed: 300 − 170 = 130 mg/L

(iii) Other sources: KH_2PO_4 and K_2SO_4
First calculate the amount of KH_2PO_4 to be used to get 50 ppm of P.

P: 50 ppm (mg/L) from KH_2PO_4

(i) 50 mg/L × 4.394 (Table 3.2 factor) = 220 mg/L

(ii) Adjust for purity (Table 3.3—98%)

$$\frac{100}{98} \times 220 \text{ mg/L} = 224 \text{ mg/L}$$

(iii) For 200× concentration:

$$200 \times \frac{224 \text{ mg}}{1{,}000 \text{ mg}} = 44.8 \text{ g/L} \text{ or } \frac{4.5 \text{ g}}{100 \text{ mL}}$$

(iv) Compare with solubility:

4.5 g/100 mL versus 33.0 g/100 mL

This is well below the solubility limit.

Now go back and calculate the K requirement from other sources (see (iii) in K: 300 ppm (mg/L)).

K: 300 ppm (mg/L)

(v) Amount of K in 220 mg/L of KH_2PO_4

220 mg/L × 0.287 (Table 3.2 factor) = 63 ppm

(vi) Balance of K needed: 300 − (170 + 63) = 67 ppm (mg/L)

(vii) Amount of K_2SO_4:

67 mg/L × 2.229 = 149 mg/L

(viii) Adjust for purity (90%):

$$\frac{100}{90} \times 149 \text{ mg/L} = 166 \text{ mg/L}$$

(ix) For 200× concentration:

$$200 \times \frac{166 \text{ mg}}{1{,}000 \text{ mg}} = 33.2 \text{ g/L} \text{ or } \frac{3.32 \text{ g}}{100 \text{ mL}}$$

(x) Compare with solubility:

3.32 g/100 mL versus 12.0 g/100 mL

This level is within the solubility range.

Mg: 20 ppm (mg/L)

(i) Amount of $MgSO_4$ required:

$$20 \text{ mg/L} \times 10.14 = 203 \text{ mg/L}$$

(ii) Adjust for purity (98%):

$$\frac{100}{98} \times 203 \text{ mg/L} = 207 \text{ mg/L}$$

(iii) For 200× concentration:

$$200 \times \frac{207 \text{ mg}}{1{,}000 \text{ mg}} = 41.4 \text{ g/L} \text{ or } \frac{4.14 \text{ g}}{100 \text{ mL}}$$

(iv) Compare with solubility:

$$4.14 \text{ g/100 mL versus } 71 \text{ g/100 mL}$$

This level is soluble.

5. Convert all compound weights to amounts for 1,200-US-gal stock tanks.

A. Convert 1,200 US gal to liters:

$$1{,}200 \times 3.785 = 4{,}542 \text{ L}$$

B. Calculate the weights of each compound for this volume.

(i) $Ca(NO_3)_2$: 154.6 g/L

$$154.6 \times 4{,}542 = 702{,}193 \text{ g or } 702.2 \text{ kg}$$

(ii) NH_4NO_3: 11.6 g/L

$$11.6 \times 4{,}542 = 52{,}687 \text{ g or } 52.7 \text{ kg}$$

(iii) KNO_3: 92.8 g/L

$$92.8 \times 4{,}542 = 421{,}498 \text{ g or } 421.5 \text{ kg}$$

That is, 421.5 kg × 2.2 lb = 927 lb.

Note that this total of 927 lb will be divided into two equal portions, one in each stock tank. Therefore, 927/2 = 463.5 lb should be added to each of stock A and B tanks.

(iv) KH_2PO_4: 44.8 g/L

$$44.8 \times 4{,}542 = 203{,}482 \text{ g or } 203.5 \text{ kg}$$

That is, 203.5 kg × 2.2 lb = 448 lb.

(v) K_2SO_4: 33.2 g/L

$$33.2 \times 4{,}542 = 150{,}794 \text{ g or } 150.8 \text{ kg}$$

That is, 150.8 kg × 2.2 lb = 332 lb.

(vi) $MgSO_4$: 41.4 g/L

$$41.4 \times 4{,}542 = 188{,}039 \text{ g or } 188 \text{ kg}$$

That is, 188 kg × 2.2 lb = 414 lb.

6. Now calculate the weights for each of the micronutrient compounds.

Fe: 5 ppm (mg/L)

(i) Source: FeEDTA (10%)

$$5 \text{ mg/L} \times 10.0 \text{ (Table 3.2 factor)} = 50 \text{ mg/L}$$

(ii) For 200× concentration:

$$200 \times 50 \text{ mg/L} = 10{,}000 \text{ mg/L or } 10 \text{ g/L}$$

(iii) For 1,200 US gal (4542 L):

$$10 \times 4{,}542 = 45{,}420 \text{ g or } 45.4 \text{ kg}$$

That is, 45.4 kg × 2.2 lb = 100 lb.

Mn: 0.8 ppm (mg/L)

(i) Amount of $MnSO_4$

$$0.8 \text{ mg/L} \times 4.061 \text{ (Table 3.2 factor)} = 3.25 \text{ mg/L}$$

(ii) Adjust for percentage purity. The purity of compounds, especially that of micronutrients, differs with the manufacturer. The grower should obtain the precise percentage purity for any given product from the fertilizer dealer. For calculation purposes, a purity of 90% will be used. Adjustments may be made after a solution analysis has been carried out for the new solution. The actual level of each element can be compared to the theoretical expected level of each.

$$\frac{100}{90} \times 3.25 \text{ mg/L} = 3.6 \text{ mg/L}$$

(iii) For 200× concentration:

$$200 \times 3.6 \text{ mg/L} = 720 \text{ mg/L or } 0.72 \text{ g/L}$$

(iv) For 1,200 US gal (4,542 L):

$$0.72 \times 4{,}542 = 3{,}270 \text{ g or } 3.27 \text{ kg}$$

That is, 3.27 kg × 2.2 lb = 7.2 lb or 7 lb 3 oz (1 lb = 16 oz; 0.2 × 16 = 3 oz).

Cu: 0.07 ppm (mg/L)

(i) Source: $CuSO_4$

$$0.07 \text{ mg/L} \times 3.93 \text{ (Table 3.2 factor)} = 0.275 \text{ mg/L}$$

(ii) Percentage purity (98%):

$$\frac{100}{98} \times 0.275 \text{ mg/L} = 0.281 \text{ mg/L}$$

(iii) For 200× concentration:

$$200 \times 0.281 \text{ mg/L} = 56 \text{ mg/L or } 0.056 \text{ g/L}$$

(iv) For 1,200 US gal:

$$0.056 \times 4.542 = 254 \text{ g}$$

Since this is less than 1 lb, it is more accurate to weigh it using a gram scale.

Zn: 0.1 ppm (mg/L)

(i) Source: ZnEDTA (14% powder)

$$0.1 \text{ mg/L} \times 7.143 = 0.7143 \text{ mg/L}$$

(ii) For 200× concentration:

$$200 \times 0.7143 \text{ mg/L} = 143 \text{ mg/L or } 0.143 \text{ g/L}$$

(iii) For 1,200 US gal:

$$0.143 \times 4{,}542 = 650 \text{ g or } 1.43 \text{ lb, which is } 1 \text{ lb } 7 \text{ oz}$$

B: 0.3 ppm (mg/L)

(i) Source: H_3BO_3

$$0.3 \text{ mg/L} \times 5.717 = 1.715 \text{ mg/L}$$

(ii) Percentage purity (about 95%):

$$\frac{100}{95} \times 1.715 \text{ mg/L} = 1.805 \text{ mg/L}$$

(iii) For 200× concentration:

$$200 \times 1.805 \text{ mg/L} = 361 \text{ mg/L or } 0.361 \text{ g/L}$$

(iv) For 1,200 US gal:

$$0.361 \times 4{,}542 = 1{,}640 \text{ g or } 3.61 \text{ lb}$$

That is, 3 lb 10 oz.

Mo: 0.03 ppm (mg/L)

(i) Source: ammonium molybdate

$$0.03 \text{ mg/L} \times 1.733 = 0.052 \text{ mg/L}$$

(ii) Percentage purity is about 95%:

$$\frac{100}{95} \times 0.052 \text{ mg/L} = 0.055 \text{ mg/L}$$

(iii) For 200× concentration:

$$200 \times 0.055 \text{ mg/L} = 11 \text{ mg/L}$$

(iv) For 1,200 US gal:

$$11 \times 4{,}542 = 49{,}962 \text{ mg or } 50 \text{ g}$$

7. Construct a table to summarize all of the information.

	Compound	Weight (lb)	Stock Solution (g/100 mL)	Maximum Solution (g/100 mL)	Nutrient Solution Elements (ppm) After Injection
STOCK A:	KNO_3	463.5	4.64	13.3	K: 85
(200×)					N: 30.5
(1,200-US-gal tank)	$Ca(NO_3)_2$	1,545	15.46	121.2	Ca: 170
					N: 119
	NH_4NO_3	116	1.16	118.3	N: 20
	FeEDTA	100	—	Very soluble	Fe: 5
	[a]HNO_3	—	—	No limit	—
	—	—	—	—	—
STOCK B:	KNO_3	463.5	4.64	13.3	K: 85
(200×)					N: 30.5
(1,200-US-gal tank)	K_2SO_4	332	3.32	12.0	K: 67
					S: 27.4
	KH_2PO_4	448	4.5	33.0	K: 63
					P: 50
	$MgSO_4$	414	4.14	71	Mg: 20
					S: 26.4
	[a]H_3PO_4	—	—	548	—
	$MnSO_4$	7 lb 3 oz	0.072	105.3	Mn: 0.8
	$CuSO_4$	254 g	0.0056	31.6	Cu: 0.07

continued

Compound	Weight (lb)	Stock Solution (g/100 mL)	Maximum Solution (g/100 mL)	Nutrient Solution Elements (ppm) After Injection
ZnEDTA	1 lb 7 oz	0.00143	Very soluble	Zn: 0.1
H_3BO_3	3 lb 10 oz	0.0361	6.35	B: 0.3
NH_4–Mo	50 g	0.0011	43	Mo: 0.03

[a] These acids are added in sufficient quantity to lower the pH to 5.5. Phosphoric acid (H_3PO_4) may be substituted for KH_2PO_4 as a source of P. Then adjust the remaining compounds containing K, especially K_2SO_4, as no K will be obtained from H_3PO_4.

Nutrient solution totals: NO_3—N: 190 ppm; NH_4—N: 10 ppm; P: 50 ppm; K: 300 ppm.

The raw water in this example contained 30 ppm of Ca and 20 ppm of Mg. This brings the total Ca to 200 ppm and Mg to 40 ppm in the final nutrient solution after injection.

Stock solutions require continuous agitation to prevent settling down of some of the fertilizer components. This may be accomplished in several ways. A motor having a long shaft with a propeller-type blade may be mounted above the opening of the tank as shown in Figure 3.7. The blade and shaft should be submersed to a position very close to the bottom

FIGURE 3.7 Stock tanks (2,300 gal) A and B with circulation pumps. (From California Watercress, Inc., Fillmore, CA. With permission.)

of the tank. It is very important that the shaft and blade are of stainless steel to resist the corrosive nature of the nutrient solution.

A submersible pump may be placed at the bottom of each tank to circulate the solution. But, it must be well sealed and should have either a plastic or a stainless steel impeller and stainless steel screws holding the pump components together. If there are any regular steel or galvanized screws in contact with the nutrient solution, they will be dissolved by the electrolytic nature of the solution within several weeks. This would then expose the motor to the solution, and the operator could easily receive an electric shock when working with the injection system.

An alternative to these methods is to use a circulating pump that has components resistant to corrosive solutions, such as a swimming pool circulation pump. The pump would be located outside and near each tank (one pump per tank). Plastic PVC piping of at least 1.5-in diameter would connect the pump inlet and outlets to the bottom of the stock solution tank as shown in Figure 3.8. An elbow is placed at the end of the outlet line in the tank to deflect the solution around the tank. The inlet end requires a check valve at its end near the base of the tank to keep the pump from losing prime. The pump should be anchored to the base of a concrete or heavy wood support with anchor bolts to prevent it from shifting position. The pump must run continuously.

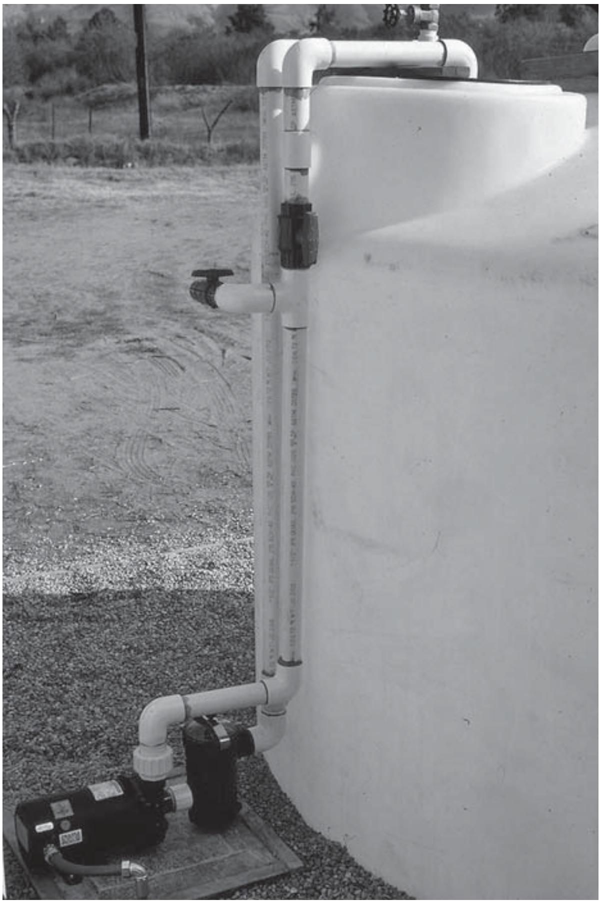

FIGURE 3.8 Circulation pump with plumbing to agitate the stock solution. (From California Watercress, Inc., Fillmore, CA. With permission.)

With smaller stock tanks of less than 500 gal, an air pump can be used to agitate the solution. Connect the air pump using a 0.5-in.-diameter polyethylene tubing and a tee forming one line to each tank. Connect the polyethylene tubing with an adapter to a 12-in. air diffuser (air stone) available from aquatic suppliers. Position the air diffuser at the base of the tank. A plastic ball valve fit into each line will allow you to balance the airflow between tanks. When making up a new stock solution, remove the remaining solution and clean the tank with a 10% bleach solution. Use a submersible pump to clean the tanks.

The pH adjustment tank (either acid or strong base) does not require agitation since the contents dissolve completely in water and do not form any precipitates.

To facilitate the filling of the stock tanks, install a 1-in. diameter raw water line above the tanks (Figure 3.7). At the inlet end to each tank, attach a gate valve. For large operations, stock tanks should be at least 2,300 gal or larger as shown in Figure 3.9.

Commercial greenhouse operations of 20 acres (8 ha) or greater may use a series of 3,000-gal tanks. Very large operations that recirculate their nutrient solution through the collection of the runoff use vinyl-lined corrugated steel tanks of 20,000 gal or more. Samples of the returned solution in the storage tanks are sent to a laboratory in Holland and results received within a few days. The nutrient solution is pasteurized at 85°C–90°C (185°F–194°F) for 3–2 min, respectively, then cooled and adjusted for nutrients and pH by injecting stock solutions A and B on its way back to the greenhouses. If these greenhouses are located in southern latitudes where frost is not severe, such as California, the tanks can be located outside. In areas of cold winters, the tanks must be placed inside the greenhouse packing-storage building, as is the case with Gipaanda Greenhouses Ltd., Delta, B.C. (Figure 3.10). Bionatur Greenhouses in Jocotitlan, Mexico, located their storage tanks in the packing-storage area of the greenhouse. Similar to those of Gipaanda Greenhouses Ltd., they are corrugated galvanized steel tanks lined with vinyl (Figure 3.11).

FIGURE 3.9 Image of 2,300-gal stock tanks with injector shed. (From California Watercress, Inc., Fillmore, CA. With permission.)

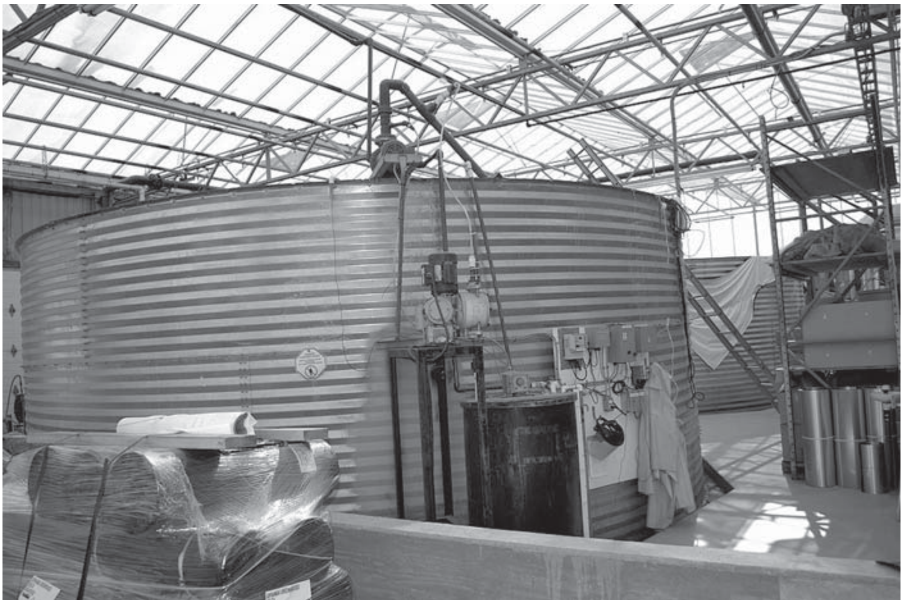

FIGURE 3.10 Large steel collection tanks for returning nutrient solution in a closed (recycled) system. (From Gipaanda Greenhouses, Delta, B.C., Canada. With permission.)

FIGURE 3.11 Large nutrient solution collection tanks in a closed system. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

Houweling Nurseries Ltd. in Oxnard, California, located a series of stock tanks of about 3,000 gal outside under a platform between the greenhouses. The platform is of heavy steel-reinforced construction so that the fertilizers can be set above the tanks. Fertilizers can be added from above directly into the tanks (Figure 3.12). A plastic barrel with the ends removed is fixed to the manhole of each tank so that the fertilizers can be added with

FIGURE 3.12 Stock tanks of 3,000 gal. (From Houweling Nurseries, Inc., Oxnard, CA. With permission.)

a minimum of spillage. These are stock solutions prepared for injection into the irrigation system on its way to the greenhouses.

In recirculation systems, the solution needs to be pasteurized before its return to the greenhouse irrigation system. This can be done by three methods: filtration, ultraviolet (UV), ozone and pasteurization by heat. Most operations use filtration, UV, and heat pasteurization. Bionatur Greenhouses in Mexico and Eurofresh Farms in Arizona use filtration and UV as shown in Figures 3.13 and 3.14. These companies mainly grow tomatoes.

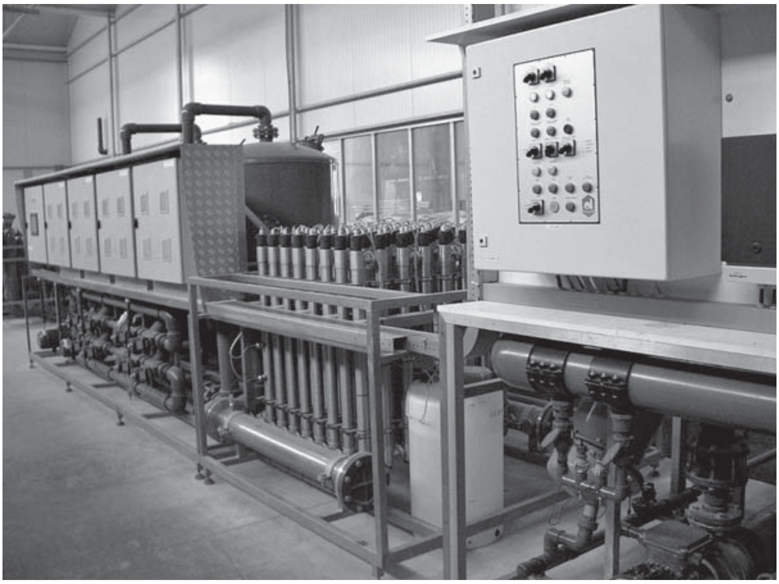

FIGURE 3.13 UV sterilization system for recirculation of nutrient solution. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

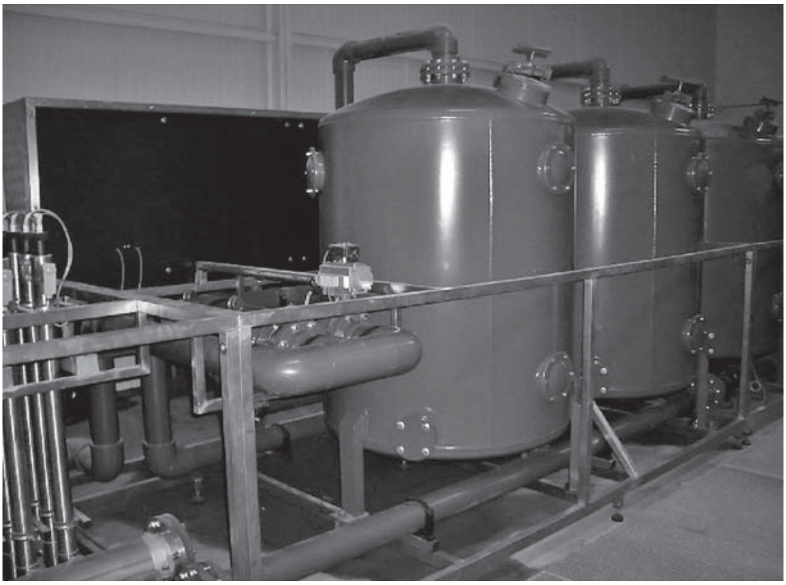

FIGURE 3.14 Filters on the right with UV on the left. (From Eurofresh Farms, Wilcox, AZ. With permission.)

They also use sophisticated injection systems as can be seen in Figure 3.13 to the left of the UV sterilizers and in Figures 3.15 and 3.16. The injectors are controlled by the computer system. They monitors pH and EC and activate the injectors to adjust the returning nutrient solution.

When using small injector system stock tanks of less than 100 US gal (378 L), the weights of individual micronutrient compounds become very small. For example,

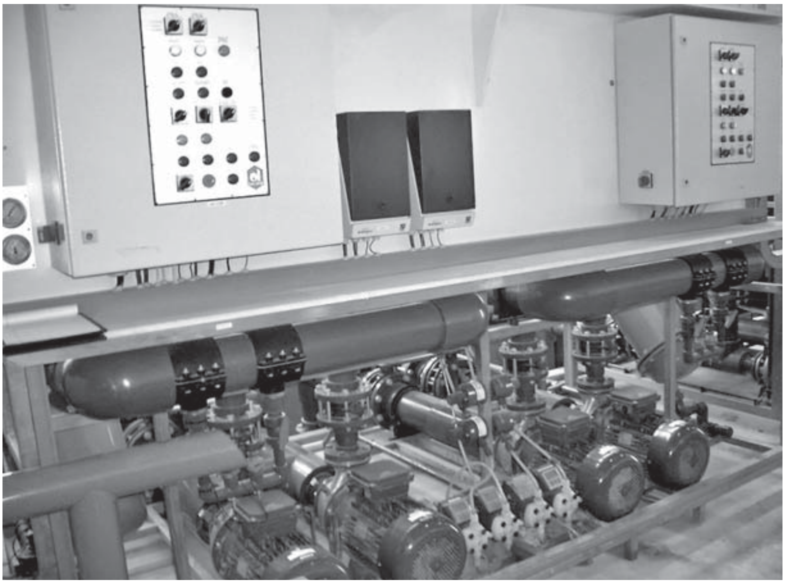

FIGURE 3.15 Fertilizer injector system. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

FIGURE 3.16 Large injector system. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

the amount of ammonium molybdate for a 200× concentration stock solution for a 100-US-gal (378 L) stock tank would be 4.17 g. Such small weights are difficult to measure on a triple-beam balance, which is accurate to 1.0 g. Also, if a nutrient solution is prepared in a storage tank at its final plant formulation without the use of stock solutions, the quantities required for micronutrient compounds are very small and therefore difficult to weigh accurately.

In these cases, it is better to use a highly concentrated stock solution for the micronutrients and store it in an opaque container. Make up a 10- to 20-gal (38- to 75-L) quantity, but not more than you expect to use within several months, as changes may have to be made in the formulation to better suit the plants during different stages of growth. Some sedimentation may occur over this period of time, so agitate the solution with a small aerator with an air diffuser in the solution as described earlier.

To illustrate the derivation of a micronutrient stock solution, the same micronutrient formulation will be used as in the above example. That is, Mn: 0.8 ppm; Cu: 0.07 ppm; Zn: 0.1 ppm; B: 0.3 ppm; and Mo: 0.03 ppm. Note that iron (Fe) is not included in this micronutrient stock solution as sufficient weight of iron is required such that it can be accurately measured on a balance.

The following situation will exemplify the calculations involved in determining the weights of micronutrient compounds and their comparisons to the solubilities for a concentrated stock solution. Prepare a nutrient solution at normal plant strength in a 1,000-US-gal nutrient tank (not a stock solution) and use a 600× strength micronutrient stock solution to supply the micronutrients to this tank. The three-step procedure is as follows:

Step 1. Determine the quantities of each compound needed for the 1,000-US-gal nutrient tank. At this time, only the calculations for the micronutrients will be demonstrated as those for the macronutrients are shown in Section 3.5.2.

Mn: 0.8 ppm (mg/L)

(i) Amount of $MnSO_4$:

$$0.8\ \text{mg/L} \times 4.061\ (\text{Table 3.2 factor}) = 3.25\ \text{mg/L}$$

(ii) Adjust for purity (90%):

$$\frac{100}{90} \times 3.25\ \text{mg/L} = 3.6\ \text{mg/L}$$

(iii) For 1,000-US-gal tank:

$$1{,}000 \times 3.785\ \text{L} = 3{,}785\ \text{L}$$
$$3{,}785 \times 3.6\ \text{mg/L} = 13{,}626\ \text{mg or } 13.6\ \text{g}$$

Cu: 0.07 ppm (mg/L)

(i) Amount of $CuSO_4$:

$$0.07\ \text{mg/L} \times 3.93 = 0.275\ \text{mg/L}$$

(ii) Adjust for purity (98%):

$$\frac{100}{98} \times 0.275\ \text{mg/L} = 0.281\ \text{mg/L}$$

(iii) For 1,000-US-gal tank:

$$3{,}785 \times 0.281\ \text{mg/L} = 1{,}064\ \text{mg or } 1.064\ \text{g}$$

Zn: 0.1 ppm (mg/L)

(i) Amount of $ZnSO_4$:

$$0.1\ \text{mg/L} \times 4.40 = 0.44\ \text{mg/L}$$

(ii) Adjust for purity (90%):

$$\frac{100}{90} \times 0.44\ \text{mg/L} = 0.4889\ \text{mg/L}$$

(iii) For 1,000-US-gal tank:

$$3.785 \times 0.4889\ \text{mg/L} = 1{,}850\ \text{mg or } 1.85\ \text{g}$$

B: 0.3 ppm (mg/L)

(i) Source: H_3BO_3

$$0.3\ \text{mg/L} \times 5.717 = 1.715\ \text{mg/L}$$

(ii) Percent purity (95%):

$$\frac{100}{95} \times 1.715 \text{ mg/L} = 1.805 \text{ mg/L}$$

(iii) For 1,000-US-gal tank:

$$3{,}785 \times 1.805 \text{ mg/L} = 6{,}832 \text{ mg or } 6.83 \text{ g}$$

Mo: 0.03 ppm (mg/L)

(i) Source: ammonium molybdate

$$0.03 \text{ mg/L} \times 1.733 = 0.052 \text{ mg/L}$$

(ii) Percent purity (95%):

$$\frac{100}{95} \times 0.052 \text{ mg/L} = 0.055 \text{ mg/L}$$

(iii) For 1,000-US-gal tank:

$$3{,}785 \times 0.055 \text{ mg/L} = 208.2 \text{ mg or } 0.208 \text{ g}$$

It is clear from these calculations that the amounts are too small to be weighed accurately by a triple-beam balance.

Step 2. Calculate the quantities of each micronutrient compound for a 600× concentration stock solution (use a 10-US-gal stock tank).

Mn: For 0.8 ppm (mg/L), use 3.6 mg/L of $MnSO_4$ (as calculated in (ii) in “Mn: 0.8 ppm (mg/L)”).

(i) For 10-US-gal stock tank:

$$10 \times 3.785 \text{ L} = 37.85 \text{ L}$$
$$37.85 \times 3.6 \text{ mg/L} = 136.26 \text{ mg}$$

(ii) 600× concentration:

$$600 \times 136.26 \text{ mg} = 81{,}756 \text{ mg or } 81.8 \text{ g}$$

(iii) Convert 81.8 g in 37.85 L to g/100 mL and compare it to the solubility limit:

$$\frac{81.8 \text{ g}}{37.85 \text{ L}} = 2.16 \text{ g/L} \quad \text{or} \quad 0.216 \text{ g/100 mL}$$

$$0.216 \text{ g/100 mL versus } 105.3 \text{ g/100 mL}$$

This concentration is well within the solubility range.

Cu: For 0.07 ppm (mg/L), use 0.281 mg/L of $CuSO_4$.

(i) For 10-US-gal stock tank:

$$37.85 \times 0.281 \text{ mg/L} = 10.64 \text{ mg}$$

(ii) 600× concentration:

$$600 \times 10.64 \text{ mg} = 6{,}384 \text{ mg or } 6.4 \text{ g}$$

(iii) Convert to grams per 100 mL:

$$\frac{6.4 \text{ g}}{37.85 \text{ L}} = 0.169 \text{ g/L} \quad \text{or} \quad 0.0169 \text{ g/100 mL}$$

$$0.0169 \text{ g/100 mL versus } 31.6 \text{ g/100 mL}$$

This is within the solubility limit.

Zn: For 0.1 ppm (mg/L), use 0.4889 mg/L of $ZnSO_4$:

(i) For 10-US-gal stock tank:

$$37.85 \times 0.4889 \text{ mg/L} = 18.505 \text{ mg}$$

(ii) 600× concentration:

$$600 \times 18.505 \text{ mg} = 11{,}103 \text{ mg or } 11.1 \text{ g}$$

(iii) Convert to g/100 mL:

$$\frac{11.1 \text{ g}}{37.85 \text{ L}} = 0.2932 \text{ g/L} \quad \text{or} \quad 0.0293 \text{ g/100 mL}$$

0.0293 g/100 mL versus 96.5 g/100 mL (from Appendix 4)

This concentration is well below the solubility limit.

B: For 0.3 ppm (mg/L), use 1.805 mg/L of H_3BO_3.

(i) For 10-US-gal stock tank:

$$37.85 \times 1.805 \text{ mg/L} = 68.32 \text{ mg}$$

(ii) 600× concentration:

$$600 \times 68.32 \text{ mg} = 40{,}992 \text{ mg or } 41 \text{ g}$$

(iii) Convert to grams per 100 mL:

$$\frac{41 \text{ g}}{37.85 \text{ L}} + 1.083 \text{ g/L} \quad \text{or} \quad 0.108 \text{ g/100 mL}$$

$$0.108 \text{ g/100 mL versus } 6.35 \text{ g/100 mL}$$

This level is within the solubility range.

Mo: For 0.03 ppm (mg/L), use 0.055 mg/L of ammonium molybdate.

(i) For 10-US-gal stock tank:

$$37.85 \times 0.055 \text{ mg/L} = 2.082 \text{ mg}$$

(ii) 600× concentration:

$$600 \times 2.082 \text{ mg} = 1{,}249 \text{ mg or } 1.249 \text{ g}$$

(iii) Convert to grams per 100 mL:

$$\frac{1.249 \text{ g}}{37.85 \text{ L}} = 0.033 \text{ g/L or } 0.0033 \text{ g/100 mL}$$

$$0.0033 \text{ g/100 mL versus } 43 \text{ g/100 mL}$$

This is well below the solubility limit.

Step 3. The final step is to calculate the volume of a 600× concentration stock solution in a 10-US-gal tank to add to a 1,000-US-gal nutrient solution to obtain 1× concentration. It must be diluted to a ratio of 1 part of stock solution to 600 parts of water, that is, 600:1. Therefore, for 1 US gal of nutrient solution, 1/600 US gal of 600× stock solution would be required. It is easiest to set up a ratio with one unknown (*x*) as follows:

$$\frac{1.0}{1/600} = \frac{1{,}000}{x} \frac{(1 \times \text{nutrient solution})}{(600 \times \text{stock solution})}$$

$$x = 1{,}000 \times 1/600 \text{ (cross multiply)}$$

$$x = 1{,}000/600 = 1.67 \text{ US gal}$$

Convert to liters:

$$1.67 \text{ US gal} \times 3.785 = 6.308 \text{ L or } 6{,}308 \text{ mL}$$

In summary, 6.308 L of 600× concentration stock solution would be added to the 1,000-US-gal nutrient tank of 1× strength solution. If the nutrient solution had to be prepared once a week, the 10 US gal of 600× stock solution would last for 6 wk. Create a summary table as follows:

Micronutrient Stock Solution 600× in 10-US-Gal Tank

Compound	Weight (g)	Element (ppm)
$MnSO_4$	81.8	Mn: 0.8
$CuSO_4$	6.4	Cu: 0.07
$ZnSO_4$	11.1	Zn: 0.1
H_3BO_4	41.0	B: 0.3
NH_4–Mo	1.25	Mo: 0.03

3.7 PREPARING THE NUTRIENT SOLUTION

The preparation of the nutrient solution will vary depending on the nutrient solution tank volume and whether a normal strength or a stock solution is used.

3.7.1 Preparing Normal Strength Solutions

For small-volume tanks (<2,000 gal), individual fertilizer compounds may be weighed in advance and placed in plastic bags. A felt pen may be used to write the compound formula on each bag to avoid any confusion in its future use. Compounds required in smaller quantities such as grams may be weighed using a triple-beam balance. The micronutrients may be placed in one bag together, with the exception of iron, which should be in a separate bag. The macronutrient compounds should be weighed using a scale capable of 20–30 lb. As mentioned earlier, any compound that is required in an amount less than 1 lb should be weighed using the gram balance. Generally, it is faster if at least five batches are weighed when making up the formulations. Do not make too many as it may be necessary to change the formulation depending on plant growth or weather conditions.

With large-volume tanks, weigh only those fertilizers needed for that batch. Weigh each fertilizer salt separately, arranging them in piles on polyethylene sheets or in buckets so that there is no loss. This should be done accurately to within ±5% using either a gram scale or a pound scale depending on the weights required of each.

Continue using the following procedure:

1. Fill the nutrient solution storage tank with water to about one-third full.
2. Dissolve each fertilizer salt individually in a 5-gal bucket of water. Add the water to the fertilizer and stir vigorously. Use a hose and nozzle to assist in mixing. Usually, the entire amount of fertilizer will not dissolve on the first addition of water. Pour off the dissolved liquid portion into the storage tank and repeat adding water, stirring and canting off the dissolved portion until the entire salt has entered the solution. Use hot water with salts that are hard to dissolve.
3. Dissolve the macronutrients first, then the micronutrients.
4. In small systems such as backyard greenhouses, the sulfates can be mixed together in the dry form before dissolving, for example, K_2SO_4, $MgSO_4$. Then the nitrates and phosphates can be mixed in dry form before dissolving, for example, KNO_3, KH_2PO_4. Add $Ca(NO_3)_2$ last.
5. With larger systems, add potassium sulfate first. For better mixing, operate the irrigation pump of the nutrient solution system with the bypass valve fully open and the valve to the greenhouses closed. Keep the pump circulating the nutrient solution in the storage tank until all of the solution is prepared.
6. Fill the tank to at least half, but no more than two-thirds, and then add potassium nitrate.
7. Fill the tank to three-quarters, and then add magnesium sulfate and monopotassium phosphate.
8. Add calcium nitrate slowly while circulating the solution.
9. Add the micronutrients with the exception of iron chelate.
10. Check the pH of the nutrient solution and adjust, if necessary, with either sulfuric acid (H_2SO_4) or potassium hydroxide (KOH). High pH (more than 7.0) causes precipitation of Fe^{2+}, Mn^{2+}, PO_4^{3-}, Ca^{2+}, and Mg^{2+} as insoluble and unavailable salts.

11. Add the iron chelate (FeEDTA), and top up the tank to the final volume.
12. Check the pH and adjust it between 5.8 and 6.4 depending on the crop's optimum pH level.
13. If a closed recirculating hydroponic system is being used, circulate the nutrient solution through the system for 5–10 min, check the pH again, and adjust it again if necessary.

3.7.2 Preparing Stock Solutions

When preparing stock solutions, larger weights of each compound will be required, so prepare only one batch of solution. Weigh each compound separately. Often whole sacks (50 or 100 lb) will be used, so only weigh the additional amount needed. For example, if 414 lb of magnesium sulfate is one component, use eight 50-lb or four 100-lb bags and then weigh out the additional 14 lb on a scale.

If 5-gal buckets are being used to dissolve the fertilizer salts, fill the bucket only to one-third capacity to allow sufficient water to dissolve the compound. By using 15–20 buckets, one person can steadily be dissolving the fertilizer while another pours off the solution into the storage tank. Another method, other than using buckets, is to have a mixing tank with a circulation pump to mix each fertilizer separately; once dissolved, pump the solution into the stock-solution storage tank as shown in Figure 3.17. When mixing, be careful not to use more water than the stock tank can hold.

When making up stock solutions, do not add a lot of water to the stock tank before beginning the mixing process, or the final volume may be exceeded in the dissolution process alone.

Add only half of the potassium nitrate to each stock tank.

For stock A, the sequence of adding the fertilizers is as follows: half of the potassium nitrate, then calcium nitrate, ammonium nitrate, and finally iron chelate after adjusting the

FIGURE 3.17 Mixing tanks with pumps to stock tanks. (From California Watercress, Inc., Fillmore, CA. With permission.)

pH to about 5.5. Top up the tank with water to within 10 gal of the final solution level before adjusting the pH and adding the iron chelate.

For stock tank B, the sequence is as follows: the other half of the potassium nitrate and then potassium sulfate. Fill the tank to three-quarters, and then continue adding magnesium sulfate and monopotassium phosphate. Adjust the pH to about 5.5 after topping up the tank with water to within 30 gal of the final level, then add the micronutrients. Finally, check the pH again and adjust it if necessary.

The acid tank C is made up last using one of the acids described earlier. Fill the acid tank to three-quarters with water before adding the acid to the water. After stirring with a plastic pipe, top up the tank slowly with water to the final level. Should you need to use a base, such as potassium hydroxide, to increase the pH, follow the same procedure. Be very careful with these strong acids or bases as they burn badly; wear a protective face mask and gloves when using them.

3.8 PLANT RELATIONS AND CAUSE OF NUTRIENT SOLUTION CHANGES

In a cyclic (closed) system in which the nutrient solution is drained back to the reservoir after use, the life of the nutrient solution is 2–3 wk, depending on the season of the year and the stage of plant growth. During the summer months, for mature high-yielding plants, the nutrient solution may have to be changed as often as every week. The reason for changing the solution is that plants differentially absorb the various elements. This results in short supply of some elements before others. Just how deficient they are at any point can be determined only by atomic absorption analyses of the nutrient solution. Such analyses can be done only in costly laboratory facilities. Consequently, many people are unable to carry out such analyses. The only safeguard against a nutrient disorder then is to change the solution periodically. In some cases, it is possible to add partial formulations between changes, but this is only by trial and error and can result in excess buildup of nutrient salts that are taken up by the plant at relatively low rates.

The relative uptake of the various mineral elements by the plant is affected by the following:

1. Environmental conditions: temperature, humidity, and light intensity
2. Nature of the crop
3. Stage of plant development

As a result of the differential uptake of the various elements, the composition of the nutrient solution changes constantly. Some of the elements are depleted more rapidly than others, and the concentration is increased by the plants' relatively greater absorption of water than of salts. In addition to changes in salt composition, the pH also changes as a result of reactions with the aggregate and the unbalanced absorption of the anions and cations from the solutions.

3.8.1 NUTRIENT ANALYSIS

Before replacing mineral elements, it is necessary to determine their concentration by chemical methods of analysis in order to determine the quantities absorbed by the plant.

The difference in concentration of the mineral elements from the time of first mixing the nutrient solution to that at the time of analysis tells how much of each element must be added to bring the concentration to its original level.

Besides testing the solutions for depletions, it is necessary to test for the accumulation of unused ions such as sodium, sulfate, or chloride or for the presence of excess of toxic elements such as copper or zinc.

3.8.2 PLANT TISSUE ANALYSIS

By conducting both plant tissue and nutrient solution analyses, we can compare and relate plant physiological upsets to imbalances of various mineral elements in the nutrient solution. It is possible to control the changes in the nutrient solution once a precise relationship is established between fluctuations in mineral elements in the plant tissue and those in the nutrient solution. Then the nutrient solution should be adjusted before visual symptoms appear in the plant tissue. This would prevent any mineral stress from occurring within the plant and thus increase yields by allowing the plant to grow under optimum mineral nutritional conditions.

An advantage of tissue analysis over nutrient analysis is that tissue analysis indicates what has been or is being absorbed from the nutrient solution by the plant, whereas nutrient analysis indicates only the relative availability of nutrients to the plant. Actual uptake of essential elements may be restricted by conditions of the medium, solution, environmental factors, or the plant itself. For instance, if the medium is not inert and reacts with the nutrient solution, ions may be retained by the particles and become unavailable to the plant. Imbalances within the nutrient solution or fluctuating pH levels will reduce uptake by the plants. Diseases or nematodes in the roots of plants would reduce their absorption capacity for nutrients. Environmental factors such as insufficient light, extremes in temperatures, and insufficient carbon dioxide levels will prevent plants from efficiently utilizing the available nutrients in the solution. Plant tissue analysis measures the effects of these conditions on nutrient uptake.

The use of tissue analysis in relating the nutrient status of a plant is based on the fact that normal, healthy growth is associated with specific levels of each nutrient in certain plant tissues. Since these normal levels are not the same for all tissues in any plant or for all species, it is necessary to select an indicator tissue that is representative of a definite stage of growth. Generally, a young, vigorous leaf near the growing point of the main stem of the plant is selected. It is more reliable to take samples at various stages of growth than to concentrate on a large number of samples at any one stage since the concentration of most nutrients decreases as the plants age and mature.

To accurately relate tissue analysis results to nutritional requirements of plants, considerable data must be available on optimum levels of nutrients in specific plant species and tissues to be compared. This information is available for greenhouse lettuce, tomatoes, and cucumbers (Table 3.8). The indicator tissue for tomatoes is the fifth leaf down from the growing tip of the main stem, and it includes both petiole and blade tissue. At least 10 samples should be taken of only one variety under one fertilizer treatment. The indicator tissue for cucumbers is a young leaf, without petiole, about 10 cm (4 in.) in diameter, usually the third visible leaf from the top of the main stem. A representative sample should consist of 10 uniform replicates. The leaves should be either oven dried (70°C for 48 h) or delivered promptly in a fresh condition to a commercial laboratory. Before drying, the blades should

TABLE 3.8
Range of Nutrient Levels in Tissues of Apparently Healthy Plants

Element	Tomatoes	Cucumbers	Lettuce
N%	4.5	5.25	4.3
	4.5–5.5	5.0–6.0	3.0–6.0
P%	0.7	0.75	1.0
	0.6–1.0	0.7–1.0	0.8–1.3
K%	4.5	4.75	5.4
	4.0–5.5	4.5–5.5	5.0–10.8
Ca%	1.5	3.0	1.5
	1.5–2.5	2.0–4.0	1.1–2.1
Mg%	0.5	0.75	0.42
	0.4–0.6	0.5–1.0	0.3–0.9
Fe (ppm)	100	125	120
	80–150	100–150	130–600
B (ppm)	50	40	32
	35–60	35–60	25–40
Mn (ppm)	70	70	70
	70–150	60–150	20–150
Zn (ppm)	30	50	45
	30–45	40–80	60–120
Cu (ppm)	5	8	14
	4–6	5–10	7–17
Mo (ppm)	2	2	2–3
	1–3	1–3	1–4
N:K ratio	1.0	1.1	0.8
	0.9–1.2	1.0–1.5	—

be separated from the petioles. Analysis for NO_3—N, PO_4—P, K, Ca, and Mg are usually performed on the petioles and for minor elements on the blades.

To examine the results, the date of planting, stage of growth, and previous fertilizer treatment must be known. A weekly series of tests will indicate clearly the trends in any nutrient level. A combination of nutrient and tissue analysis will allow the grower to anticipate any problems before they occur and make the necessary adjustments in the nutrient solution formulation.

3.8.3 Changing of Solutions

Work by Steiner (1980) on nutrient solutions indicates that if the ratios of nutrient uptake for a certain crop under given conditions are known, ions can be applied continuously to the solution in these mutual ratios, controlled only by a conductivity meter. While generally this is true, extended use of the same nutrient solution may result in accumulation of toxic quantities of minor elements such as zinc and copper from fertilizer impurities, or from the water itself.

The useful life of a nutrient solution depends principally on the rate of accumulation of extraneous ions, which are not utilized by the plants at rapid rates. Such an accumulation results in a high osmotic concentration of the nutrient solution. An EC device, commercially available, should be used to determine the rate at which the nutrient solution becomes concentrated. Determinations should be made on a new nutrient solution and then repeated after each makeup with nutrient salts. As the total salt level increases, it will more readily conduct an electric current. The unit of measurement used to express conductance is a mho. For simplicity, conductivity is often expressed as millimhos (mmho) per centimeter, with the desired range being 2.00–4.00. Salt levels above 4 mmhos/cm may result in wilting, suppressed growth, and fruit cracking. [1 mmho/cm = 1 milliSiemen/cm (mS/cm).]

The total concentration of elements in a nutrient solution should be between 1,000 and 1,500 ppm so that osmotic pressure will facilitate the absorption processes by the roots. This should correspond to total salt conductivity readings between 1.5 and 3.5 mmhos. In general, the lower values (1.5–2.0 mmho) are preferred for crops such as cucumbers, while higher values are better for tomatoes (2.5–3.5 mmho). (A conductance of 1 mmho/cm is approximately equal to 650 ppm of salt.)

While in the past we recommended complete replacement of nutrient solutions after 2 mo, new systems of sterilization in recirculating systems and computer monitoring and adjusting of the solutions for ions and pH have favored keeping the solutions much longer. This has come about because of the need to conserve water and lessen contamination of the environment, groundwater, and surface water, especially in countries such as Holland (Van Os, 1994). But this is possible only with very pure raw water sources or after water treatment by reverse osmosis (RO) to eliminate extraneous trace elements and sodium chloride.

Closed (recirculating) systems always run the risk of infection, so efficient disinfection must be part of the system. Disinfection is a combination of pasteurization, slow sand filtration (biofiltration), UV radiation, and other methods.

Pasteurization is used mainly in vegetable crops and is effective against nematodes, fungi, bacteria, and viruses. In the process, the drain water is heated to 95°C–97°C (203°F–207°F) for 30 s. It is then pumped to a disinfected water tank and then diluted with new nutrient solution in a mixing tank.

Slow sand filters are used mainly in flowering and potted plants. UV radiation (Figure 3.13) can be used with slow sand filters (Figure 3.14) as the prefiltration method before passing through the UV sterilizer as all color caused by organic compounds must be removed before the UV treatment. Injection of hydrogen peroxide (1 mmol/L) improves the efficiency of UV treatment (Runia and Boonstra, 2004). Extra iron has to be added downstream because of the degradation of iron chelates by UV. UV does not kill all pathogens or viruses.

The disinfection system is part of the overall irrigation–injection system as shown in Figure 3.18. Disinfected water makes up about 30% of the irrigation water. This disinfected water is stored in an opaque tank and from there it is mixed with raw water and nutrients in the mixing tank before returning to the greenhouse irrigation system. In large greenhouses, enough nutrient solution is mixed for daily use and stored in a day stock tank. In this way, adjustments can be made in the formulation on a daily basis, depending on changes in weather, crop stage of growth, and growing balance between vegetative and generative phases.

3.8.4 ADJUSTMENT OF NUTRIENT SOLUTIONS BY USE OF ELECTRICAL CONDUCTIVITY

Total dissolved solutes (TDS) instruments, which determine the dissolved solids in water, are basically water conductivity measuring instruments. The quantity of dissolved solids

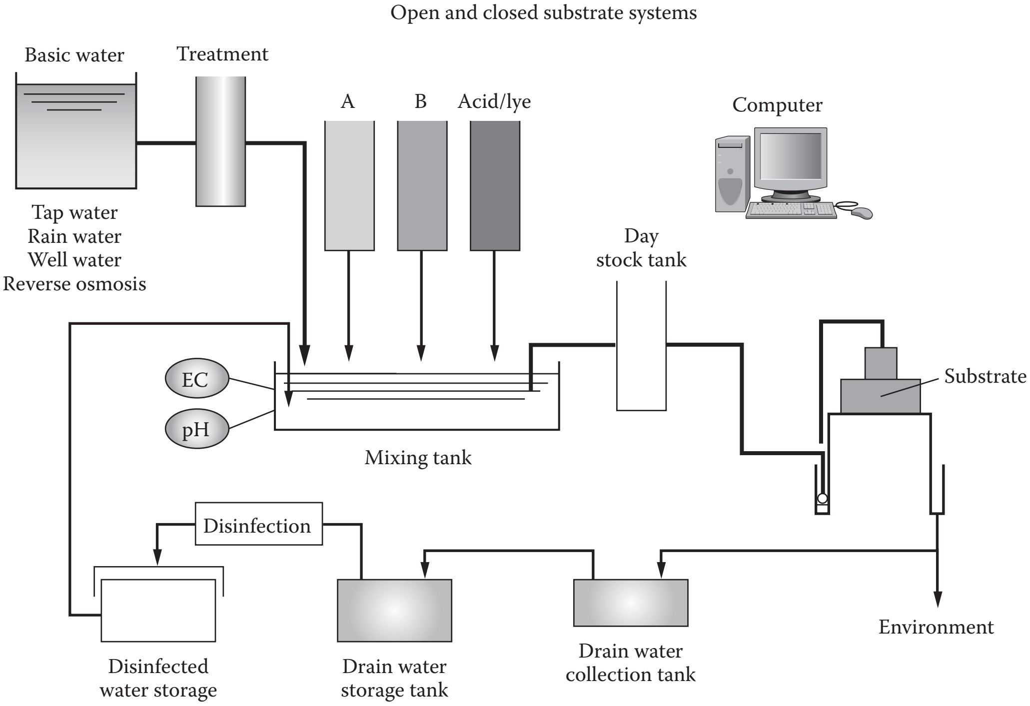

FIGURE 3.18 Overview of a complete disinfection–injection–irrigation system. (Adapted from K. Welleman, The Netherlands. *6th Curso Y Congreso Internacional de Hidroponia en Mexico*. Toluca, Mexico, April 17–19, 2008a. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

in parts per million (ppm) or milligrams per liter by weight is directly proportional to conductivity in millimhos per unit volume. However, the EC varies not only with the concentration of salts present but also with the chemical composition of the nutrient solution. Some fertilizer salts conduct electric current better than others. For instance, ammonium sulfate conducts twice as much electricity as calcium nitrate and more than three times that of magnesium sulfate, whereas urea does not conduct electricity at all. Nitrate ions do not produce as close a relationship with EC as do potassium ions (Alt, 1980). The higher the nitrogen to potassium ratio, the lower will be the EC values for the nutrient solution. EC measures total solutes; it does not differentiate among the various elements. For this reason, while a close theoretical relationship exists between TDS and EC, standard solutions of a nutrient formulation should be measured to determine their correlation in a given solution. For example, in Table 3.9, a 666-ppm TDS is equivalent to 1.0 mmho, which is the measurement of a solution containing 490 ppm of sodium chloride or 420 ppm of calcium carbonate. That is, a 490-ppm solution of sodium chloride or a 420-ppm solution of calcium carbonate gives an EC reading of 1.0 mmho.

Table 3.9 relates the concentration of sodium chloride and calcium carbonate with conductivity. A list of conductivities for 0.2% solution (2 g of fertilizer in 1 L of distilled water) of various fertilizers is given in Table 3.10.

Conductivities for various concentrations of calcium nitrate are outlined in Table 3.11. These conductivity standards should be used to derive a theoretical relationship between

TABLE 3.9
Relationship between Total Dissolved Solutes (TDS) and Electrical Conductivity (EC) for Sodium Chloride and Calcium Carbonate Solutions

TDS (ppm)	EC (mmho)	NaCl (ppm)	$CaCO_3$ (ppm)
10,000	15	8,400	7,250
6,600	10	5,500	4,700
5,000	7.5	4,000	3,450
4,000	6	3,200	2,700
3,000	4.5	2,350	2,000
2,000	3	1,550	1,300
1,000	1.5	750	640
750	1.125	560	475
666	1	490	420
500	0.75	365	315
400	0.6	285	250
250	0.375	175	150
100	0.15	71	60
66	0.10	47	40
50	0.075	35	30
40	0.06	28	24
25	0.0375	17.5	15
6.6	0.01	4.7	4

TABLE 3.10
Conductivity (EC) of 0.2% Solution in Distilled Water

Fertilizer Compound	EC (mmho)
$Ca(NO_3)_2$	2.0
KNO_3	2.5
NH_4NO_3	2.9
$(NH_4)_2SO_4$	3.4
K_2SO_4	2.4
$MgSO_4 \cdot 7H_2O$	1.2
$MnSO_4 \cdot 4H_2O$	1.55
NaH_2PO_4	0.9
KH_2PO_4	1.3
HNO_3	4.8
H_3PO_4	1.8

conductivity and TDS. Actual conductivity measurements for fertilizers may vary somewhat from those in Tables 3.10 and 3.11 because of the solubility and purity of the particular fertilizer source. If EC readings are not taken at the standard temperature of 25°C, a correction factor must be used (Table 3.12). Many conductivity meters have a built-in temperature compensation, which automatically makes the necessary adjustment.

TABLE 3.11
Conductivity (EC) of Various Concentrations of Calcium Nitrate in Distilled Water

Concentration (%)	EC (mmho)
0.05	0.5
0.1	1.0
0.2	2.0
0.3	3.0
0.5	4.8
1.0	9.0

TABLE 3.12
Temperature Factors for Correcting Conductivity Data to Standard Temperature of 25°C

Degree Centigrade	Degree Farenheit	Temperature Factor
5	41.0	1.613
10	50.0	1.411
15	59.0	1.247
16	60.8	1.211
17	62.6	1.189
18	64.4	1.163
19	66.2	1.136
20	68.0	1.112
21	69.8	1.087
22	71.6	1.064
23	73.4	1.043
24	75.2	1.020
25	**77.0**	**1.000**
26	78.8	0.979
27	80.6	0.960
28	82.4	0.943
29	84.2	0.925
30	86.0	0.907
31	87.8	0.890
32	89.6	0.873
33	91.4	0.858
34	93.2	0.843
35	95.0	0.829
40	104.0	0.763
45	113.0	0.705

Source: From *Saline and Alkali Soils*, U.S. Salinity Laboratory Staff, Agricultural Handbook, 1954, No. 60, p. 90.

Several plant laboratories capable of analyzing nutrient solutions are listed in Appendix 2. In addition, many universities are prepared to do such analyses.

The management of nutrient solutions through the use of EC applies particularly to closed systems of nutrient film technique (NFT) and subirrigation. However, it can be used to monitor open systems having large storage tanks of solution rather than those using proportioners.

Today, all modern greenhouses with hydroponic systems are reusing the leachate and operating as closed systems with pH and nutrient solution concentration monitored by pH and EC meters that feedback to a central computer controller that adjusts the return solution with injectors from stock tanks of acid/base and concentrated nutrient solutions (stock solutions) as discussed above in Sections 3.6.2 and 3.8.3.

3.8.5 MAINTENANCE OF SOLUTION VOLUME

The solution volume must be kept relatively constant in order to secure adequate plant growth. Plants take up much more water than the essential elements, and at a much greater rate. As water is removed from the nutrient solution, the volume of the solution naturally decreases. This effects an increase in the total solution concentration and in the concentration of the individual nutrient ions.

The average daily water loss can range from 5% to 30%, depending on the volume of the unit and the number and type of plants. Water to compensate for this loss can be added daily as long as the solution is used. Using NFT systems, workers can more accurately determine the rate of water uptake by plants. In England, Spensley and coworkers (1978) found that on a clear summer day fully grown tomatoes consumed 1.33 L (1/3 gal) of water per plant. Winsor and associates (1980) determined that tomato plants lost through evapotranspiration 15 mL/plant/h during the night, rising to a maximum of 134 mL/plant/h at midday on a clear summer day. Adams (1980) calculated that cucumbers consumed water at approximately twice the rate for tomatoes because of their greater leaf area. Water uptake reached a maximum of 230 mL per plant per hour during maximum light intensity and temperatures of the afternoon. A rule-of-thumb estimate of water usage in a greenhouse is about 1 L/ft^2/d for vine crops such as tomatoes and cucumbers. Experienced commercial growers can add water weekly, or they can attach an automatic float valve assembly to the inlet valve to the nutrient tank, which will fill it daily. When water is added weekly, water in excess of the original volume of the solution is introduced. The solution is then allowed to concentrate as the plants remove water to below the original solution level. Usually, the best procedure is to allow the solution volume to fluctuate equally on both sides of the original level. It follows that a solution testing technique must be used in conjunction with the method of regulation of the solution volume. This applies to closed systems in which the solution is recirculated to a nutrient tank or cistern.

Most greenhouses today, however, as described earlier in Section 3.8, use return storage tanks, treatment systems, and storage of treated solution. From there as it returns to the plants it is monitored and adjusted by injection systems. This system is a dynamic flow-through system, so the adjusted nutrient solution is not stored before returning to the plants as it is in some NFT systems and simplified cistern return tanks as described above. This blended raw water (about 70%) and treated return solution (30%) from storage tanks enters an injection loop on its way back to the plants.

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4 The Medium

A soilless medium, such as water, foam, gravel, rockwool, sand, sawdust, peat, coco coir, perlite, pumice, peanut hulls, polyester matting, or vermiculite, must provide oxygen, water, nutrients, and support for plant roots just as soil does. The nutrient solution will provide water, nutrients, and, to some extent, oxygen. How each of these soilless cultural methods satisfies plant needs is discussed in detail in the chapters to follow.

4.1 MEDIUM CHARACTERISTICS

Moisture retention of a medium is determined by particle size, shape, and porosity. Water is retained on the surface of the particles and within the pore space. The smaller the particles, the closer they pack, the greater the surface area and pore space, and hence the greater the water retention. Irregular-shaped particles have a greater surface area and hence higher water retention than smooth, round particles. Porous materials can store water within the particles themselves; therefore, water retention is high. While the medium must be capable of good water retention, it must also be capable of good drainage. Therefore, excessively fine materials must be avoided so as to prevent excessive water retention and lack of oxygen movement within the medium.

The choice of medium will be determined by the availability, cost, quality, and type of hydroponic method. A gravel subirrigation system can use very coarse material, whereas a gravel trickle-irrigation system must use a finer material (Chapter 7).

The medium must not contain any toxic materials. Sawdust, for example, often contains high sodium chloride content because of logs having remained in salt water for a long period. The salt content must be tested, and if any amount of sodium chloride is present, it will be necessary to leach it through with fresh water. Similarly, coco coir, which comes from coconut trees, often contains high concentrations of sodium chloride when its source comes from trees near the ocean. Most coco coir sold as a substrate for hydroponic culture is treated to remove the salt. If not, it must be soaked well in clean raw water to leach out the sodium chloride. This can usually be done by soaking it in good quality water for a number of hours and then flushing several times with new water. Drain the coco coir well after soaking in water to remove the sodium and chloride.

Gravel and sand of calcareous (limestone) origin should be avoided. Such materials have a very high content of calcium carbonate ($CaCO_3$), which is released from the medium into the nutrient solution, resulting in high pH. This increased alkalinity ties up iron, causing iron deficiency in plants. Such materials can be pretreated with water leaching or acid leaching or by soaking in a phosphate solution. This will buffer the release of carbonate ions. Nonetheless, this procedure is only a short-term solution, and eventually nutritional problems will arise. This problem makes gravel and sand culture very difficult in some areas, such as the Caribbean, where the materials are all of calcareous origin. The best gravel or sand is that of igneous (volcanic) origin.

The media must be of sufficient hardness in order to be durable for a long time. Soft aggregates that disintegrate easily should be avoided. They lose their structure and their particle size decreases, which results in compaction leading to poor root aeration. Again, aggregates of granitic origin are best, especially those high in quartz, calcite, and feldspars. If a hydroponic system is to be set up outdoors, particles having sharp edges should be avoided, since wind can abrade the plant stem and crown against them, leading to injury and a port of entry for plant parasites. If a relatively sharp medium must be used, the top 2 in. (5 cm) should consist of a smooth-edged medium so that the area where most plant movement takes place will be protected from abrasion.

Igneous gravel and sand have little influence on the nutrient solution pH, whereas calcareous material will buffer the nutrient solution pH at about 7.5. Treatment with phosphate solutions can bring the pH down to 6.8 (Chapter 7).

4.2 WATER CHARACTERISTICS

Water quality is of prime concern in hydroponic growing. Water with a sodium chloride content of 50 ppm or greater is not suitable for optimum plant growth. As sodium chloride content is increased, plant growth is restricted; high levels result the in death of the plant. Some plants are less sensitive to salt levels than others. For instance, herbs such as watercress and mint tolerate higher levels of sodium and chloride than do tomatoes and cucumbers. The levels of sodium chloride and other extraneous ions present in raw water as a source for a nutrient solution becomes even more critical in closed (recirculation) systems. These systems add raw water to the return solution to make up for the loss due to evapotranspiration by the plants. With continued addition of raw water, more ions will be added if the raw water contains significant levels, which will eventually lead to toxicity.

Hardness is a measure of the carbonate ion (HCO_3^-) content. As mentioned earlier, as hardness increases (pH increases), certain ions such as iron become unavailable. In particular, ground water that lies in calcareous and dolomitic limestone strata could contain high levels of calcium and magnesium carbonate, which may be higher than or equal to the normal levels used in the nutrient solution.

Hard water contains salts of calcium and magnesium. Normally such waters are just as suitable as soft water for growing plants. Both calcium and magnesium are essential nutrient elements, and ordinarily the amount present in hard waters is much less than that used in nutrient solutions. Most hard waters contain calcium and magnesium as carbonates or sulfates. While the sulfate ion is an essential nutrient, carbonate is not. In low concentrations, carbonate is not injurious to plants. In fact, some carbonate and/or bicarbonate in the raw water is helpful in stabilizing the pH of the nutrient solution. The carbonate or bicarbonate found in most waters causes the pH to rise or remain high. With the presence of these ions, the pH resists dropping.

This stabilizing effect is called *buffering capacity*. Smith (1987) advises taking advantage of this buffering action on pH by maintaining the carbonate/bicarbonate level at about 30–50 ppm, which is sufficient to prevent sudden fluctuations in pH. With very pure raw water, having little or no carbonate or bicarbonate, he suggests adding some potassium carbonate or bicarbonate to obtain this level to improve the buffering capacity.

Before any water is used, an analysis should be made for at least calcium, magnesium, iron, boron, molybdenum, carbonate, sulfate, and chloride. If a commercial hydroponic complex is being planned, water should be analyzed for all major and minor elements. Once the level of each ion has been determined, correspondingly less of each of these elements should be added to make up the nutrient solution. For example, the magnesium concentration of some well waters is so high that it is not necessary to add any to the nutrient solution. In some cases, boron may be excessively high (normal required is 0.30 mg/L) up to 2–3 times or more; then it must be removed through reverse osmosis (RO) treatment of the water.

The naturally occurring dissolved salts in the water accumulate with the additions of makeup water. Over a period of time, this buildup will exceed the optimum levels for plant growth, and the nutrient solution will have to be changed to avoid injuring the plants.

The concentration of salts in a nutrient solution may be specified in terms of parts per million (ppm), millimolar (mM), and milliequivalents per liter (mequiv/L). Parts per million, as mentioned in Chapter 3, is based on a specified number of units by weight of salt for each million parts of solution. The millimolar unit of concentration involves the molecular weight of the substance. One mole of a substance is a weight in grams numerically equal to the molecular weight and commonly called *gram molecular weight*. A solution of one molar concentration has 1 mol of the substance dissolved in 1 L of solution. A millimolar concentration is 1/1,000 as concentrated as one molar concentration and amounts to 1 mol in 1,000 L of solution.

Solutions of both KNO_3 and KCl would have the same number of potassium ions, and the number of chloride ions in one solution would be the same as that of nitrate ions in the other. In the absorption of nutrients, it is the concentration of ions and not the weight of the element or ion that is of significance.

When bivalent ions are present in a compound, it is better to use milliequivalents per liter. Milliequivalents per liter is similar to the millimolar unit, but involves gram equivalents instead of the mole or gram molecular weight. The gram equivalent is the gram molecular weight divided by the valency (number of charges on the ion). The gram equivalent of a salt such as KCl, which consists of singly valent ions (K^+, Cl^-), is numerically the same as the mole, but where there are bivalent ions (SO_4^{2-}), as in potassium sulfate (K_2SO_4), a gram equivalent would contain numerically only half as much as a mole. Thus two solutions, K_2SO_4 and KCl, having the same milliequivalents per liter concentration, would have in solution the same concentration of potassium ions but half as many sulfate ions (SO_4^{2-}) as chloride ions (Cl^-).

Use of milliequivalents per liter is the most meaningful method of expressing the major constituents of water. This is a measure of the chemical equivalence of an ion.

The total concentration of a nutrient solution or water source is occasionally specified in terms of its potential osmotic pressure. It is a measure of the availability or activity of the water. The osmotic pressure difference between cells usually determines the direction in which water will diffuse. The osmotic pressure is proportional to the number of solute particles in solution and depends on the number of ions per unit volume for inorganic materials. Osmotic pressure is usually given in atmosphere units, where 1 (atm) atmosphere is 14.7 lb/in.^{2} or 101.3 kPa (kilopascals).

In summary,

$$1\,\text{molar}\,(\text{M}) = \frac{\text{M.W.}}{1\,\text{L}}$$

For example, for KNO_3, M.W. = 101

$$1\,\text{M} = \frac{101\,\text{g}}{1\,\text{L}}$$

For KCl, M.W. = 74.6

$$1\,\text{M} = \frac{74.6\text{ g}}{1\text{L}}$$

$$1\text{ millimolar (mM)} = \frac{\text{M.W.}}{1{,}000\text{ L}}$$

For KNO_3,

$$1\text{ mM} = \frac{101\text{ g}}{1{,}000\text{ L}}$$

$$10\text{ mM} = \frac{1{,}010\text{ g}}{1{,}000\text{ L}}$$

For KCl,

$$1\text{ mM} = \frac{74.6\text{ g}}{1{,}000\text{ L}}$$

$$10\text{ mM} = \frac{746\text{ g}}{1{,}000\text{ L}}$$

where M.W. = molecular weight of the compound.

$$1\text{ equivalent (equiv)} = \frac{\text{M.W.}}{\text{Valence}}$$

For example, for K_2SO_4, M.W. = 174.3, valence = 2

$$1\text{ equiv} = \frac{174.3}{2} = 87.15$$

$$1\text{ milliequivalent (mequiv)} = \text{equiv}/1{,}000$$

For example, for K_2SO_4, $\text{mequiv} = \frac{87.15}{1{,}000} = 0.08715$

$$1\text{ milliequivalent/L (mequiv/L)} = \text{mequiv} = \text{equiv}/1{,}000\text{ L}$$

$$1\text{ mequiv/L} = \frac{\text{ppm}}{\text{equiv}}$$

For example, 100 ppm of SO_4^{2-}: equivalence of SO_4^{2-} is 96/2 = 48; mequiv/L = 100/48 = 2.08.

The use of saline water for hydroponic growing of crops has been investigated by several workers (Schwarz, 1968; Victor, 1973). The possibilities of using saline water of 3,000 ppm total salt were investigated by Schwarz (1968). Salt tolerance of varieties, stage of development, addition of nutrients absent in the raw water, and frequency of irrigation are some factors to be considered in using saline water. The concentration expressed by 0.4 atm osmotic pressure was recommended as the best for good development of tomato plants in tropical areas (Steiner, 1968).

Saline waters are those containing sodium chloride. Highly saline water can be used for hydroponics, but a number of considerations are involved. Plants that can be grown are limited to salt-tolerant and moderately salt-tolerant species, such as carnation, tomato, cucumber, and lettuce. Even among salt-tolerant species, one variety may be more tolerant than another. A grower should conduct his own varietal trials to determine the most salt-tolerant varieties. Today, however, with readily available RO equipment, it is better to remove the salts from the water using this method, especially when planning a commercial greenhouse.

Salt tolerance is also dependent on plant growth stage. No mature cucumber plants have yet been shown to adapt gradually to saline conditions; however, Schwarz (1968) points out that cucumbers started in nonsaline conditions may be irrigated with solutions of gradually increasing salinity until the desired level is reached. The younger the plant, the easier it adapts to saline conditions. Schwarz (1968) reported that tomatoes and cucumbers generally take about 20% longer to germinate under saline than under nonsaline conditions.

Depending on the species and variety and on the salinity of nutrient solutions, yields may be lowered by 10%–25% under saline conditions. Schwarz (1968) reported yield reductions of 10%–15% in tomatoes and lettuce and 20%–25% in cucumbers grown with water containing 3,000 ppm salts.

The total solute concentration (high osmotic pressure), by leading to a reduction in water uptake, is responsible for the inhibitory effect of saline solutions on plant growth. Schwarz (1968) found that extremely high osmotic pressures (over 10 atm) for short periods are less damaging than long periods of moderately high pressures (4–5 atm). Symptoms of salt toxicity are general stunting of growth with smaller and darker green leaves, marginal leaf burn, and bluing and bleaching of the plant tissues.

Salinity may inhibit the uptake of certain ions. High sulfate concentrations promote the uptake of sodium (leading to sodium toxicity), decrease the uptake of calcium (leading to calcium deficiency, especially in lettuce), and interfere with potassium uptake. High calcium concentrations in nutrient solutions also affect potassium uptake. High total salt contents are thought to affect calcium uptake, leading to “blossom-end rot” symptoms in tomatoes. Saline conditions reduce the availability of certain microelements, especially iron, so that additional iron must be added. In addition to chloride and sodium toxicity, boron toxicity is relatively common with some saline waters.

Schwarz (1968) reported that saline waters have some favorable effects on cucumbers and tomatoes in giving them a sweeter taste than those grown with freshwater solutions. Lettuce heads are generally more solid, and carnations are longer lasting. Plants grown in saline solutions apparently have a much higher tolerance to zinc and copper, so that zinc and copper levels previously considered toxic may be present without causing injury.

4.3 IRRIGATION

The frequency of irrigation cycles depends on the nature of the plant; plant stage of growth; weather conditions (greenhouses), particularly light intensity, day length, and temperatures; and type of medium.

Plants that are more succulent with an abundance of leaves require more frequent irrigation, as they lose water rapidly through evapotranspiration from their leaves. The greater the leaf area, the more water they will consume. As plants mature, producing a large canopy of leaves and developing fruit, their water demand increases.

Under greenhouse conditions of high light intensity, generally accompanied by high temperatures, especially during summer months, the evapotranspiration rate of plants is greatly increased, and as a result water uptake also increases significantly. As pointed out in Section 3.8.5, researchers have found that a mature cucumber plant may take up as much as 230 mL of water per hour during midday conditions.

Water retention of the medium is a factor that determines the frequency and duration of irrigation. Finer media such as coco coir, peat, foam, or rockwool will retain more moisture than coarser ones such as sawdust, perlite, vermiculite, sand, or gravel. A water culture system, such as the nutrient film technique (NFT), must flow continuously to provide adequate water. In this case, only the plant root mat contains a small amount of residual moisture should the flow of solution be interrupted. Coarse aggregates may need watering as often as once every hour during the day, while fine media such as coco coir and peat could get by on 1–2 irrigations per day under similar conditions.

Both the frequency and duration of irrigation cycles are important. The frequency of the cycles must be sufficient to prevent any water deficit for the plants between cycles, but the cycle must be long enough to provide adequate drainage of the medium so that proper oxygenation of plant roots occurs.

Wilting of plants indicates possible water deficit. However, root dieback caused by diseases, pests, or lack of oxygen can also cause wilting, so the health of the roots should always be examined when wilting occurs. Healthy roots will appear white, firm, and fibrous. No browning of sections or tips of roots should be present.

The duration of any given irrigation cycle must be sufficient to provide adequate leaching of the medium. With some of the finer media, such as foam or rockwool, 20%–30% runoff is needed to flush excessive nutrients through the substrate. If this is not done, salt levels will build up, causing slowing of growth or even toxicity in the plants. More specific details are presented for each type of hydroponic system in the following chapters.

4.4 PUMPING OF NUTRIENT SOLUTION INTO BEDS

As mentioned earlier, the nutrient solution must provide water, nutrients, and oxygen to the plants. The frequency of irrigation will depend on the nature of the medium, the size of the crop, and the weather conditions. To provide these plant needs most efficiently during each irrigation cycle, the solution must moisten the bed uniformly and drain completely and rapidly so that oxygen will be available to the plant roots.

Details of pumping frequency are discussed more thoroughly in the chapters on each soilless system. In all cases, free water must not remain in the medium. The voids (air spaces between the particles) should be filled with moist air, not water, in order to maintain oxygen concentration around the roots at high levels. In most systems, irrigation should be done mainly during the daylight hours, with only several or none at night (depending on the medium).

Ideally, moisture levels in the medium can be maintained at optimum levels through a feedback system. Such a system has a moisture-sensing device, such as a tensiometer or electrode, placed in the medium. This apparatus is connected to an electrical circuit that activates a valve or pump that waters the plants when the moisture falls below a preset level. In this way, optimum moisture conditions are maintained within a fairly narrow range of variation.

A good presentation of the relationship between solar radiation and irrigation is given by Broad (2008a, b). He explains that solar radiation is the main driver of transpiration by plants. He states that 70% of the sunlight passes through the greenhouse cover. Of the 70% that the plant receives, it reradiates 30%, so the plant absorbs only 50% of the total available light from the sun (70% × 70%) and uses that for transpiration. With large vine crops, therefore, 20% (30% × 70%) of the solar energy is left to heat the greenhouse air.

In greenhouse culture, the temperature of the nutrient solution in contact with the roots of plants should be maintained between 60°F and 65°F (15.5°C–18°C). Immersion heaters can be placed in the sump of smaller operations to heat the nutrient solution. Recent experiments have demonstrated that by heating the nutrient solution, air temperatures can be decreased to conserve heat in the greenhouse. During winter, some crops such as tomatoes grow better if the temperature of the root medium is maintained a few degrees above the average night air temperature.

In no case should heating lines or electric heating cables be placed in the bed itself. Such placement causes localized high temperatures around the heating elements, which injure the roots.

4.5 STERILIZATION OF MEDIUM

When crops are grown for extended periods in any substrate, soil-borne pathogenic microorganisms accumulate in the medium, and the chances of a disease occurring increase with each successive crop. It may be possible to grow several crops successively without sterilization in between; however, for best results the medium should be sterilized after each crop to prevent any possible disease carryover. The most common methods of sterilization use steam and chemicals.

If a greenhouse is heated by a central hot water system or steam boiler, sterilization by steam would be the most economical. A steam converter attachment would be installed on the boiler and steam pipes run to the greenhouse with outlet attachments at each bed. A steam line is run down the center of each bed and covered with canvas or some heat-resistant material. Steam is then injected along the entire length of the bed at 180°F (82°C) for at least half an hour. This surface steaming is effective to a depth of 8 in. (20 cm) for sawdust beds but only to 4 in. (10 cm) for a 3:1 sand–sawdust mixture. Where surface steaming is not effective, install a permanent tile or perforated rigid pipe at the bottom of the bed through which steam can be injected.

Several chemicals may also be used in place of steam for sterilization, keeping in mind that some of these chemicals are toxic to humans and should be applied only by persons trained in their use. In all cases, precautions prescribed by the manufacturer should be observed.

Formaldehyde is a good fungicide but is not reliable for killing nematodes or insects. A mixture of 1 gal (3.785 L) of commercial formalin (40% strength) with 50 gal (189 L) of water is applied to the medium at a rate of 2–4 qt/ft^2 (20.4–40.7 L/m^2). The treated area should be covered immediately with an airtight material for 24 h or more. Following the treatment, about 2 wk should be allowed for drying and airing before planting.

Chloropicrin is applied as a liquid, using an injector, adding 2–4 mL into holes 3–6 in. (8–15 cm) deep, spaced 9–12 in. (23–30 cm) apart, or it may be applied at a rate of 5 mL/ft^3

(5 mL/0.0283 m^3) of medium. Chloropicrin changes to a gas, which penetrates the medium. The gas should be confined by sprinkling the medium surface with water and then covering it with an airtight material for 3 d. About 7–10 d are required for thorough aeration of the medium before it can be planted. Chloropicrin is effective against nematodes, insects, some weed seeds, *Verticillium*, and most other resistant fungi. Chloropicrin fumes are very toxic to living plant tissue.

Methyl bromide will kill most nematodes, insects, weed seeds, and some fungi, but it will not kill *Verticillium*. Methyl bromide is no longer available, as it has been banned for use in agriculture.

Vapam, a water-soluble fumigant, kills weeds, most fungi, and nematodes. It is applied as a spray on the surface of the medium through irrigation systems or with injection equipment at a rate of 1 qt (0.95 L) of Vapam in 2–3 gal (7.6–11.4 L) of water sprinkled uniformly over an area of 100 ft^2 (9.3 m^2). After application, the Vapam is sealed with additional water. Two weeks after application, the area can be planted.

Basamid, a granular soil fumigant, kills germinating weed seeds, soil fungi, and soil-borne nematodes. It is applied evenly over the substrate surface with a fertilizer spreader after the substrate has been cultivated to eliminate any compaction, thus allowing the chemical to enter all air spaces within the medium. Before application, remove any undecomposed roots and plant residues. Keep the soil moisture level suitable for seed germination for a 5- to 7-d period before treatment. Use a rate of 3.25–5 kg per 100 m^2 (7–16 lb/1076 ft^2). After application, incorporate the Basamid into the medium to a depth of 15–23 cm (6–9 in.).

Seal the chemical in the medium immediately after application by compacting it with a roller and covering the treated area with polyethylene. At temperatures above 18°C (64°F), the medium can be uncovered after 5–7 d and cultivated. At cooler temperatures, the period of being covered can be from 2 to 4 wk. A waiting period of 10–30 d, depending on the temperature (over 18°C, 10 d; under 8°C, 30 d), is needed to aerate the substrate. Finally, test the substrate by germinating seeds such as cress or lettuce in a jar of the sampled substrate. Once the seeds germinate evenly in the samples, it is safe to plant.

In gravel culture systems, common bleach (sodium or calcium hypochlorite) or hydrochloric acid can be used. A concentration of 10,000 ppm of available chlorine is made up in the sump tank, and the beds are thoroughly moistened for half an hour. The beds must be thoroughly leached with fresh water to eliminate any chlorine before planting.

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5 Water Culture

5.1 INTRODUCTION

Of all the soilless methods, water culture, by definition, is true hydroponics. Water culture includes aeroponics. In aeroponic sysems, plant roots are suspended into a closed dark chamber in which jets of nutrient solution are periodically sprayed over them to maintain 100% relative humidity. In water culture, plant roots are suspended in a liquid medium (nutrient solution), while their crowns are supported in a Styrofoam insulation cover as in the case of raft culture or by a plastic cover as in the case of nutrient film technique (NFT). NFT is a form of water culture in which plant roots are contained in a relatively small channel through which a thin "film" of solution passes.

For successful operation, a number of plant requirements must be met:

Root aeration. This may be achieved in one of two ways. First, forced aeration (by a pump or compressor) is used to bubble air into the nutrient solution through a perforated pipe or airstone placed at the bottom of the bed and/or in the nutrient tank. Second, the nutrient solution is circulated with a pump through the beds and back to a reservoir. A series of baffles placed at the end of the beds will aerate the water as it returns to the reservoir. A rate of about 1–2 complete changes per hour is required for a bed 100 ft (3.5 m) long containing 4–6 in. (10–15 cm) of nutrient solution (raft culture system). Best results can be achieved in a system in which the nutrient solution is pumped into the beds and allowed to flow past the plant roots continuously. In this way, freshly aerated solution will be in constant contact with the plant roots.

Root darkness. Plants can function normally with their roots exposed to light during the daytime, provided they are always at 100% relative humidity. However, light will promote the growth of algae, which interferes with plant growth by competing for nutrients, reducing solution acidity, creating odors, competing for oxygen from the nutrient solution at night, and producing toxic products through its decomposition, which could interfere with plant growth. To eliminate algae growth, construct beds of or cover containers with opaque materials.

Plant support. Plants may be supported by use of Styrofoam sheets or plastic covers in the case of NFT. This will prevent light from entering the nutrient solution, and Styrofoam also acts as an insulating barrier against high temperatures.

5.2 RACEWAY, RAFT, OR FLOATING SYSTEM

Dr. Merle Jensen of the University of Arizona, Tucson, developed a prototype raceway lettuce production system during 1981–1982. He projected that such a system could produce 4.5 million heads of lettuce per year per hectare.

FIGURE 5.1 Raft system of Bibb lettuce. Lettuce from left to right is 4, 3, 2, and 1 d after transplanting. The first bed from the right was just harvested, the second is being cleaned and the third is ready to transplant. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

The system consists of relatively deep (15–20 cm or 6–8 in.) beds holding a large volume of nutrient solution. The solution in the beds is fairly static, with a circulation of 2–3 L/min. The bed dimensions are about 60 cm wide by 20 cm deep by 30 m long (24 in. × 8 in. × 98 ft) (Figure 5.1). Such a bed has a volume of 3.6 m^3 (127 ft^3), which is equivalent to 3600 L (about 950 U.S. gal). Therefore, the flow through each bed at 2–3 L/min amounts to an exchange rate of 1 per 24-h period.

The nutrient solution from the beds is recirculated through a nutrient tank of 4,000–5,000 L (1,000–1,250 U.S. gal). There the solution is aerated by an air pump, chilled with a refrigeration unit, and then pumped back to the far ends of each bed.

On its return to the beds, the nutrient solution is passed through an ultraviolet sterilizer (Figure 5.2). These sterilizers are manufactured by several companies (Appendix 2) for use in soft drink, beer, distillery, aquaculture, clothing dye, and cosmetic industries, as well as those now specifically designed for commercial greenhouse applications. They are effective against many bacteria, fungi, viruses, and protozoa such as nematodes.

Evaluation of the effectiveness of a UV sterilizer against selected species of pathogenic and nonpathogenic fungi commonly associated with greenhouse crops by Mohyuddin in 1985 demonstrated that the unit significantly reduced or eliminated the following fungi from an aqueous solution: *Botrytis cinerea, Cladosporium sp., Fusarium spp., Sclerotinia sclerotiorum, Verticillium albo-atrum,* and several others.

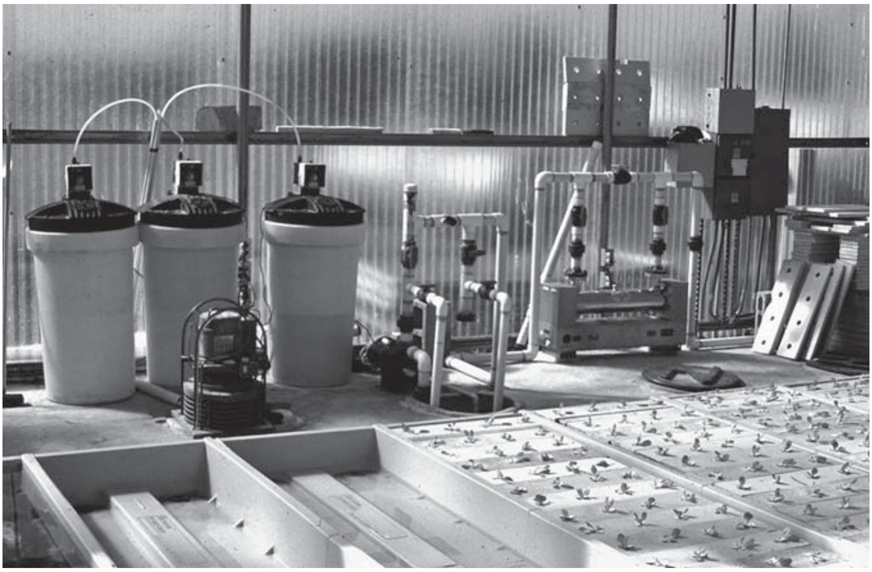

FIGURE 5.2 Raft system of water culture. Chiller unit on left in front of acid and stock-solution tanks with individual injectors. Circulation pumps in center and UV sterilizer on right. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

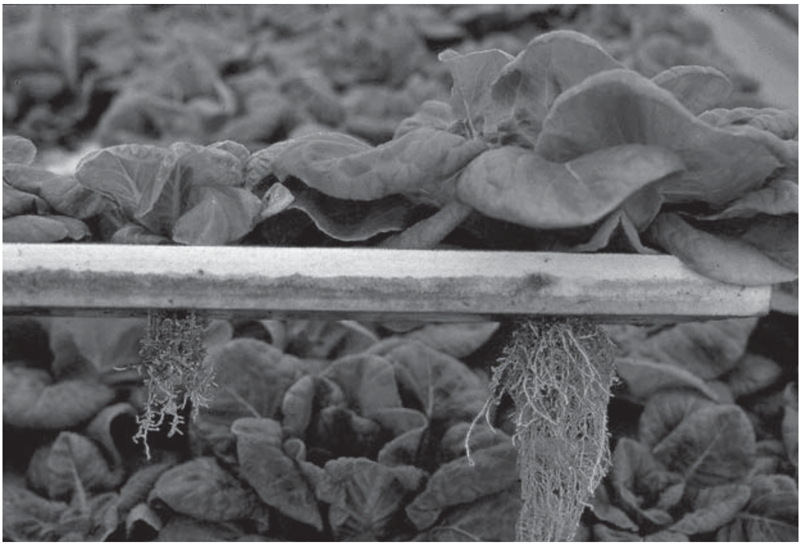

FIGURE 5.3 *Pythium* infection of Bibb lettuce. Healthy plant on right, infected on left. Note: The difference in growth of the head and roots between the healthy and infected plants.

Pythium infection of roots causes stunting of plants (Figure 5.3). Ultraviolet sterilization of nutrient solutions does not combat this disease organism. It can be controlled only by sterilization between crops of all beds, pipes, tanks, and so on with a 10% bleach solution.

The cost of these sterilization units varies with their capacity. The larger the volume of water they can effectively treat, the larger the unit and higher the price. Prices for small units may be from \$3,000 to \$5,000, while larger Dutch systems can be well in excess of \$50,000 for large-acreage greenhouses.

One side effect of the use of UV sterilizers is their effect on a few of the micronutrients. Mohyuddin (1985) found that the boron and manganese contents in a nutrient solution were reduced by more than 20% over a period of 24 h of sterilization. The most significant effect was on iron, which was precipitated as hydrous ferric oxide. Nearly 100% of the iron was affected. The iron precipitate coated lines and the quartz sleeve of the sterilizer, thereby reducing the UV transmission. Such precipitate could be removed with a filter. Hydrogen peroxide injection before passing the solution through the UV sterilizer also improves effectiveness. However, the loss of iron from the nutrient solution during UV sterilization must be corrected downstream by the addition of iron chelate.

The pH and electrical conductivity (EC) are monitored with sensors in the return line. Automatic injection of nitric acid (HNO_3), sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), or potassium hydroxide (KOH) is used to adjust the pH. All of these variables are monitored and adjusted by a computer controller such as Argus or Priva (Appendix 2). Similarly, the EC is raised by injection of calcium nitrate and a mixture of the remaining nutrients from two separate stock concentrate tanks (Figure 5.2) to keep it at 1.2–1.3 mmhos.

It is also now standard practice when growing lettuce in a raft culture system to use a water chiller in the nutrient tank (Figure 5.2) to maintain the temperature of the nutrient solution between 65°F and 75°F (18°C–23°C). This cooling of the nutrient solution will delay bolting of lettuce (lettuce going to seed) in desert and tropical regions.

5.2.1 Small and Medium-Sized Commercial Raft Systems

European Bibb lettuce was grown commercially by Hoppmann Hydroponics, Ltd., Florida, at temperatures exceeding 110°F (43°C) in the greenhouses by the use of the floating system using a water chiller in the nutrient tank.

Similarly, at CuisinArt Resort & Spa, Anguilla, British West Indies, in the Caribbean, various lettuces are grown at air temperatures of 90°F (32°C) using a raft culture system with chillers as shown in Figure 5.13, to maintain the nutrient solution temperature at 65°F (18°C). This temperature differential between the roots and upper part of the plant delays bolting by 3–4 d and also reduces fungal infection of the roots by *Pythium*.

Water-chiller units cool, aerate, and circulate the solution. They are available in one-sixth, one-half, and 1 horsepower units. The 1-horsepower unit is capable of cooling 1,000 gal of water in a temperature range from 35°F to 70°F (2°C–21°C). For nutrient solutions, units with stainless steel drive shaft, evaporator tube, and circulator blade should be used. These units are used in aquarium tanks for raising fish.

Hoppmann Hydroponics produced Bibb lettuce on a 30- to 34-d cycle in the beds after transplanting (Figures 5.4 through 5.6). Lettuce can be sown using rockwool cubes, Jiffy pellets, or directly in a peat mix medium in plastic seeding trays. While rockwool cubes placed in 240-compartment trays are easily sown by automatic sowing equipment, the cost of rockwool is greater than that of using a peat mix in 273-compartment trays, which can also be sown automatically using pelletized seed.

Seedlings should be 12–14 d old before transplanting to the beds. The seedling trays can be bottom irrigated through the use of a capillary mat (Figure 5.7). This prevents overhead watering, which can burn the seedlings under extreme solar conditions of tropical and desert regions. Seedlings should be irrigated with a dilute nutrient solution when the

FIGURE 5.4 Lettuce 6 d after transplanting. The solution inlet pipe to the bed is in the foreground. Note: The wire hook attached to the first board (raft) to allow pulling of the boards during harvest.

FIGURE 5.5 Lettuce 12 d after transplanting.

cotyledons unfold. The capillary mats can be either replaced or sterilized between seeding crops (12–14 d) using a 10% bleach solution to eliminate algae, fungal spores, and insects such as fungus gnats.

Seeding and transplanting are carried out daily so that continuous production is achieved. Late evening transplanting after sunset will assure successful "take." Plants will have time to acclimate before full-light conditions of the following day. This is especially significant if transplants are bare rooted as is the case when the lettuce is sown in a peat medium. Bare-rooted plants are placed in paper supports, which are then placed in the 1-in. (2.5-cm) diameter holes of the Styrofoam "rafts" (Figure 5.8).

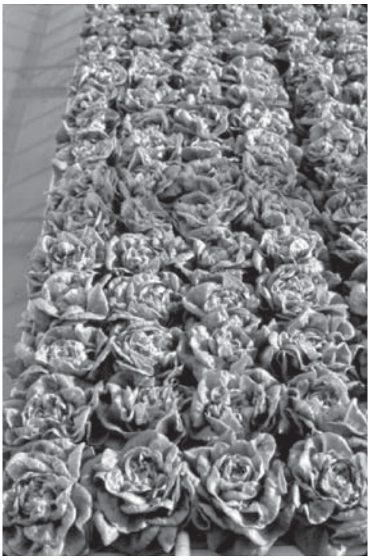

FIGURE 5.6 Lettuce 32 d after transplanting. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

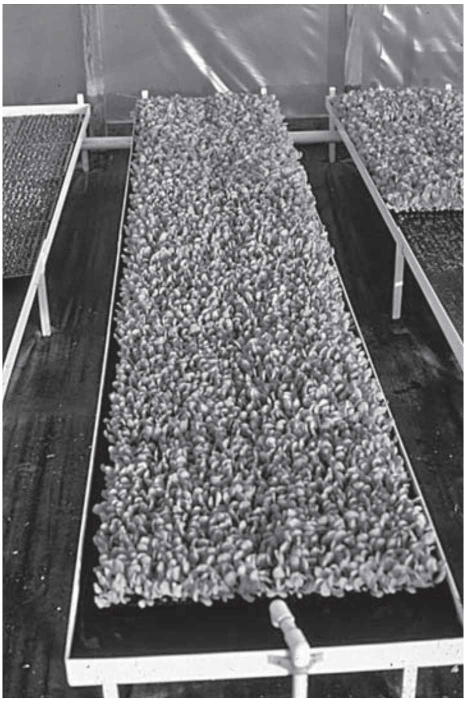

FIGURE 5.7 Lettuce seedlings 10–12 d old.

This technique of starting the plants in a peatlite mix and then bare rooting to place in the rafts is no longer used, as it is more convenient to use rockwool or Oasis cubes to retain the roots without damaging them during transplanting. These cubes can be placed in a normal plastic “flat” instead of the capillary matting tray used for the peat mix (peatlite) substrate.

FIGURE 5.8 Lettuce seedlings being planted into 1-in. holes in "rafts." (From Hoppmann Hydroponics, Waverly, FL. With permission.)

In small greenhouse operations of 1 acre (0.45 ha) or less, the most common raft system is the use of "raceway" beds placed together over the entire floor area of the greenhouse such as was used at Hoppmann Hydroponics. The beds are about 2 ft (61 cm) wide by the length of the greenhouse. For example, the useable length of a greenhouse 120 ft (36.5 m) in length is about 108 ft (33 m). In the beds are the "floats" or "rafts" of 1 in. × 6 in. × 24 in. (2.5 cm × 15 cm × 61 cm) boards of Styrofoam (Figure 5.9). The Styrofoam may be ordered in specific dimensions from the manufacturer if large quantities are purchased. They will cut the boards to the required dimensions with holes for placement of the plants. A high-density "roofmate" type of material (blue in color) used in house construction is the most suitable.

The rafts insulate the underlying solution in the bed and are a moveable system of transplanting and harvesting. Maintenance of cool solution temperatures (optimum 70°F or 21°C) is a prime factor in preventing bolting of lettuce in hot climates. In fact, we have found at CuisinArt Resort & Spa hydroponic farm in Anguilla in the Caribbean that keeping the solution temperature at about 65°F (18°C) under air temperatures of 90°F–95°F (32°C–35°C) delays bolting of lettuce for 4–5 d. The chillers are located in the nutrient tank, from where the solution is circulated into the beds that possess the largest volume of solution.

The rafts simplify harvesting. A string placed under the rafts in the bed, attached to three or four wire hooks, which in turn are attached in several places to the rafts along the entire bed length, can be pulled in by a boat winch at the harvesting end of the greenhouse (Figures 5.4 and 5.10). The rafts float mature lettuce plants *in situ* within the beds. Easier flotation is possible by raising the solution level in the bed before harvesting, by plugging the return pipe of the nutrient-circulation system.

FIGURE 5.9 "Raft" supporting four lettuce plants. Note: The vigorous healthy root growth. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

FIGURE 5.10 Boat winch used to reel in boards. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

During transplanting, the boards are pushed along the bed from the harvesting end as the plants are placed in them (Figure 5.8). Long lines of floats with growing lettuce are readily moved.

Between crops, the boards must be cleaned and sterilized by hosing with water before dipping them in a 10% bleach solution. Similarly, the beds must be drained and cleaned after each harvest (Figure 5.11). A new nutrient solution is prepared in the bed after cleaning and is ready for transplanting the same day.

Sowing, transplanting, and harvesting must be coordinated to get a continuous daily cycle. The growing period in the beds may vary from 28 to 35 d for Bibb lettuce, depending on sunlight and temperature conditions. In semitropical, tropical, and desert regions where sunlight is abundant and day length averages between 14 and 16 h, it is possible to obtain 10–12 crops annually, whereas in the temperate climates where sunlight is lower and day length may be 8 h or less during the winter months, it may only be possible to reach 7–8 crops annually. In temperate regions, winter crops may take 13 wk (including 40 d from sowing seed to transplanting), whereas summer crops take 5 wk (including 12 d from sowing to transplanting). By use of supplementary artificial lights, the sowing to transplanting period could be shortened during winter to perhaps half the time.

Individual heads are packaged in plastic bags. Some growers leave about 1 in. of roots on the plants when packaging, with the expectation of longer shelf life than without roots. However, some consumers may not like the presence of roots. In Arizona (Collins and Jensen, 1983) the roots-on package did not increase shelf life, and it was found to be three

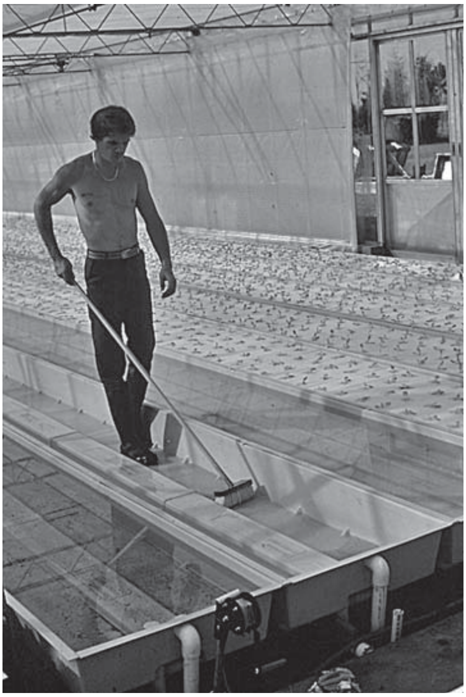

FIGURE 5.11 Beds are cleaned between crops. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

times more expensive to prepare and pack. The roots-on packaging was not well accepted by wholesalers or retailers and added to the cost of transportation because of increased volume and weight. Generally, 24 heads are packaged in a case.

The raceway system maximizes the usage of greenhouse floor space for production of lettuce or other low-profile crops. For example, a greenhouse of 1 acre (43,560 ft^2) with dimensions of 108 ft × 403 ft (33 m × 123 m) allowing front and back aisles of 8 ft (2.4 m) and 2 ft (0.6 m), respectively, with 2-ft access aisles every 29 ft (11 sets of beds), has a useable production area of 37,000 ft^2 (3,439 m^2). This is 84% utilization of greenhouse floor area. Such a growing area could produce 112,100 heads of lettuce per crop. That is, 2.6 heads per square foot (28 heads/m^2) of greenhouse area, or 3 heads per square foot (32 heads/m^2) of the available growing area.

Another method of raft culture for smaller greenhouse structures, for example, 30 ft × 120 ft (9 m × 36.6 m), is to construct beds 8 ft × 108 ft (2.4 m × 33 m). These are inside dimensions so that a standard 4 ft × 8 ft (1.2 m × 2.4 m) sheet of Styrofoam would fit inside the beds. The boards should be cut in half so that they are easier to handle during transplanting and harvesting. Beds could be constructed of concrete blocks or wood to obtain a minimum depth of at least 8 in. (20 cm). A 20-mil thick swimming pool vinyl liner is used to contain the solution. Each bed has a volume of about 3,000 U.S. gal (11,355 L). Air stones, such as those used in aquaculture of fish, can be distributed along the bed length to aerate the solution. The stones may be connected by poly tubing to an air pump. A chiller could also be installed in each bed if lowering of the solution temperature is required. The bed layout would be to have three beds per greenhouse with 2-ft (61-cm) aisles between. If 6 in. × 6 in. (15 cm × 15 cm) spacing is used, each board 4 ft × 4 ft (1.2 m × 1.2 m) would contain 64 lettuce or basil. One bed would contain 27 full boards or 54 half boards having a capacity of 3,456 plants.

On a small scale, raft culture may be set up in ponds having dimensions in a multiple of 4 ft, as the Styrofoam sheets come in 4 ft × 8 ft (1.2 m × 2.4 m) size. Cut the sheets in half as indicated above for ease of handling. Each board will hold 64 heads of lettuce (Figure 5.12).

At CuisinArt Resort & Spa in Anguilla, two ponds were constructed. The dimensions of the ponds are 20 ft × 32 ft (6 m × 9.8 m) and 20 ft × 16 ft (6 m × 4.9 m). The sidewalls of the ponds were formed using two tiers of concrete blocks to achieve a depth of 1 ft (30 cm). The bottom of the pond was sloped toward one corner where a circulation pump and two chillers were located (Figure 5.13). Initially, the pond was lined with 20-mil vinyl. However, since the pond was not rectangular, but had inside and outside corners, it made it very difficult to seal the angles of the vinyl. Continued water loss from the liner made it necessary to remove the vinyl liner and pour concrete with wire mesh on the base and grout the sides of the blocks. This was then treated with a concrete sealer such as “Thoroseal,” which goes on as a thick paste. After that, a bituminous base paint used for foundations was applied. The important point is to make the pond rectangular, having only inside corners to enable using a vinyl liner. A circulation pump is connected to a 2-in.-diameter PVC pipe placed at the bottom inside corner around the pond with tees having a reducer to 0.25 in. located every 24 in. (61 cm) to aerate and mix the nutrient solution continuously, as shown in Figures 5.13 and 5.14.

After two consecutive crops, the lettuce pond is cleaned with a 10% bleach solution. The ponds are drained, and the lettuce boards containing young plants are removed and stacked with roots together board to board (Figure 5.14). In this way, the moisture is maintained in

FIGURE 5.12 Styrofoam boards with 64 heads of lettuce. (From CuisinArt Resort & Spa, Anguilla. With permission.)

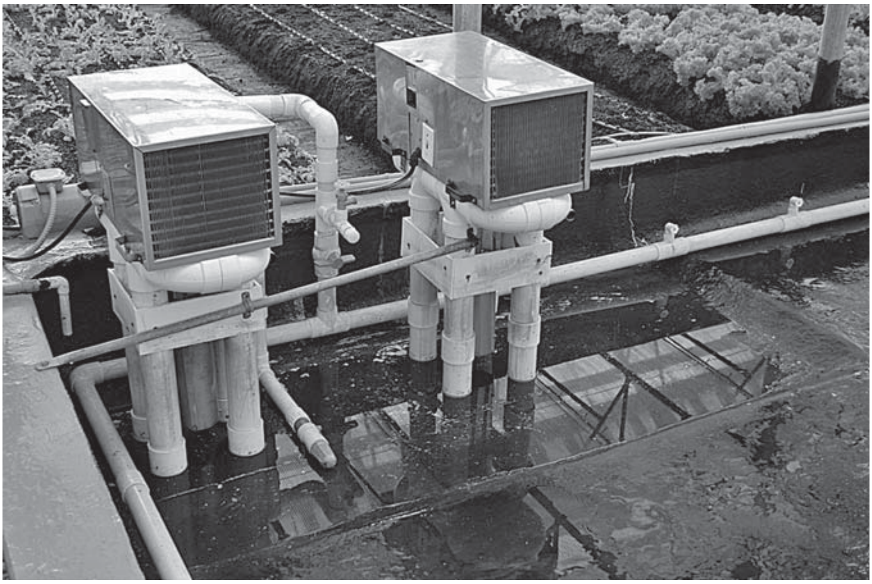

FIGURE 5.13 Circulation pump with chillers. (From CuisinArt Resort & Spa, Anguilla. With permission.)

the roots while the ponds are being cleaned. In addition, they may be sprinkled with water every half hour to keep them from drying.

The pond is cleaned by spraying the bleach solution using a back-pack sprayer and mopping it (Figure 5.15). The system is flushed by pumping the solution through the circulation pipes followed by flushing them with clean water before refilling the pond and making up the nutrient solution. This cleaning and changing of nutrient solution takes about 1–2 h.

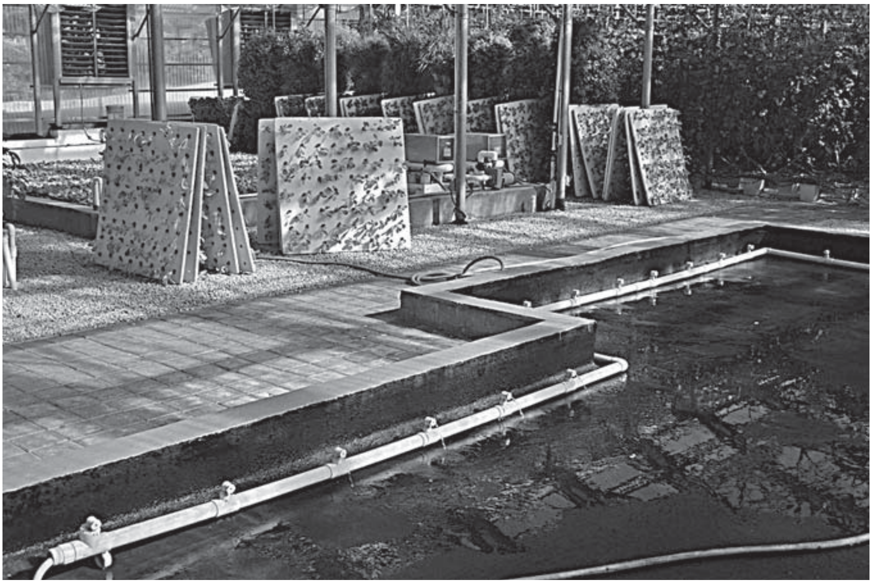

FIGURE 5.14 Perimeter mixing pipe with tees. Note: Stacking of boards in background. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 5.15 Sterilizing the lettuce pond. (From CuisinArt Resort & Spa, Anguilla. With permission.)

5.2.2 LARGE COMMERCIAL RAFT CULTURE SYSTEMS

A world leader in large commercial raft culture greenhouses is Hydronov, Inc. They are based in Quebec, Canada; they started in 1982 as Bioserre, Inc. and then expanded to 2.7 ha (6¾ acres) in Mirabel, Quebec, as Hydroserre Mirabel, Inc. in 1987. In 1992, they expanded again with an additional 2.0 ha (5 acres) in Phase 2, as shown in Figure 5.16. In 1995, they incorporated a subsidiary, Hydronov, Inc., to market their hydroponic technology of

FIGURE 5.16 Hydroserre Mirabel, Inc., Mirabel, Quebec, Canada. (From Hydronov, Inc. With permission.)

"Floating Rafts Growing Technology," as turnkey operations for other locations in North America, Mexico, and worldwide.

They formed joint ventures in China with Shenzhen Evergreen Vegetable Co. Ltd. in 1998 and Beijing Evergreen Vegetable Co. Ltd. in 1999. They established a 1.5-ha (3.75-acre) greenhouse operation in Shenzhen, China, and another 1.5-ha (3.75-acre) greenhouse operation in Beijing as joint ventures (Figure 5.17).

FIGURE 5.17 Shanghai Evergreen Vegetable Co. Ltd., greenhouse of 1.5 ha. (From Hydronov, Inc. With permission.)

They expanded operations in Quebec, Canada, as Hydroserre Mirabel, Inc., Phase 3, in 2000 with 2.3 ha (5.75 acres) and continued developing more operations in China from 2001 through 2003: Shanghai Evergreen Vegetables Co. Ltd. in Shanghai of 1.5 ha (3.75 acres); Dalian Hualu Vegetables Co. Ltd. of 1.5 ha (3.75 acres) in Dalian, China; and Shenyang Huanji Elite Vegetables Co. Ltd. of 1 ha (2.5 acres) in Shenyang, China.

During the period from 2003 through 2008, they established 5.2 ha (13 acres) in Leon, Mexico, as Omnilife Hydroponic Greenhouses; 1.5 ha (3.75 acres) in Hiroshima, Japan, as Japan Plantation Co. Ltd.-Nippon Noen; 1.0 ha (2.5 acres) in Shenyang, China; 5 ha (12.5 acres) in Livingston, Tennessee, in 2007 as Mirabel Inc. Hydroserre, and continued expanding in Quebec with two other 1.0-ha (2.5-acre) operations. The total area worldwide that Hydronov has established is close to 30 ha (75 acres). They are presently planning other projects in Slovakia, Alberta, Canada, British Columbia, Canada, Martinique, and Qujing, China.

Although they specialize in leafy types of lettuce, they are now growing more herbs and even have entered into aquaculture, combining fish culture with hydroponics. Most of their lettuce production is Bibb or Boston lettuce. They have branched into producing various European-type leaf lettuces, such as red and green oakleaf, Lollo Rossa, Lollo Bionda, Batavia, combinations of three types of lettuce grown together, Romaine or cos lettuce, and baby leaf lettuces and mesclun mixes. Herbs include Italian and purple basils, watercress, chervil, arugula, parsley, amaranth, mizuna, Asian greens, and medicinal herbs.

Hydronov claims that they achieve production levels up to 500 heads (200 grams per head) of lettuce per square meter (10.76 ft^2) per year. It takes about 45 d per crop, with 20 crops annually. They compare that to an annual production of 36 plants per square meter in field production and 108 plants per square meter for normal greenhouse soil production.

The main advantage of their system is using mechanization to move plants from their growing area to harvesting or from seeding and transplanting. Workers do not have to bend over to perform their tasks, so back injuries are avoided. The plants in their boards move from the floating production area to an area of mechanical conveyors specially designed for seeding, transplanting, harvesting, packaging, and cooling. The number of workers needed per hectare varies from 5 to 15, depending on the crop, type of packaging, and level of mechanization.

The cropping process is as follows:

Seeding. Seeds are sown by mechanical seeders into Oasis cubes placed in plastic flats. Trays containing the sheets of Oasis cubes are watered and then transported to a floating table bench system using Styrofoam boards underneath the seedling trays and irrigated with an overhead boom irrigator as shown in Figures 5.18 and 5.19. This is the germination stage.

Transplanting. Once the seedlings have germinated (4–6 d and formed their first true leaf), they are transplanted to seedling Styrofoam boards that are then placed in the floating raft culture system. They are very closely spaced at this stage, with 288 seedlings per 2 ft × 4 ft board as shown in Figures 5.20 and 5.21.

The second transplant stage is at the third true-leaf stage, about 10–12 d from sowing. The exact time depends on the weather conditions. Under more sunlight and higher temperatures the growing period may be reduced by several days. In Figure 5.21, the plants in the foreground are much younger than those in the background. The second transplant is into boards 2 ft × 4 ft containing 72 seedlings

FIGURE 5.18 Initial watering of sown flats of Oasis cubes. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.19 Sown trays of lettuce on a floating table system. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.20 Transplanting germinated seedlings in cubes to Styrofoam boards containing 288 seedlings. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

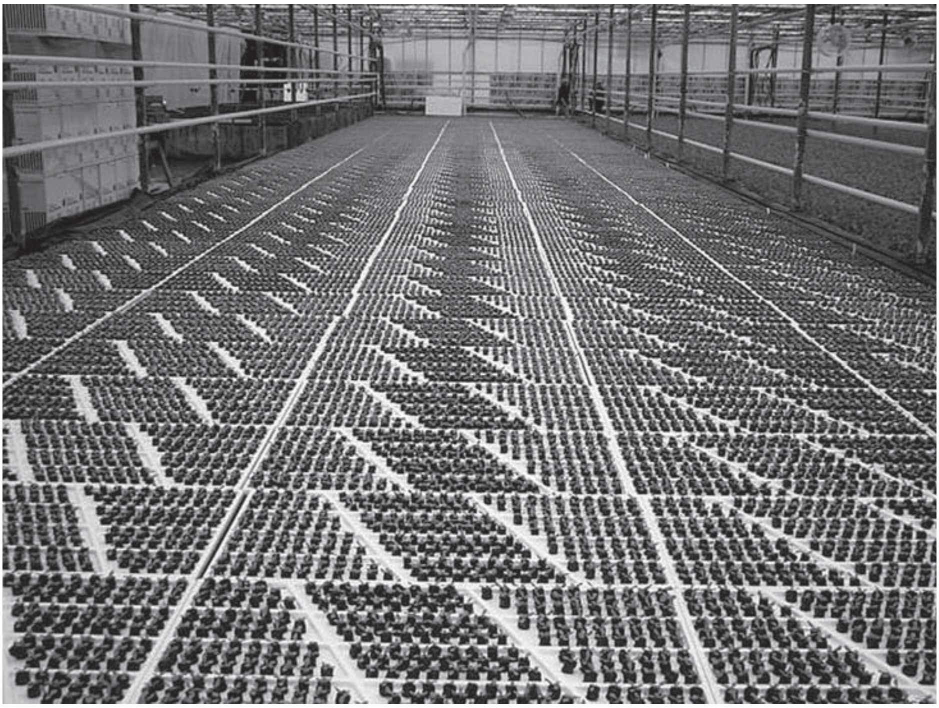

FIGURE 5.21 Transplanted stage 1 seedling boards. (From Hydronov, Inc., Hydroserre Mirabel Inc., Mirabel, Quebec, Canada. With permission.)

(6 × 12). This is done at the transplanting station, and then the boards are moved by a conveyor belt to the raft pond location where they will grow during this second transplant stage as shown in Figures 5.22 through 5.24.

The seedlings are grown to their fourth true-leaf stage (about 18–21 d from sowing or 8–10 d from last transplant stage depending on weather conditions) before transplanting to the final growing stage (Figures 5.25 and 5.26). At this stage, 18 plants (3 × 6) are set in each board of 2 ft × 4 ft. The boards are then transported to the final growing raft pond and will be ready to harvest within another 24–30 d when they are harvested at about 45 d from sowing (Figure 5.27).

Harvesting. The mature lettuce is harvested from its board, which is picked up and transferred to a conveyor system that takes the board to the packing facility (Figure 5.28). A specialized winch pulls the boards toward the end where they are being set onto the conveyor system. The conveyor system contains water so that the rafts can float while being pulled by the chain links underneath, as can be seen in Figures 5.28 and 5.29. At the packing facility, the lettuce is removed, trimmed, and either placed on another belt to go to the boxing area or boxed immediately at the same work station as shown in Figures 5.30 and 5.31. Once the lettuce is boxed, it moves to a rapid chilling (vacuum cooling) chamber and then into a cooler (Figure 5.32). The boards move on a conveyor from the packing area where the lettuce is removed to a board washing machine as seen in Figures 5.31 and 5.33. From there, the boards are returned to the planting area of the greenhouse to start the cycle over again.

FIGURE 5.22 Transplanting stage 1 plants to stage 2, with 72 seedlings per board. (From Hydronov, Inc., Hydroserre Mirabel Inc., Mirabel, Quebec, Canada. With permission.)

FIGURE 5.23 Transplanted stage 2 plants on conveyor transporting to raft pond. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.24 Seedlings at stage 2 in raft pond. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.25 Seedlings at stage 2 ready to transplant to final growing boards. (From Hydronov, Inc., Hydroserre Mirabel, Inc., Mirabel, Quebec, Canada. With permission.)

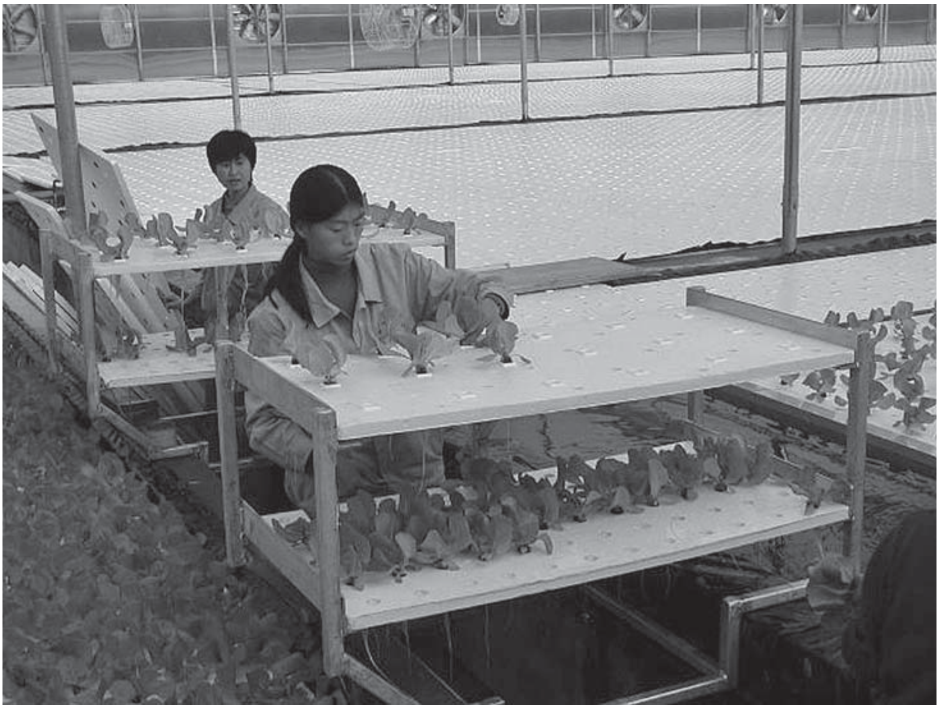

FIGURE 5.26 Final transplant to growing boards of 18 plants per board. (From Hydronov, Inc., Shanghai Evergreen Vegetables Co. Ltd., Shanghai, China. With permission.)

FIGURE 5.27 Lettuce at about 45 d ready to harvest. (From Hydronov, Inc., Japan Plantation Co. Ltd.-Nippon-Noen, Hiroshima, Japan. With permission.)

FIGURE 5.28 Harvesting boards of lettuce and placing into the conveyor system for transport to the packing facility. Note: The winch system that pulls the boards in the growing raft pond toward the harvesting end. (From Hydronov, Inc., Japan Plantation Co. Ltd.-Nippon-Noen, Hiroshima, Japan. With permission.)

FIGURE 5.29 Lettuce traveling on conveyor system to packing facility. Note: The winch that pulls the boards to the harvesting end of the lettuce raft pond. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.30 Packing facility where the lettuce is removed from the boards and placed in boxes. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

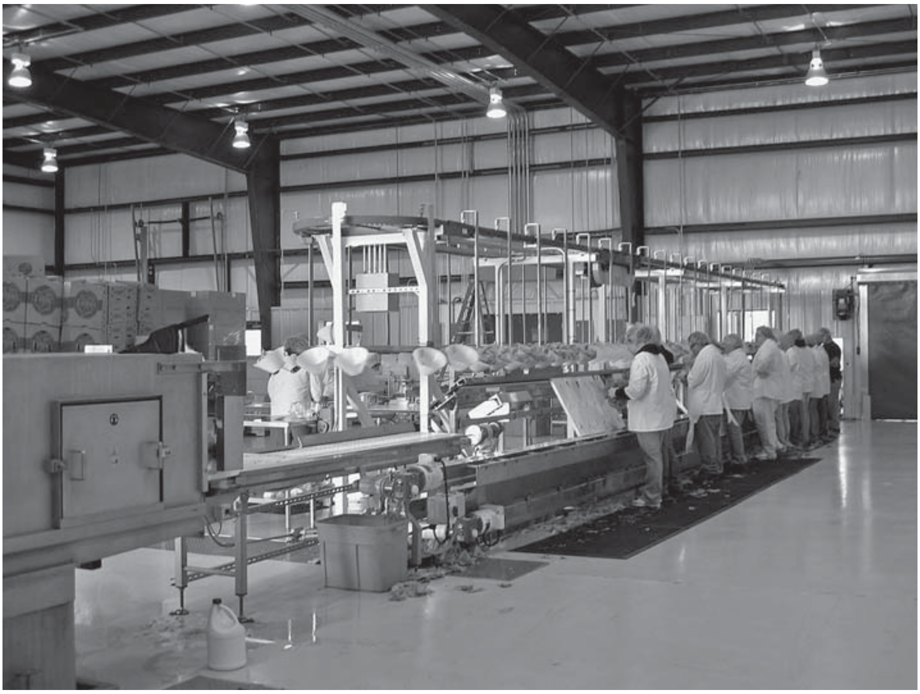

FIGURE 5.31 Removing lettuce from boards and boxing in the packing area. The board washing machine is on the left. (From Hydronov, Inc., Hydroserre Mirabel Inc., Tennessee, Livingston, TN. With permission.)

FIGURE 5.32 Boxed lettuce moving through a vacuum cooler. (From Hydronov, Inc., Hydroserre Mirabel Inc., Tennessee, Livingston, TN. With permission.)

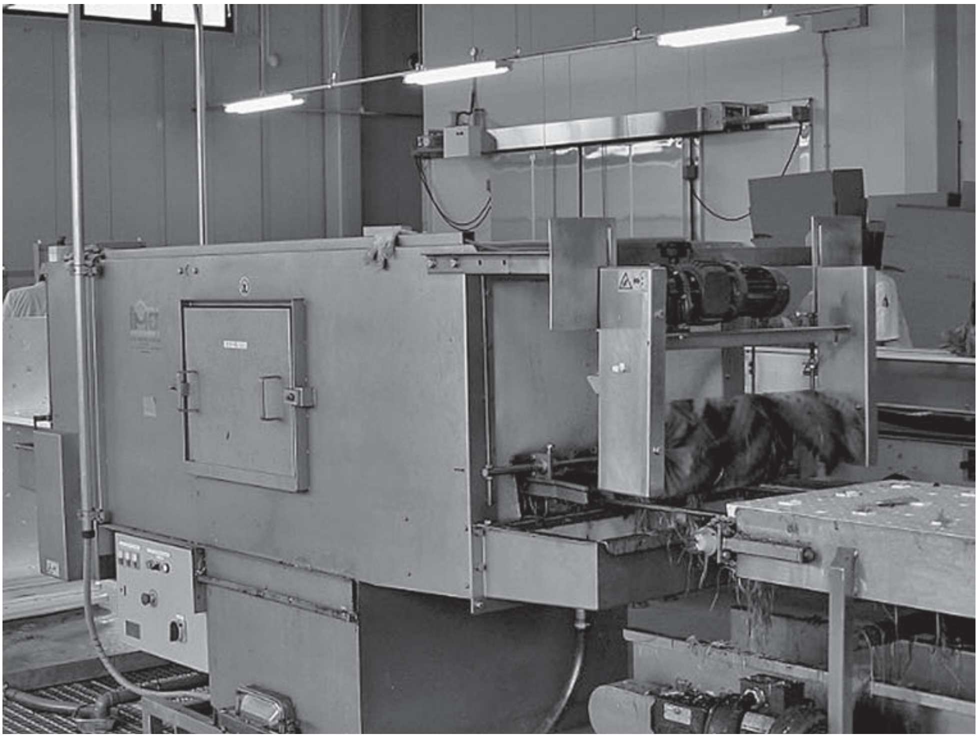

FIGURE 5.33 Board washer to clean and sterilize the boards. (From Hydronov, Inc., Japan Plantation Co. Ltd.-Nippon-Noen, Hiroshima, Japan. With permission.)

The nutrient solution is recycled to a treatment area and then adjusted for pH and EC by use of injectors with stock solutions as shown in Figure 5.34. A typical greenhouse operation of 1.5 ha or 3.75 acres in Japan is shown in Figure 5.35.

5.3 AEROPONICS

Aeroponics is the growing of plants in an opaque trough or supporting container in which their roots are suspended and bathed in a nutrient mist rather than a nutrient solution. This culture is widely used in laboratory studies in plant physiology, but not as commonly used as other methods on a commercial scale. Several Italian companies are, however, using aeroponics in the growing of numerous vegetable crops such as lettuce, cucumbers, melons, and tomatoes (Vincenzoni, 1976). Also, a number of commercial ventures are using aeroponics for growing medicinal plants, especially those in which the end product is in the roots. Seed potatoes are being grown in an aeroponic system in Brazil.

The best location to visit futuristic agriculture using hydroponics and aeroponics is “The Land Pavilion,” located in “Future World” in Epcot at the Walt Disney World Resort near Orlando, Florida. Epcot houses the Land Pavilion. With the “Living with the Land” boat tour in the experimental greenhouses, a special “behind the scenes” tour can be taken to visit the various hydroponic and aeroponic displays.

Several types of aeroponic systems are demonstrated, the A-frame system and the moveable overhead rail system. The A-frame is constructed of Styrofoam board sides supported by a frame above a nutrient reservoir (Figure 5.36). The plants are inserted into the holes

FIGURE 5.34 Adjustment of the nutrient solution using an injection system. (From Hydronov, Inc., Japan Plantation Co. Ltd.-Nippon-Noen, Hiroshima, Japan. With permission.)

FIGURE 5.35 Hydronov, Inc., Japan Plantation Co. Ltd., Hiroshima, Japan. (From Hydronov, Inc., Quebec, Canada. With permission.)

FIGURE 5.36 Cabbage growing in aeroponic A-frame system. Note: The misting system below in the nutrient tank. (From Epcot, near Orlando, FL. With permission.)

of the Styrofoam sides with their roots suspended on the inside. High-pressure misting nozzles spray the solution onto the roots from below, and the excess solution drains back to the tank. The roots of the plants get good oxygen from the spray of solution and from the volume of air within the chamber. This type of system is best used for lettuce, herbs, and medicinal plants whose roots would be harvested for the commercially active ingredient used for vitamins or drugs.

An overhead aeroponic culture system is a moveable rail supporting columns of herbs and ornamentals that move around the display area (Figures 5.37 and 5.38). They are misted with nutrient solution from the top of the column and permitted to drain below. Another system is one in which papaya grows from an overhead mobile supporting system. As they move around their fixed path, their suspended roots pass through a misting chamber at one section that feeds them on each cycle (Figure 5.39). As the plants pass out of the nutrient chamber, the excess solution drains to the rocks below where it is conducted away from the area.

Early work by the University of Arizona's Environmental Research Laboratory (ERL) in the 1980s grew lettuce on the interior of a large drum rotating around an artificial light source (Jensen (1980); Jensen and Collins (1985)). Lettuce was planted through holes in an inner drum that rotated at 50 rpm. As the inner drum rotated, the plant tops grew toward the center. The roots, sealed between the two drums, were misted regularly with nutrients. This type of culture has now been developed for hobby and commercial hydroponic

FIGURE 5.37 Herbs in moveable rail supporting columns. Cabbage in A-frame behind. (From Epcot, near Orlando, FL. With permission.)

FIGURE 5.38 Hot peppers in moveable column. Nasturtiums behind. (From Epcot, near Orlando, FL. With permission.)

FIGURE 5.39 Papaya in overhead mobile system. Roots being misted from mist chamber below. (From Epcot, near Orlando, FL. With permission.)

growing by Omega Garden in Vancouver, British Columbia, Canada, as shown in Figures 5.40 through 5.43. They sell individual carousels for hobby use and commercial vertical carousels that carry six 8-ft (2.4-m) long Omega Gardens^{TM}, equivalent to 1,500 ft^2 (139 m^2) of greenhouse, which use only 150 ft^2 (14 m^2) of floor space. These systems are stackable, and multiple units can be positioned together for larger operations as shown in Figure 5.43.

The system is fully automated in that each rotating garden is in turn rotated on the carousel down to the water/feeding tray at floor level. The water tray sits above a reservoir at the bottom of the carousel, watering all the plants as the cylinders rotate and pass through this watering tray.

This simplified irrigation system minimizes plumbing and eliminates possible plugging of drip emitters and lines found in conventional drip irrigation systems.

5.4 HYDROPONIC GRASS UNITS

The growing of grains with a nutrient solution within an enclosed environmentally controlled chamber or unit has gained commercial significance as a source of year-round fresh grass feed for animals (Arano, 1998).

Grains such as oats, barley, rye, wheat, sorghum, or corn are presoaked for 24 h before being placed in growing trays (about 0.5 m^2) for 6 d. The trays may be watered manually on shelves with excess nutrient solution draining to waste, or the entire system of trays may be mounted on rotating drums that are automatically fed with a nutrient solution, which is

FIGURE 5.40 Hobby Omega Garden growing basil. (From Omega Garden, Int., Vancouver, Canada. With permission.)

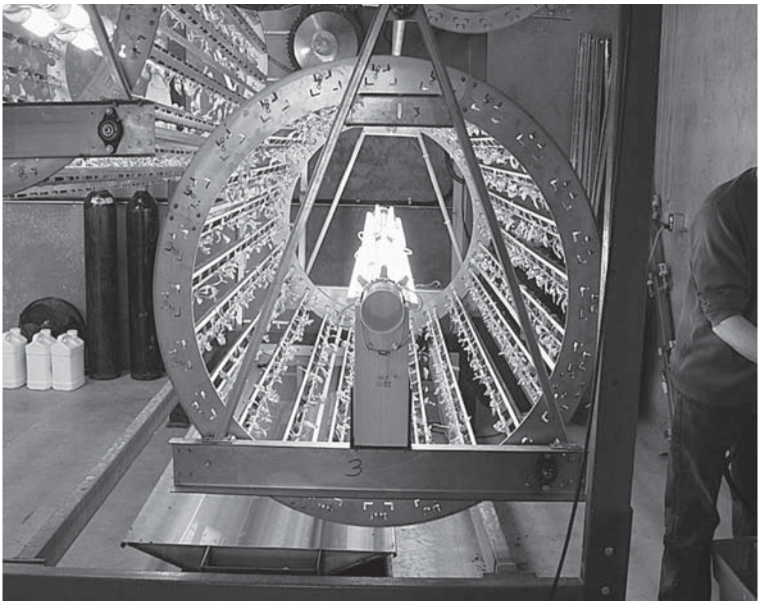

FIGURE 5.41 Single Omega Garden growing young chard plants. (From Omega Garden, Int., Vancouver, Canada. With permission.)

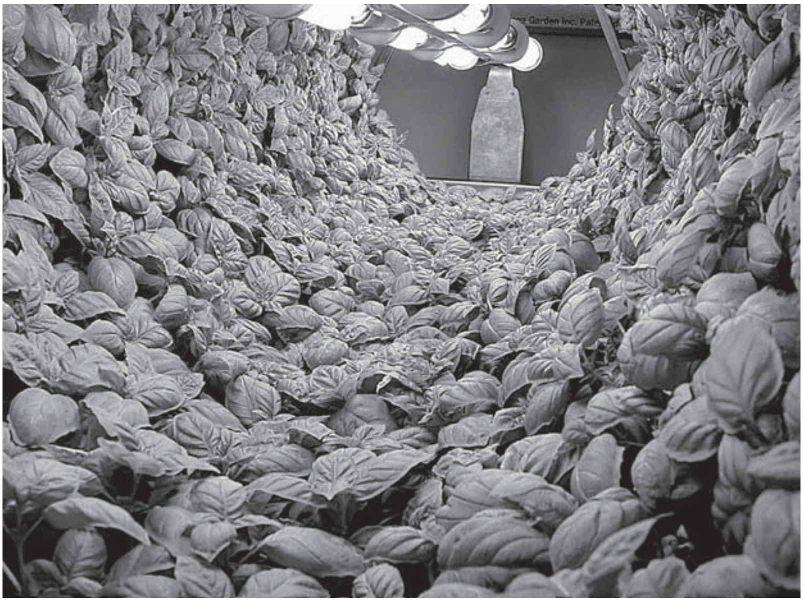

FIGURE 5.42 Omega Garden single carousel growing sweet basil. (From Omega Garden, Int., Vancouver, Canada. With permission.)

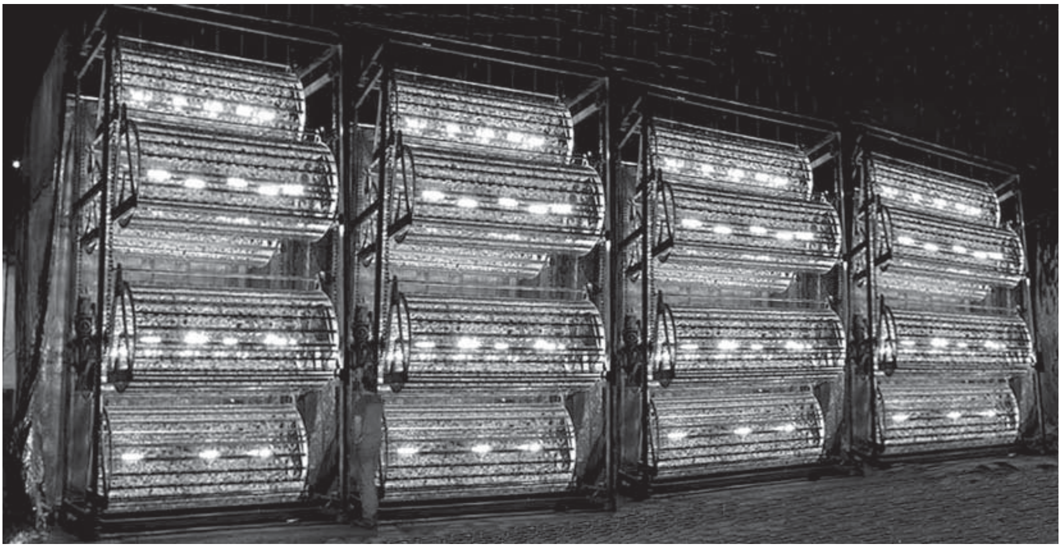

FIGURE 5.43 Omega Garden series of carousels in stackable framework. (From Omega Garden, Int., Vancouver, Canada. With permission.)

recycled. Light is provided artificially by use of cool-white fluorescent lighting. After 6 d of growth, the grain (grass) has grown to 4–5 in. (15–20 cm) and is ready for harvesting and feeding to the animals.

Various commercial grass-growing units are available in a number of sizes. A 20-ft long by 8-ft high by 10-ft wide (6.0 m × 2.4 m × 3.6 m) unit is shown in Figure 5.44.

In this unit, a fourfold bank of six layered trays separated by about 30 cm (12 in.) rotates under artificial lighting. Each layer has a set of five trays, 0.9 m × 0.45 m (36 in. × 18 in.),

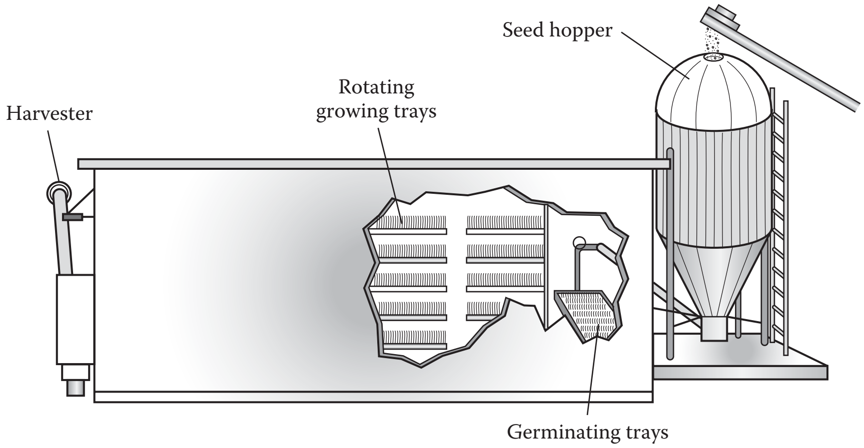

FIGURE 5.44 An automatic commercial grass-growing unit. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

giving a total area per layer of 2.0 m^2 (22.5 ft^2). Into each layer (five trays), about 11.3 kg (25 lb) of grain is placed daily. The temperature is maintained at 22°C–25°C (72°F–77°F), and the relative humidity at 65%–70%.

The unit of four banks of 30 trays is said to produce up to one-half ton (450 kg) per day of fresh green grass from 100 lb (45 kg) of grain. The grass is fed to animals in its entirety—roots, seeds, and green foliage.

The cropping schedule is set up so that one series of trays is harvested each day and at the same time one series is also seeded. In this way, continuous production 365 d a year is possible.

It is stated (Arano, 1976a) that each kilogram (2.2 lb) of grass is equivalent nutritionally to 3 kg (6.6 lb) of fresh alfalfa. Arano also states that 16–18 kg (35–40 lb) of grass is sufficient as the daily food requirement for one cow in milk production.

He speculates that a standard grass-growing unit of six separate tiers, each having 40 trays, could feed 80 cows all year. In a test of milk production with a diet of grass versus one of normal feed (such as grain, hay, and silage), the group of 60 cows on the grass diet increased their milk production by 10.07% over those on the normal diet. In addition, the group fed on grass produced a butterfat content of 14.26% higher than those fed the regular diet.

The grass-growing units have proved to be beneficial to other animals besides dairy cows. Race horses fed on grass performed better, and zoo animals, which are accustomed to a grass diet in their normal habitat, were healthier in confinement when fed fresh grass year-round.

Evidence is given (Arano, 1976b) that the hydroponic grass units produce animal feed at about one-half the cost of that produced conventionally. This is based on the larger amounts of fuel needed in the production and transportation of traditional animal feeds. The grass-growing units enable animal producers to grow feed year-round *in situ*. No storage of hay or silage is necessary since fresh grass is produced daily. This grass can be grown in a very small area compared to field-grown grasses and feeds. Costs of insecticides, fertilizers, machinery for cultivation and harvesting, and labor of filed-grown feeds are estimated to be at least 10 times greater than that of hydroponically grown grass.

An inexpensive grass unit has been established in Peru by Sr. Enrique Valdivia Benavides (1997) to supply green fodder to beef and milk cattle. This is particularly important in an arid area where fresh grass is unavailable. An enclosed structure with roof vents to allow cooling and partially open sides to permit light to enter is adequate to house the trays tiered on shelving. In the Peru operation, seven levels of shelving were used to support the trays. Above each level is a series of mist nozzles to supply water and nutrients as the seeds grow.

Seeds are washed to remove impurities and poor seeds, and then imbibed by soaking in a tank for 18–24 h depending on the temperature. Less time is required under higher temperatures. The imbibed seed is then partially dried 24 h in wooden boxes. All boxes, tanks, and so on must be sterilized before each use. When moving the imbibed seed to the germination trays, care must be taken not to damage the developing radicals.

The seeds are placed in the trays to a depth of about 1.5 cm (Figure 5.45). The seed trays are placed in a production room on shelving with a mist system where they will remain for 6–7 d (Figure 5.46). Watering cycles range from 8 to 10 times per day with a period of 20–60 s each cycle. A dilute fertilizer solution is applied through the mist system.

Production achieved by this method averages about 1:5 times by weight. This may be increased as high as 1:12 with the use of good seed. A general production ratio of 1:8 is expected in alfalfa or bean sprout systems. This operation uses wheat, barley, and corn as the seed sources. The animals consume all of the plant matter, including roots, seeds, and foliage (Figures 5.47 and 5.48).

The operation claims that with a daily rationing of 12 kg of grass per day for dairy cows they have achieved a greater than 7% increase in milk production in cows producing more than 28 L of milk per day and a 53% increase in cows producing 14 L or less daily. In pregnant cows abortions were reduced to near zero. Cows also stayed dry for less time after bearing calves. Beef cattle gained 1.4 kg/d when fed 7–8 kg of green fodder plus 7 kg of concentrate.

FIGURE 5.45 Seeds placed in trays. Left tray is 1 d after a 20-h soaking period plus 24-h drying. Right tray is after soaking and drying. (From V. Enrique Valdivia Benavides, Peru. With permission.)

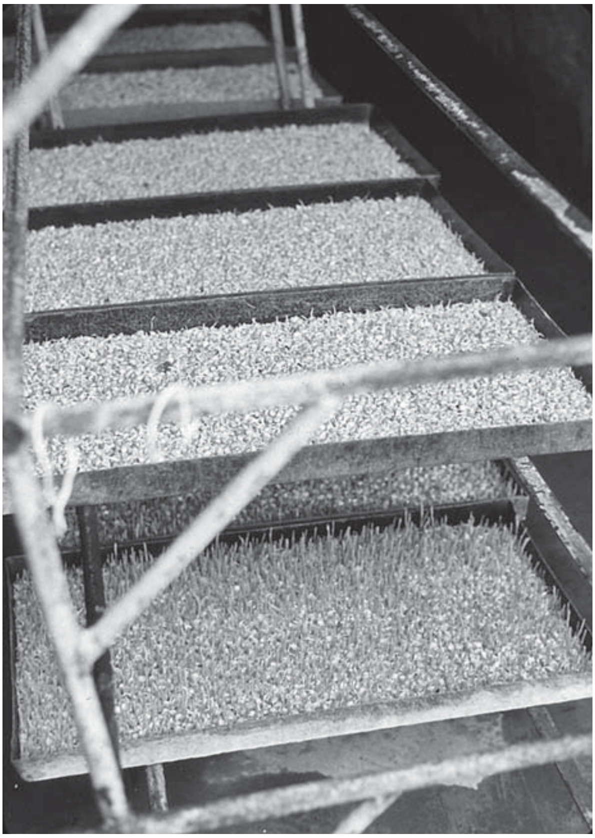

FIGURE 5.46 Production room with mist. (From V. Enrique Valdivia Benavides, Peru. With permission.)

FIGURE 5.47 Finished corn ready for animal consumption. (From V. Enrique Valdivia Benavides, Peru. With permission.)

FIGURE 5.48 Finished barley. (From V. Enrique Valdivia Benavides, Peru. With permission.)

5.5 ALFALFA AND BEAN SPROUTS

Sprouts of alfalfa, beans, radish, broccoli, and mixtures of alfalfa with onions, garlic, clover, cabbage, fennel, leek, lentil, cow peas, and green peas are popular for human consumption in salads, sandwiches, and oriental cooking. Most alfalfa blends are made up of 60%–80% alfalfa with the remaining part one or more of the others.

5.5.1 ALFALFA CULTURE

Raw seed must be surface sterilized to kill fungi and bacteria. Of particular concern is possible contamination by *Salmonella*, which may be killed by 2,000–4,000 ppm active chlorine for at least 10 min. The author has used a concentration of 2,000 ppm for up to 30 min without any reduction in seed viability.

Seeds are rinsed in plastic bins with raw water several times until all dirt is removed before sterilization. Rinse the seeds until the drain water is clear, then surface sterilize the seed. One part bleach to 19 parts raw water will give a 3,000-ppm chlorine solution. Rinse the seeds several times after surface sterilizing until the water drains clear.

Spread the seeds in 5-cm (2-in.)-deep plastic trays or bins and soak for 4–6 h to imbibe. Change the water every hour to aerate. All water used in these processes should be chlorinated before filtering with sand and activated charcoal. It is convenient to store the clean water in plastic tanks having covers and connecting them using pipes to a closed system pressurized by a pump. Of course, all containers, trays, and so on must be sterilized with a 10% bleach solution before use. Water temperature must be maintained at 21°C (70°F) by the use of a boiler before entering the growing facilities. Seeds must swell but not break their seed coats. Wash them several times again before placing them in the growing trays.

The two most common types of growing systems are racks and rotary drums (Figure 5.49). Stainless steel racks may be single or double (Figure 5.50) mounted on casters to facilitate their movement. Single racks are 61 cm (24 in.) wide by 1.4 m (56 in.) long and 2 m

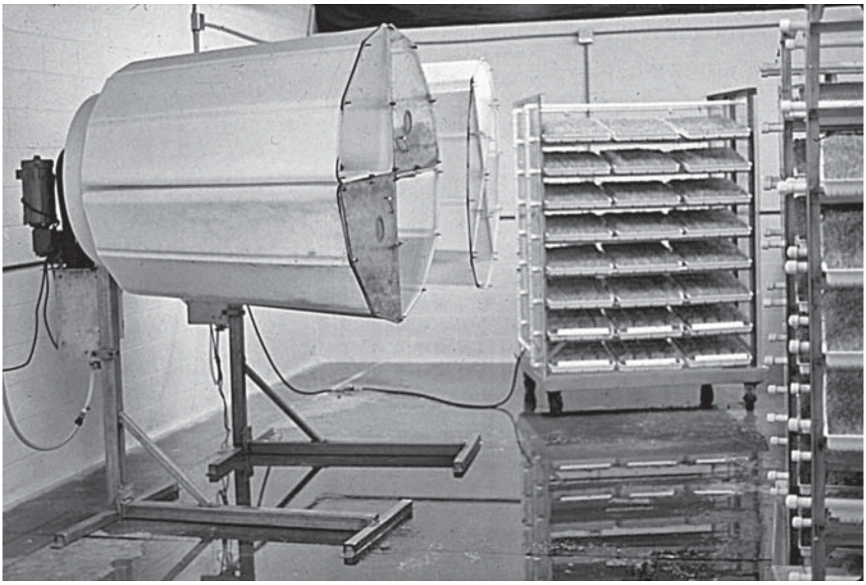

FIGURE 5.49 Alfalfa sprout growing systems of racks and rotary drums.

FIGURE 5.50 Stainless steel racks on casters.

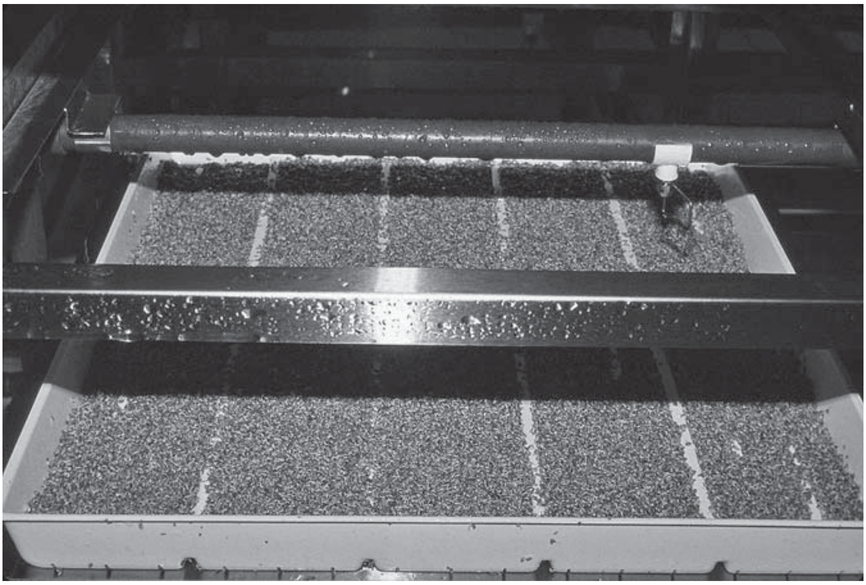

FIGURE 5.51 Mist nozzles above growing trays. Sprouts are 1 d after soaking. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

(80 in.) high. Racks may contain 7–10 shelves depending on the crop. With alfalfa, use the 10-shelf rack.

Growing trays are of high-impact rubber-modified polystyrene (Figure 5.51). Ribbing maximizes drainage and minimizes root compaction. Ten-level single racks hold 20–30 trays, whereas, double racks with eight levels hold 48 trays. Set up sufficient racks in a growing room to meet market demand.

Elaborate commercial systems use a computerized automatic water car that travels between the rows of racks. Less sophisticated fixed mist nozzles mounted above each level of the rack will perform the same task. Three trays per rack level may be watered by two mist nozzles located equidistant above each level (Figure 5.51).

An irrigation controller with solenoid valves automatically irrigates the sprouts at set intervals. Alfalfa sprouts are greened by passing the rack(s) through a light room for a few hours to a day depending on the amount of greening required by the market.

The growing cycle is between 4 and 5 d. The seeds may be sprouted in bulk trays or placed in clamshell plastic containers. Bulk trays hold about 1 lb or 0.5 kg of imbibed seed or 20 clamshells. Spread 0.25–0.5 in. (0.6–1.3 cm) of seed in the trays. Set the irrigation cycles at 30 s/h or 1 min/2 h. Within 4 d the sprouts will grow about 2.5 in. or 6 cm in height (Figure 5.52). Rinse the sprouts in cold water at 36°F–37.5°F (2°C–3°C) as soon as they are harvested. At all times during production and harvest, handle sprouts with strict sanitation procedures using gloves, smocks, and hair caps. During the washing process immediately after harvesting at least 60% of the seed coats should be removed. This will usually occur as the sprouts are gently agitated during the washing process. Sprouts are then spin dried in a centrifuge before packing so they will have a shelf life of at least 5 d.

When growing the sprouts in clamshell trays, wash them after the second day when they reach about 1 in. (2–3 cm) in height; then place the same amount of sprouts in the 20 clamshells that would fill the trays. Grow them on for another 2–3 d. All equipment,

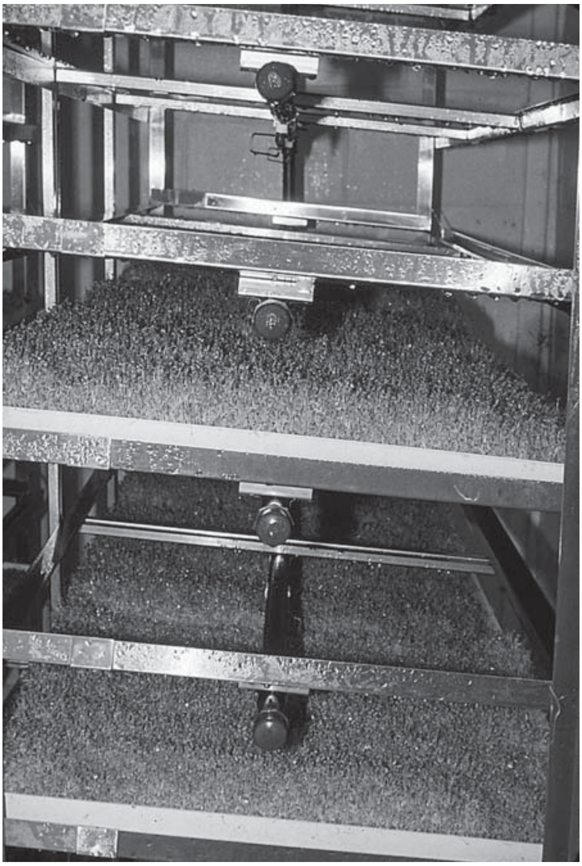

FIGURE 5.52 Alfalfa sprouts ready to harvest after 4 d. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

including trays and washing bins, must be sterilized with a 10% bleach solution immediately after use.

A fully automated rotary drum system washes, soaks, presprouts, and grows the seed (Figure 5.49). The drum is divided into four quadrants or growing chambers. Temperature, ventilation, water flow, rotation speed, and light may be programmed for a specific crop. During growth, the drum rotates once per hour and waters every 6 min.

With each quadrant containing 11.25 lb (5 kg) of seed, or 45 lb (20.5 kg) per drum, production will reach 350–450 lb (160–205 kg) of alfalfa sprouts in about 4 d. The alfalfa sprouts should weigh from 8 to 10 times that of the seeds. A rack system housing 30 trays will produce 330 lb (150 kg) of bulk sprouts or 900 clamshells per growing cycle of 4–6 d. This assumes that each tray sown with 1 lb (0.5 kg) of seed will produce 11 lb (5 kg) of bulk sprouts. This is equivalent to 30 clamshells containing 4 oz (115 g).

5.5.2 MUNG BEAN CULTURE

Preparation of the seeds before placing them in the growth room is similar to that of alfalfa. The soaking time varies from 4 to 6 h at 72°F (22°C), depending on seed age, quality, and source. Like alfalfa, the seed must imbibe but not break the seed coat before transferring to the growing chambers. The growth room temperature must be maintained between 72°F and 75°F (22°C–24°C). Large commercial bins mounted on stainless steel frames measure 37 in. (95 cm) × 40 in. (1.0 m) × 67 in. (1.7 m) height. They are constructed of corrugated plastic sides with removable slatted bottoms, which provide rapid drainage without the seed passing through. This system is automatically irrigated with a traveling boom irrigator that applies an even water flow over the seeds. The water cycles may be set from 0 to 6 passes every 2 h. Numerous manufacturers offer a basic system of five bins with the computer-controlled overhead irrigator.

In Venezuela, at Hidroponias Venezolanas, we constructed smaller bins from plastic tubs used in the laundry industry. They are 24 in. × 24 in. × 22 in. high (60 cm × 60 cm × 55 cm high). They are supported on stainless steel frames having casters to facilitate moving them from the growing area to the packing facilities. The water was dispersed by the use of two showerhead breakers mounted above each bin and a perforated plastic top as shown in Figure 5.53. A perforated false bottom provided drainage. Irrigation cycles are regulated by the use of a controller and solenoid valve in the header line for the showerheads mounted above the bins. During irrigation cycles ventilation fans are activated to exchange the air in the growing room.

The addition of dilute phosphorus and potassium nutrients during the second and third days of the growth cycle produces thicker sprouts.

Within 4–5 d, the sprouts are about 2.5 in. (6–7 cm) in length from the tip of the radical to the epicotyls (Figure 5.54). As the sprouts grow, the entire bin of sprouts should rise evenly. If low spots develop, there may be a lack of water, temperature increase, or insufficient oxygen.

Seed coats must be removed during the washing process after harvesting. Float the sprouts in an ice water bath, slightly agitating the water while skimming the sprouts from the surface with a strainer. Care must be taken in handling the sprouts to prevent contamination

FIGURE 5.53 Mung bean sprout bins. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 5.54 Mung beans harvested at 4–5 d. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

(Figure 5.54). Spin dry the sprouts with a centrifuge, package, and immediately refrigerate them at 36°F–37.5°F (2°C–3°C). A commercial washing system that cools, washes, removes seed coats, and partially dries the sprouts is available. Bacteria are controlled with a chlorine injection system within the washer.

Similar to alfalfa, mung beans should produce 8–10 times their weight in sprouts. To achieve this production, it is important to purchase high-quality seed with high viability. It should be uniform in size and free of contaminants. Each seed source and batch should be tested before ordering a large amount. Bean sprouts suffer more than alfalfa from physiological disorders and diseases. Poor oxygenation, ventilation, or high temperatures result in poor germination and uneven growth. Iron or excessive chlorine in the water produces brown roots. As with other agricultural crops successful management through constant monitoring and adjustment of environmental conditions determines productivity and quality.

5.6 MICROGREENS

Microgreens are very similar to sprouts, the difference being that they are grown in light, not darkness. They, like sprouts, can be grown on a small scale as a hobby at home or as small or large commercial operations.

Typical microgreens often include mixes of crops, Asian greens, tangy or mild mesclun mixes, radishes, and so on. To view the diversity of plants that can be used, one can view common garden seed catalogs such as Johnny's Selected Seeds (www.Johnnyseeds.com). Some common seeds include red amaranth, arugula, beets, borage, cabbages, chards, cress, kales, Mizuna, mustards, Pac Choi, purslanes, radishes, Shiso, sorrel, Tatsoi, and others.

Microgreens may be grown at home by following the simple procedure set forth here. Materials needed include plastic trays without holes, thick paper towels, a hydroponic nutrient concentrate, seeds, several compact fluorescent lights, and some bleach to sterilize the seeds. Johnny's Seeds defines a "Micro mix" as "gourmet vegetable confetti made from a variety of crops harvested at the seedling stage."

Purchase seeds specifically listed for use as microgreens, as they are not treated with fungicides. Since they are not treated, they may have fungal spores and/or bacterial spores on their surface. These pathogens must be eliminated by surface sterilization to prevent them from causing death of the germinating seedlings. If different seedlings need to be combined in the same tray, select varieties having the same growth rate. Do not combine seeds that germinate quickly with those that germinate slowly. For example, radish is ready to harvest in 5–6 d, whereas some lettuce and other greens may take 7–10 d. Some useful combinations include purple and Diakon radishes, amaranth and all greens (Figure 5.55), amaranth and mild mesclun or mizuna, amaranth and spicy mesclun or spicy greens, and Komatsuna (green or red) with wildfire lettuce.

Surface sterilization of the seeds before placing them on the paper towels or capillary matting is critical to success. Use a 10% bleach solution (1 part bleach to 9 parts water) in a plastic cup to swirl the seeds around for 3–4 min; then rinse with raw water using a household strainer (Figure 5.56). Moisten the paper towels or mat with some raw water and then place the seeds from the strainer into the tray with a spoon and spread evenly around the surface using the spoon or clean fingers (Figure 5.57). When adding raw water for the first 3 d until the seed germinates, be careful to pour the water slowly along the edge of one end of the tray so that the seeds do not float.

Keep the sow tray under two compact fluorescent lights of about 30 W. The lights should be about 12 in. (30 cm) above the tray. Operate the lights for 12–14 h/d using a simple household time clock. After germination and the seeds have grown into the paper towels or mat (usually 3 d), start using a dilute nutrient solution (half the normal recommended strength). Nutrient concentrates can be purchased from hydroponic shops. Harvest the seedlings after 7–10 d using a pair of scissors to cut off the shoots as the roots are not consumed (Figure 5.58).

FIGURE 5.55 All greens and amaranth ready to eat at 7–10 d.

FIGURE 5.56 Surface sterilizing seeds with 10% bleach solution. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 5.57 Spreading clean radish seed over capillary mat in tray.

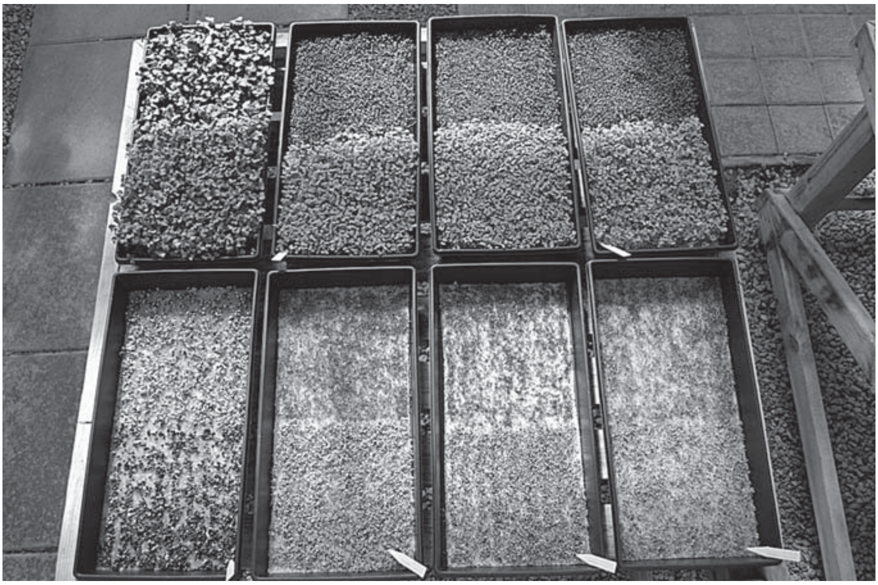

FIGURE 5.58 Trays at 2 d and 9 d from sowing. (From CuisinArt Resort & Spa, Anguilla. With permission.)

In general, commercial microgreen operations are not very large as the market demand is very limited. Usually a grower of other crops such as herbs and/or lettuce will set up a small area in his greenhouse for microgreen production. CropKing in Ohio (www.CropKing.com) builds systems for small commercial operations. They have two different sizes of microgreen packages, a two-rack system that fits in 18 ft × 28 ft (5.5 m × 8.5 m) of a greenhouse that is capable of producing 50 lb/wk (23 kg/wk) and a four-rack system that requires 22 ft × 56 ft (6.7 m × 17 m) that should produce 100 lb/wk (46 kg/wk).

Their basic one-rack system consists of 24 PVC growing channels on a galvanized steel frame housing 4 channels on each of 6 levels with the plumbing system delivering nutrient solution to each growing channel (Figure 5.59). Each rack is 14 ft (4.27 m) long by 44 in. (1.1 m) wide by 6 ft 4 in. (1.9 m) high. A submersible pump in a tank below circulates the solution to the trays, and the solution returns to the tank or cistern (Figure 5.60). This system can easily be part of an NFT lettuce or herb system using the same tank, pump, chiller, and so on.

The microgreens are seeded on a capillary mat; in the case of the CropKing's system they use burlap mats (Figure 5.61). The mats hold the seeds in place so that they will not wash away on irrigation. The mats are needed to distribute the nutrient solution and retain moisture between irrigation cycles.

The irrigation system is a closed system, with the solution entering via drip lines on one end and collected by return pipes to the cistern (Figures 5.59 and 5.60). Valves at each channel permit adjustment of flow to each channel. The channels are sloped to the drain ends, similar to an NFT system. A typical system growing microgreens is shown in Figures 5.62 and 5.63.

Crops are ready to harvest from 7 to 14 d, depending on the growth rate of the particular species. The burlap mat is removed from the growing channels with the plants attached and hung to "drip dry" for a short time. Then the mat is moved to a supporting area where

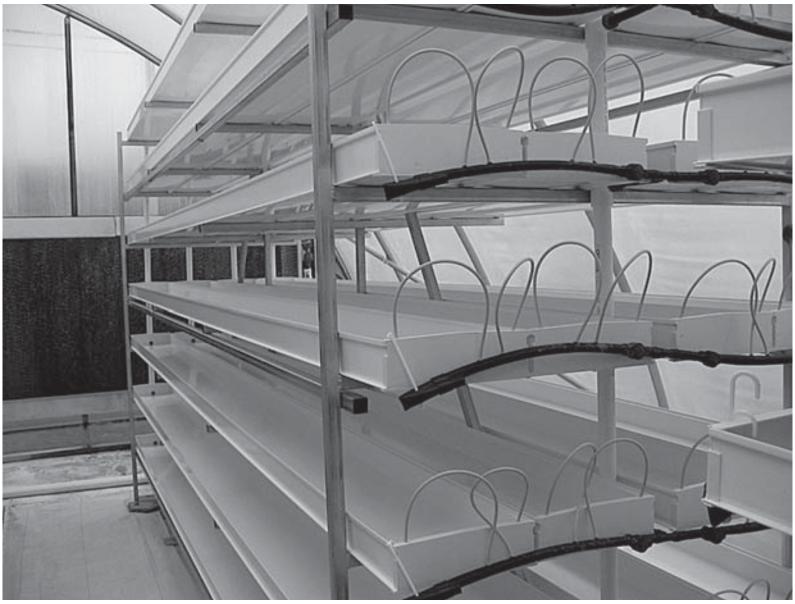

FIGURE 5.59 A basic one-rack microgreen system. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.60 The basic one-rack microgreen system showing the drain ends. (From CropKing, Inc., Lodi, OH. With permission.)

they hang over a tub that collects the product as it is cut with an electric knife (Figure 5.64). They are then placed in clamshell containers and packaged for delivery. This is a different approach from Koppert Cress B.V. that grows the microgreens within the clamshells.

One of the largest growers of microgreens is Koppert Cress B.V. with greenhouse operations in Holland and other European countries as well as in North America. They grow in

FIGURE 5.61 Microgreens germinating on burlap mat. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.62 Microgreens growing in channel on the rack showing the inlet drip line. (From CropKing, Inc., Lodi, OH. With permission.)

an ebb and flood system (Chapter 6). They focus on the restaurant trade worldwide, but also sell products in clam shell (rigid plastic) containers (similar to sprouts) to the retail supermarket trade (Figure 5.65) and in sleeved plastic containers without lids (Figure 5.66). They sow the seeds in a clean medium of natural fibers (Figures 5.67 and 5.68). Products are food safe and can be used as is without washing.

FIGURE 5.63 Microgreens growing in the rack system. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.64 Microgreens “drip drying” before harvesting. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.65 Sakura cress microgreens in a clam shell container.

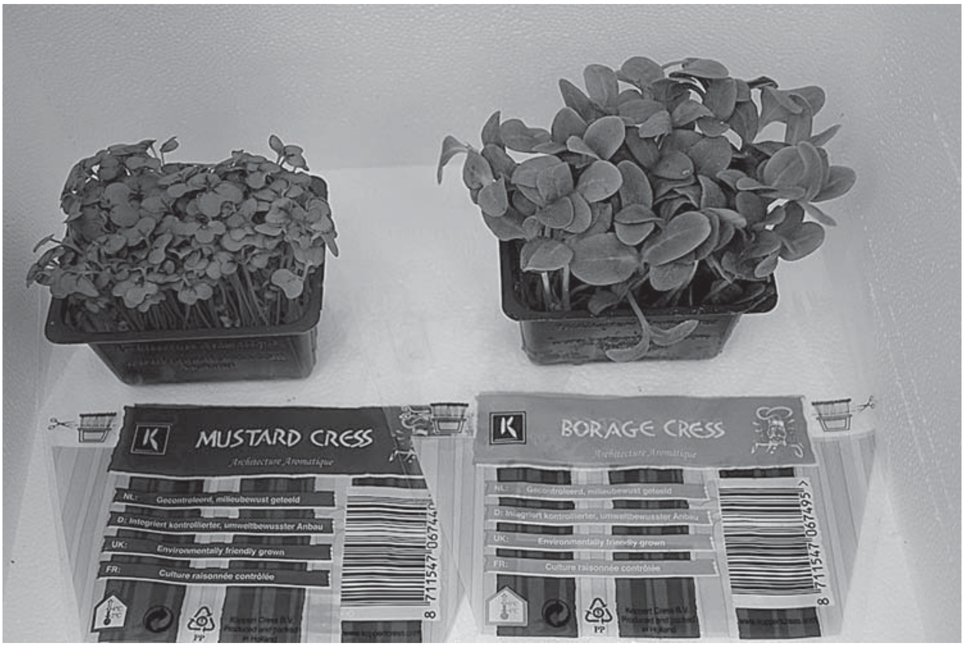

FIGURE 5.66 Mustard and borage cress microgreens.

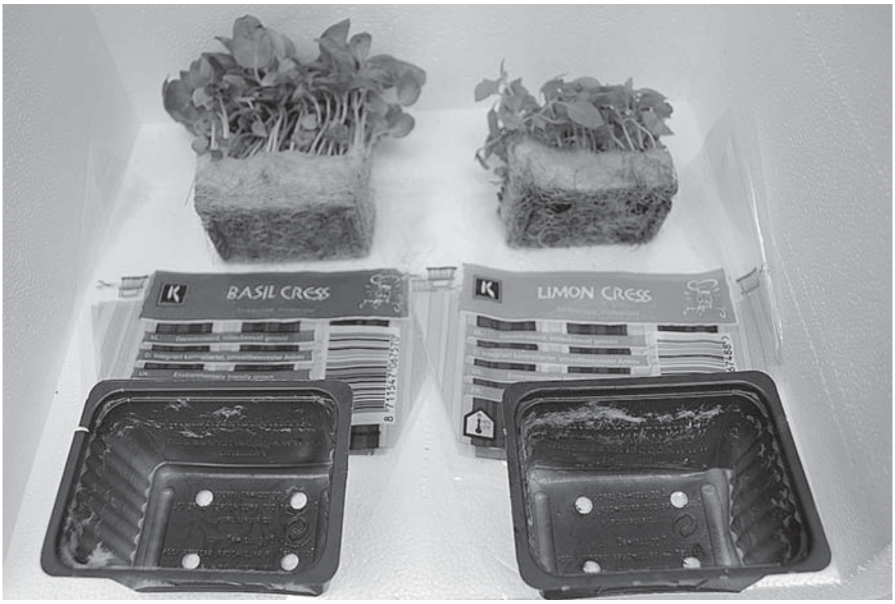

FIGURE 5.67 Sweet and lemon basil cress.

FIGURE 5.68 Italian sweet basil microgreens growing in natural fiber.

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6 Nutrient Film Technique

6.1 INTRODUCTION

The nutrient film technique (NFT) is a water-cultural technique in which plants are grown with their roots contained in a plastic film trough or rigid channel through which nutrient solution is continuously circulated.

Work on NFT cropping was pioneered by Allen Cooper at the Glasshouse Crops Research Institute in Littlehampton, England, in 1965. He continued with modifications of the NFT system and wrote reviews during the 1970s and 1980s (Cooper, 1973, 1985, 1987a, 1987b). The term *nutrient film technique* was coined at the Glasshouse Crops Research Institute to stress that the depth of the liquid flowing past the roots of the plants should be very shallow in order to ensure that sufficient oxygen would be supplied to the plant roots. Other workers (Schippers, 1977) call it *nutrient flow technique* since the nutrient solution is continuously circulated.

6.2 EARLY NFT SYSTEM

In the earliest NFT system, a catchment trench was dug across the middle of the greenhouse floor and the ground sloped on either side toward the trench. A minimum slope of 1% to a maximum of 4% was tested. The steeper slopes reduced the effect of localized depressions. The trench was lined with either vinyl or polyethylene film. "Layflat" polyethylene troughs were placed on strips of board 8 in. (20 cm) wide at the normal spacing of plant rows sloping toward the central catchment trench from each side (Figure 6.1). Holes were punched in the layflat film at centers suitable for the specific crop to be grown. The lower end of each trough hung down into the catchment trench, while the upper end of each line was turned upward and over and sealed with PVC tape to prevent the loss of nutrient solution.

Nutrient solution in the catchment trench was circulated to the upper ends of each layflat by a submersible pump and ABS plastic piping. Gate valves installed at the inlets to each layflat line regulated the flow of nutrient solution evenly into each trough. The roots of the plants were inserted into the layflat through the planting holes, and the upper parts of the plants were supported in the normal way by tie strings suspended from support cables in the greenhouse.

6.3 LATER NFT SYSTEMS

The NFT system went through many modifications in an attempt to resolve oxygen deficit and ethylene buildup problems in plant roots. Plants were sown and grown to transplants in peat pots, peat pellets, or rockwool cubes and then placed on a narrow polyethylene sheet in each plant position in the row. The edges of the polyethylene were turned up and around the sides of these growing pots or cubes and stapled between every other pot (or cube) to form a gully through which a thin stream of nutrient solution flowed.

While this configuration (Figure 6.1) permitted better ventilation within the gully and reduced ethylene buildup, it still was not the solution for many longer term vine crops such

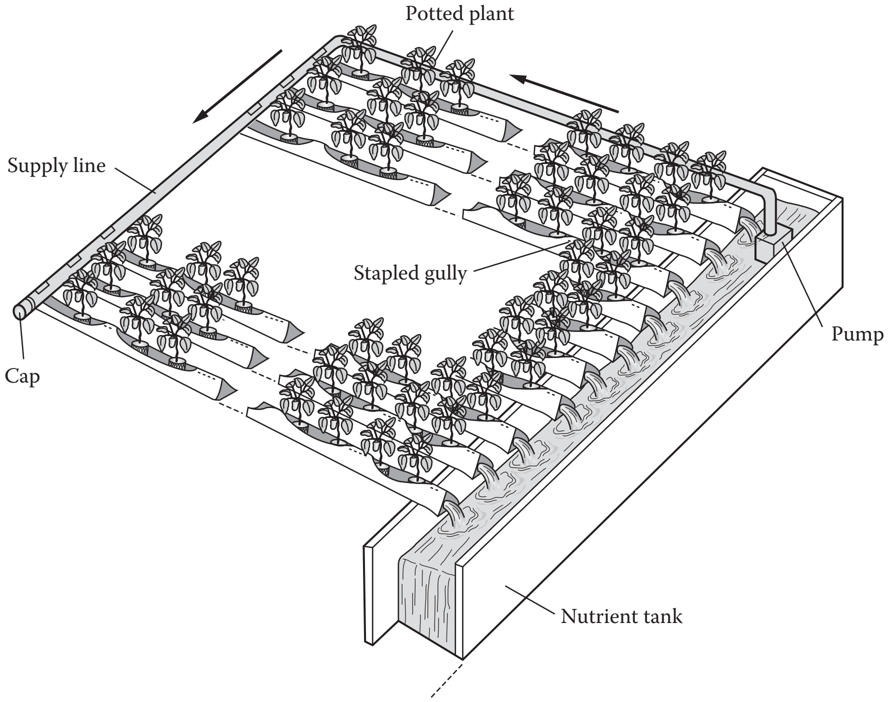

FIGURE 6.1 Layout of a series of NFT gullies and solution tank. (Adapted from Cooper, A.J., *The Grower*, 79, 1048–1052, 1973. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

as tomatoes, cucumbers, and peppers. The roots of these crops quickly grow through the pots (or cubes) and spread out in the shallow stream of nutrient solution flowing down the gullies. They merge to form a single, thick, continuous mat at the bottom of the gullies, which eventually blocks the flow of solution and causes the solution to rise within the gullies, reducing oxygenation to the roots.

6.4 COMMERCIAL NFT SYSTEMS

In the early 1990s, large commercial operations growing tomatoes were attempted in over 68 countries. However, these oxygen deficit problems continued, with the exception of the growing of low-profile, short-term crops such as lettuce and some herbs. Rockwool was introduced in the 1990s, and it soon became the most accepted method of growing vine crops such as tomatoes, peppers, and cucumbers. Today, the NFT system is used principally for lettuce and herbs.

A layout of an NFT system is shown in Figure 6.2. Nutrient solution is pumped through a main PVC pipe to headers that are located at the high ends of the NFT channels. The solution is discharged from the headers into the gullies or channels through small flexible drip lines. The solution flows by gravity down the channels and is drained at the lower end to a large catchment pipe, which conducts the solution back to the cistern. Such channels for growing low-profile crops are located on benches to facilitate caring of the plants. This is discussed later in this chapter under Section 6.6.

Some growers have developed a modified rockwool-NFT system in which they grow the plants in partial slabs of rockwool placed in NFT channels. This system grew vine crops

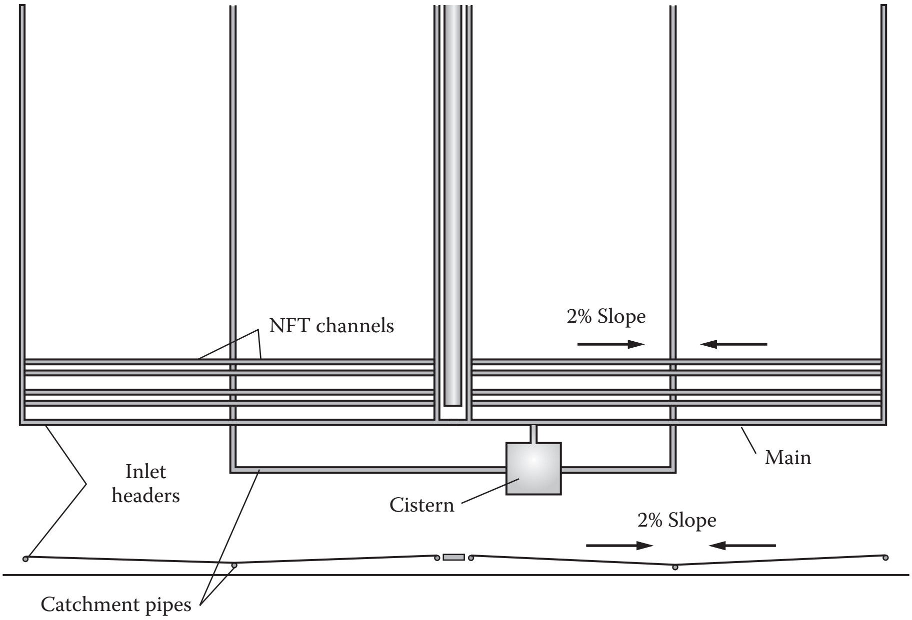

FIGURE 6.2 Layout of an NFT system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

without any lack of oxygen. But, it is more complicated and still does not provide as much oxygenation to the plant roots as a complete rockwool setup. For further information on NFT systems refer to Edwards (1985), Burrage (1992), Goldman (1993), and Gilbert (1996).

6.5 NUTRIENT FLOW TECHNIQUE: VERTICAL PIPES, A-FRAME, OR CASCADE SYSTEMS

In 1977, Dr. P.A. Schippers developed what he termed the *nutrient flow technique* at the Long Island Horticultural Research Laboratory of Cornell University at Riverhead, New York. He modified the NFT system in an effort to save greenhouse space. By increasing the number of plants that can be grown in a given area of greenhouse, the cost per plant can be reduced. Experimental work was performed with lettuce in vertical pipes, down which the nutrient solution dripped, moistening and feeding the plants. Such a system is demonstrated at Epcot at the Walt Disney World Resort near Orlando, Florida, as shown in Figures 5.37 and 5.38.

A nutrient solution is sprayed into the vertical pipes traveling on a conveyor system. As the pipes carrying the plants pass the point where nutrients are sprayed onto the roots within the pipe, they travel above a nutrient collector reservoir; thus the immediate drainage flows back into the system.

This system is used to grow lettuce, herbs, strawberries, and squash. The best prospect for this system is for crops that are harvested over a longer period, such as strawberries, peas, beans, and so on.

He pursued different ways to increase the use of vertical space in the greenhouse by use of the NFT, particularly for low-growing crops such as lettuce (Schippers, 1980). He built what he termed the *cascade system*. Growing troughs of 3-in. (7.6 cm)-diameter PVC plastic pipe were cut open and suspended one above the other up to eight troughs high.

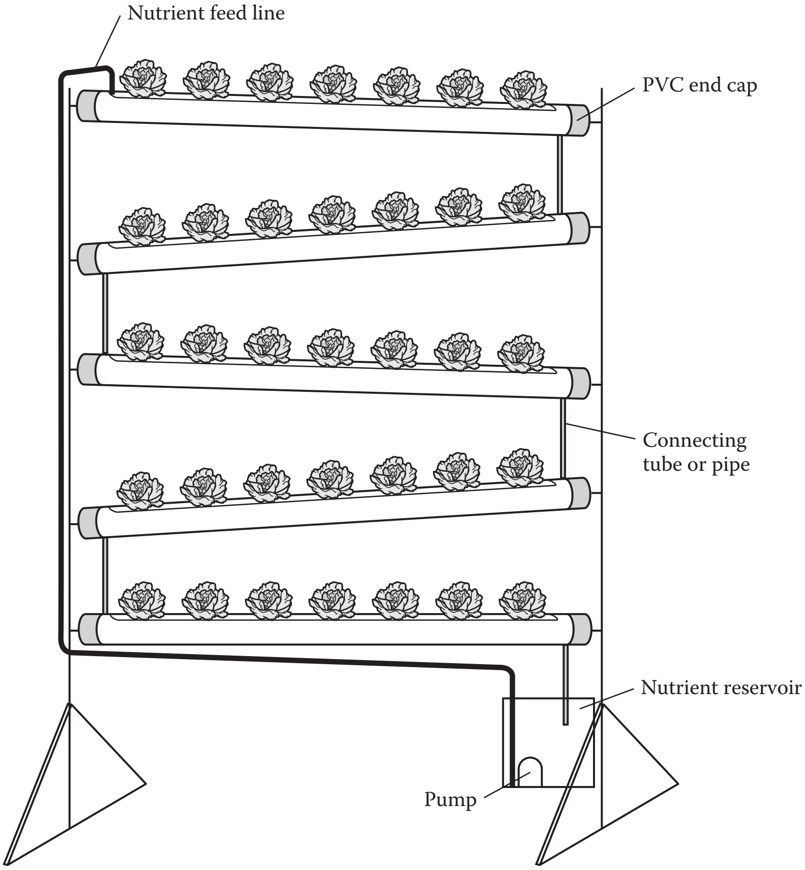

FIGURE 6.3 Details of a "cascade" NFT system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

The nutrient solution entered the high end of the slightly sloping top pipe, exited at the low end of that pipe into the high end of the next one, and so on, to the reservoir from where it was pumped. The system was successful with lettuce, radish, peas, and other crops. This system, shown in Figure 6.3, is used for fairly small plants.

The system is more efficient in utilization of greenhouse space if the growing channels are mounted on A-frames. The A-frames must be oriented north–south in the northern latitudes so that shade from one side will not be cast on the other. The system is suitable only for low-profile plants such as lettuce, strawberries, spinach, and some herbs.

Several factors must be considered in the design of the A-frame system. The base of the frame must be wide enough to eliminate any mutual shading of one tier over the next lower one. The tiers of growing channels must be separated from each other with adequate distance to allow for the mature height of the crop grown. That is, the plants of a lower tier must not grow into those of the tier above. Finally, since this is basically an NFT system, all principles of oxygenation, nutrition, and optimum solution temperature apply. The total channel length for any combination of tiers should not exceed 30 m (100 ft) in order to provide sufficient oxygenation. The distance of the combination of tiers can be reduced by draining sections into a main return header to the cistern below. A minimum slope of 2% is necessary to provide adequate solution flow.

Plants may be sown in rockwool cubes (1.5 in. × 1.5 in. × 1.5 in.) and later placed in mesh pots that fit into the plant spaces of the NFT channels. A large root mat will form at the base of the pots and grow together.

While the productivity is greater, the capital cost of such a cascade system and the additional time required to clean each channel between crops do not make it economically feasible when almost the same plant density can be achieved using the floating (raft) system.

6.6 GUTTER AND PIPE NFT CHANNEL SYSTEMS

A gutter NFT system may be constructed of conventional plastic eaves troughs used for homes, or a system may be purchased from several manufacturers of rigid PVC extruded growing channels, such as those available from American Hydroponics and CropKing (Appendix 2). This NFT channel is 4 in. (10 cm) wide and 1.5 in. deep (4 cm). Rehau Plastics, Inc. also makes an NFT gutter with a slightly different configuration. NFT channels are also available in extruded aluminum and are fabricated on-site by companies such as Zwart Systems (Appendix 2). These NFT channels are particularly suited for the growing of lettuce and herbs. While some manufacturers of NFT gullies make wider and deeper channels for other crops, the author would not recommend growing crops other than low-profile ones such as lettuce, bok choy, and herbs. Long-term crops with larger root systems plug the gutters, causing lack of flow of the nutrient solution and a resultant lack of oxygen, leading to blossom-end rot on fruit and eventual death of the plant.

The channels are available in any length but should not exceed 50 ft (15 m), as insufficient oxygenation, blockage of channels by roots, and nutrient gradients may occur. Channels of 50 ft length would be awkward to handle during harvesting and cleaning.

The maximum practical length would be about 15 ft (4.6 m). The channels are supported on metal frame benching to be at about waist height for convenience of working with the plants (Figure 6.4). Channels are sloped at 2%–3% away from a central aisle to a catchment

FIGURE 6.4 Benching system constructed for support of the NFT channels. Note: The channels placed on the bench in the back. Also, note that the benches are sloping toward the greenhouse sidewall posts and there are 3-in. PVC drain pipe risers for the catchment trench to drain to for return to the nutrient cistern. (From American Hydroponics, Arcata, CA. With permission.)

FIGURE 6.5 Basil in NFT channels (ribbed) with drain ends of channels into open collection (catchment) gutter. (From American Hydroponics, Arcata, CA. With permission.)

channel (Figure 6.5). For example, in a 30-ft (9-m)-wide greenhouse, two sets of NFT gullies (two 13 ft or one 12 ft and one 14 ft long) (4 m, 3.6 m, 4.3 m) can be sloped away from a 4-ft (1.2-m) central aisle to the catchment channel at the sidewall of the greenhouse. Channels are ribbed on the bottom for central flow of the solution.

Channels should have covers to prevent light entering and thus avoiding algae growth inside (Figure 6.6). Most leafy plants such as lettuce are spaced at 8 in. (20 cm) within the channel, and channels are spaced at 6–7 in. (15–18 cm) from center to center. Smaller herbs

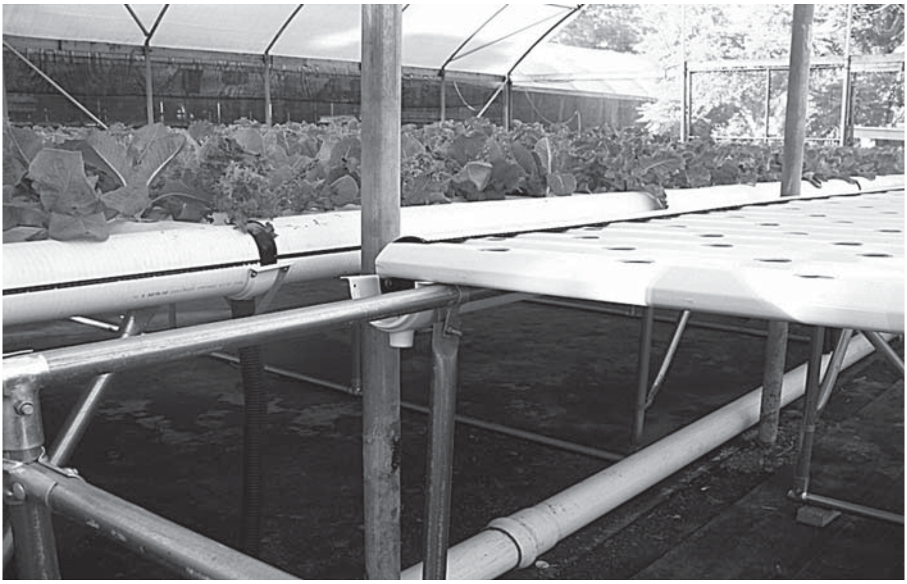

FIGURE 6.6 Closed catchment gutter. Note: The drain line from the catchment trench to the main return to the cistern. (From American Hydroponics, Arcata, CA. With permission.)

FIGURE 6.7 Basil growing in an NFT system. Note: The inlet tubes, header and risers with valves from main below at floor level. (From American Hydroponics, Arcata, CA. With permission.)

can be spaced 6 in. (15 cm) within the channels and 6 in. (15 cm) between channels. Basil and lettuce grow very well in an NFT system (Figure 6.7).

Plants are seeded in 1-in. rockwool cubes or Oasis cubes (stage 1) and after 10–18 d are transplanted to nursery channels (stage 2) (Figure 6.8). These nursery channels have plant holes at 2 in. (5 cm) within the gully and are separated by 4 in. (10 cm) center to center.

FIGURE 6.8 Numerous varieties of lettuce. Note: The four nursery channels on the right side. (From American Hydroponics, Arcata, CA. With permission.)

This NFT system utilizes approximately 80% of the greenhouse floor area. In a 1-acre greenhouse with 30-ft (9.1-m)-wide ranges, allowing for central aisles of 4 ft (1.2 m), two sets of 13-ft beds (4 m) could be oriented perpendicularly to the gutters and posts of the greenhouse. The greenhouse with 12 ranges of 30 ft × 120 ft (9.1 m × 36.6 m) would contain, using 8 in. × 6 in. spacing of channels, 105,000 plants (8,800 plants per range). This assumes using two benches 13 ft × 110 ft of useable greenhouse floor area per range.

An example of a cropping sequence for lettuce is as follows:

(Note: This sequence will vary by location, as it is dependent on sunlight and day length).

1. Sow in 1-in. rockwool cubes in 200 pads per flat (1 ft × 2 ft trays) (30.5 cm × 62 cm).
2. Grow in these flats on a propagation bench for 18 d (stage 1).
3. Transplant to nursery channels at 18 d (stage 2).
4. Grow for 10–12 d (28–30 d from sowing) in nursery channels.
5. Transplant finally to growing (finishing) channels at 28–30 d from sowing (stage 3).
6. Grow for 20–25 d (25 d gives 14 crops per year) in growing channels.

Total days from sowing to harvest: 18 + 12 + 25 = 55 d. The reason for using the nursery channels is to make more efficient use of the bench area, as the final growing stage 3 will be of less duration than if the plants were placed in the finishing channels after stage 1.

To harvest, the channels are removed with the plants intact (Figure 6.9). This allows the grower to select the more advanced plants to harvest earlier than smaller heads of the same age, should this occur during unfavorable weather conditions. After selectively harvesting, the channels may be replaced in their original position to allow the remaining lettuce to continue growing until they reach harvestable weight. However, on a large-scale operation, this is not possible, as the cropping cycle would be interrupted. Plants are cut off at the crown with a sharp knife. In some cases, the plants may be packaged in clamshell

FIGURE 6.9 Removal of entire NFT channel from growing table to allow easy harvesting. (From Gourmet Hydroponics, Inc., Lake Wales, FL. With permission.)

containers so the roots are pruned back, but still intact in the growing cube to keep the product fresh in the market.

Any dead or yellowing leaves at the base of the plants are removed before moving them to the packing area. The channels are transported to a central cleaning and sterilizing vat where they are rinsed with clean water followed by soaking in a 10% bleach solution for at least 1 h. The trays should be rinsed with water upon removal from sterilization and allowed to dry.

Lettuce is packed in polyethylene bags and placed in cardboard boxes for shipping. It must be refrigerated at 35°F (1.7°C). The shelf life for Bibb lettuce is 7–10 d.

In many countries, including Brazil, the NFT system of growing lettuce, herbs, and particularly arugula has become popular, resulting in a rapidly expanding hydroponic industry. Often it starts out as experimental work in a university and then gets applied on a commercial scale. In Florianopolis, Brazil, Universidade Federal de Santa Catarina conducts research on the growing of herbs, lettuce, and arugula using NFT (Figures 6.10 through 6.12).

They are experimenting with coating the surface of the NFT channels with an aluminum foil tape to reflect heat from the gullies in an effort to maintain lower temperatures of the

FIGURE 6.10 Arugula (Roquette) in NFT channel. Note: The plants are sown in a type of "Oasis" cube. Also, two cubes with about 10 seedlings are set into each planting hole of the NFT channel. (From Universidade Federal de Santa Catarina, Florianopolis, Brazil. With permission.)

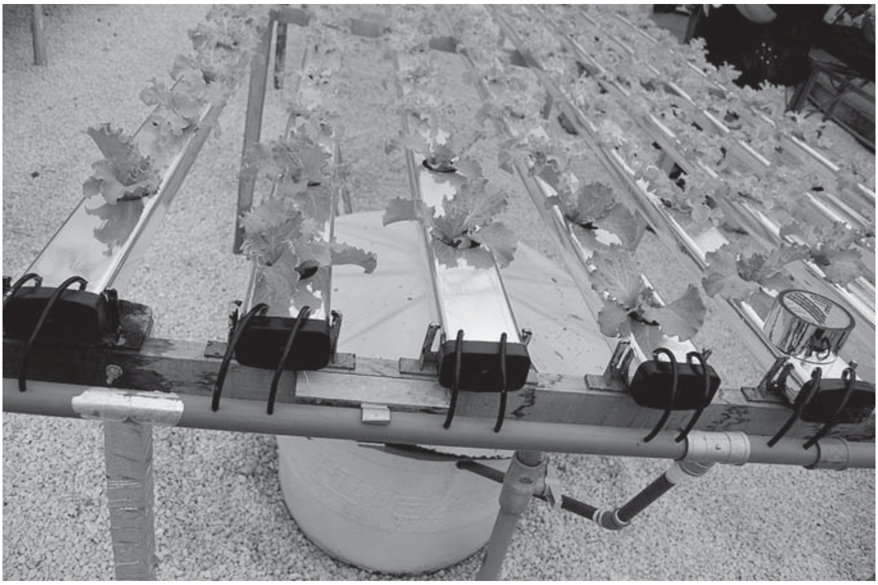

FIGURE 6.11 Lettuce in NFT channels coated with reflective foil tape to reduce root temperatures. (From Universidade Federal de Santa Catarina, Florianopolis, Brazil. With permission.)

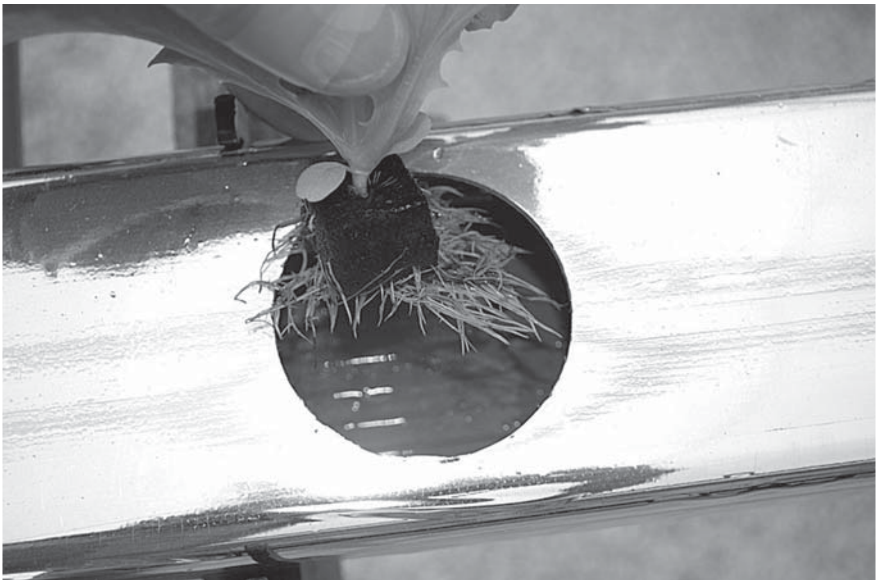

FIGURE 6.12 Young lettuce seedling rooting well into the NFT channel. Note: The healthy roots spreading out from the growing cube. Also, notice the ridges in the bottom of the NFT channel, which direct the flow of the nutrient solution under the plants. (From Universidade Federal de Santa Catarina, Florianopolis, Brazil. With permission.)

nutrient solution. Once an industry develops a method for growing these crops with NFT, companies manufacture NFT channels and other hydroponic supplies and components, such as greenhouses, irrigation equipment, nutrients, substrates, and pest and disease control products. For example, Dynacs in Sao Paulo, Brazil, manufactures NFT channels of numerous dimensions.

FIGURE 6.13 Arugula marketed in sleeved packages containing two bunches. (From Hidroponia Mandala, Brazil. With permission.)

Harvested arugula is often sold in sleeve packages with two bunches of arugula as shown in Figure 6.13. The roots and cubes are kept on the bunches.

6.7 AGRI-SYSTEMS NFT

A highly efficient system of NFT was developed in the 1980s by Agri-Systems, Somis, California. Seedlings are grown in 154-celled "cream cup" trays. Holes are slit in the bottom with a special multibladed table saw. The trays are filled with coarse vermiculite and seeded with European Bibb lettuce using a flat filler machine and automatic seeder. The seedlings are grown either in a small seedling greenhouse or in a controlled environment growth room with artificial lighting, automatic watering, and temperature control (Figure 6.14). To reduce electrical costs, the seedlings were later grown in a separate seedling greenhouse using an ebb-and-flow (E&F) system. Within 3 wk, the seedlings are ready to be transplanted into the NFT channels in a greenhouse. The small cells containing the seedlings in the plastic trays are punched out of the trays, and the small lettuce plant with its cell is planted directly into a moveable tape within the growing channel (Figures 6.15 and 6.16). The slits in the bottom of the cells allow roots to grow through into the nutrient solution of the growing channel.

A planting–harvesting machine feeds a coiled heavy plastic tape into the grooves of the growing channel. Holes are punched in the tape at the correct spacing for the lettuce. The operator of the planting machine simply drops the cells containing the seedlings into the holes of the tape as it feeds into the NFT channel (Figure 6.16).

Agri-Systems tested lettuce production with 2–5 tiers of channels. They found that the five-tier system did not allow sufficient natural sunlight to enter the lower levels to support plant growth adequately in order to achieve a marketable product. The two-tier system was the most productive in utilizing all available light; however, a large percentage of the lettuce in the lower level was not of top quality because of lack of light (Figure 6.17).

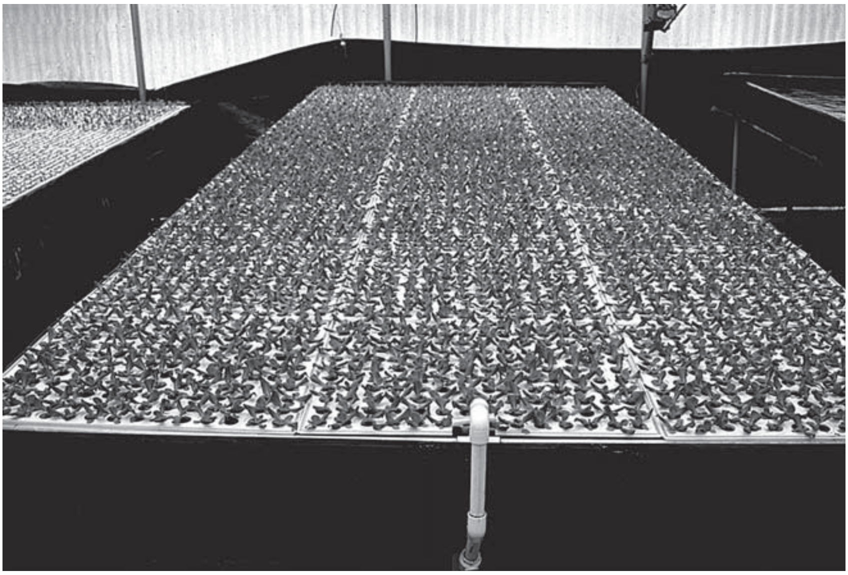

FIGURE 6.14 Lettuce seedlings in vermiculture in 154-celled plastic trays in a seedling greenhouse with an ebb-and-flow hydroponic system. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

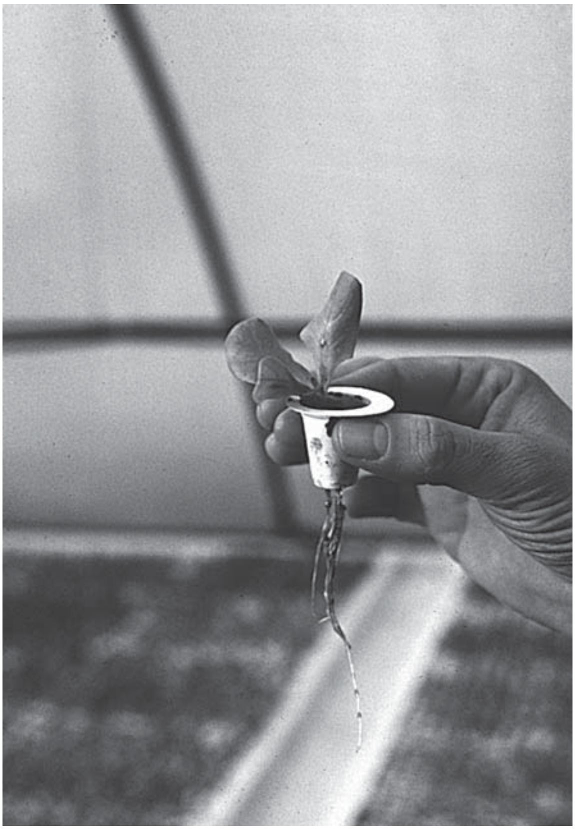

FIGURE 6.15 Lettuce seedling growing in plastic cell.

FIGURE 6.16 Transplanting lettuce seedlings into moving tape cover of NFT channels. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

FIGURE 6.17 Agri-Systems lettuce production in four tiers of NFT troughs. (From Whittaker Corporation's Agri-Systems division, Somis, CA. With permission.)

Planting was scheduled so that rows at various stages of maturity were mixed to allow maximum light penetration to the lower tier. If plants of similar age were placed in the channels adjacent to each other, insufficient light would pass to the lower tier as the lettuce matured.

The company claimed that with their system, 8 million heads of lettuce could be grown annually on a 2.5-acre (1-ha) operation in comparison with 75,000 produced in the same area by conventional open-field farming. This is equivalent to 9 lettuces per square foot of greenhouse area per crop, or 72 heads per annum if 8 crops are produced per year. If only 6.5 million are marketable from the total production of 7.5–8 million, the estimated labor cost is just over \$0.02 per head compared to \$0.07–\$0.10 per head for field-grown lettuce.

It is doubtful that these objectives were reached, as the greenhouse operation was repossessed by the original owners and the tier system of growing channels was abandoned in favor of a single level. Agri-Systems, in the early 1990s, helped establish two other greenhouse operations of about 0.5 acre each in the Somis area. Agri-Systems provided the NFT growing system components and the transfer of technology to these growers.

One of these greenhouses, F.W. Armstrong Ranch, operated about 20,000 ft^2 (1,860 m^2) of lettuce production. The NFT channels were raised about 3 ft (1 m) above the floor of the greenhouse with an aluminum supporting frame (Figure 6.18). From the cooling pad end, fans blew cool air underneath the beds.

The fans brought air through the cooling pad and blew the cooled air down convection tubes located on the floor going across the house and under the lettuce channels. This positive-pressure cooling system was contained under the NFT channels by use of perimeter polyethylene curtains (Figure 6.19). The air rose up through the greenhouse to exit by overhead vents in the saw-tooth structure.

The NFT channels, constructed of aluminum, were approximately 3 in. (7.6 cm) wide by 2 in. (5 cm) deep, with heat sink ridges built into their bottoms to assist in cooling (Figures 6.20 and 6.21). Plants are supported in the flexible plastic tape that sits between several ridges on the inside top edge of the channel.

The NFT channels were 150 ft (46 m) long, but later reduced to 73 ft (22 m) and 70 ft (21 m) with a 7-ft (2-m) aisle in the middle of the greenhouse. Each of the two sections contained 228 channels. In this way, two separate systems operate, each with its own nutrient-solution tank. If a problem arises in one section, it is easier to isolate and remedy it

FIGURE 6.18 NFT channels raised about 3 ft by a metal frame. Note: The convection tubes underneath the table and the cooling pad behind the deflector panels at the upper right. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

FIGURE 6.19 Perimeter polyethylene curtain around beds contains cooled air under the beds. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

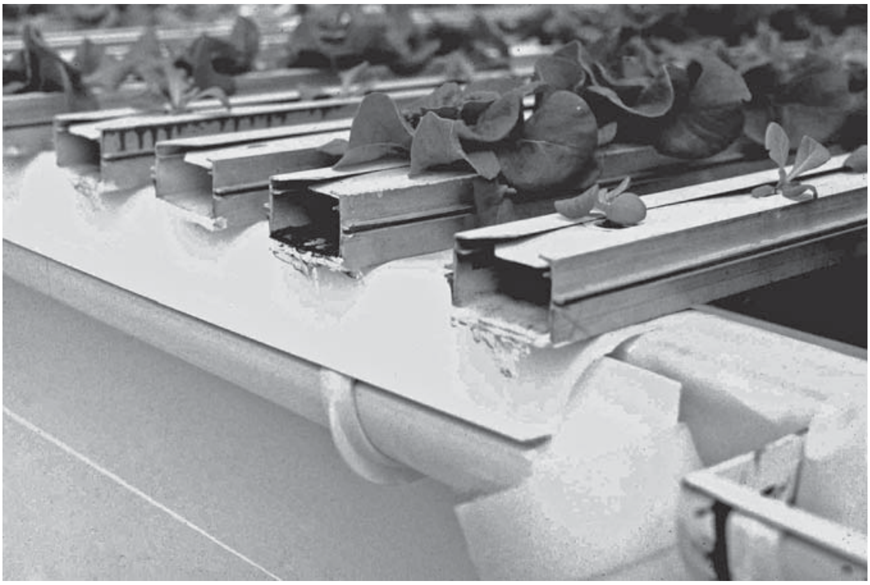

FIGURE 6.20 Aluminum NFT channels exit to a catchment pipe that returns nutrient solution to a cistern. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

without interrupting the production of the other. Nutrient solution is pumped from a 500-gal (1,890-L) cistern at the cooling pad end of the greenhouse to the inlet end of each channel via a 1.5-in. (3.8-cm)-diameter PVC header and a 0.25-in. (0.6-cm) drip line (Figure 6.21). The NFT channels have a 2% slope toward the catchment end, where the nutrient solution is collected and returned to the nutrient tank (Figure 6.20). Plants are spaced at 6 in. × 6 in. (15 cm × 15 cm) to make a total of 70,000 plants in the 20,000 ft^2 of the greenhouse.

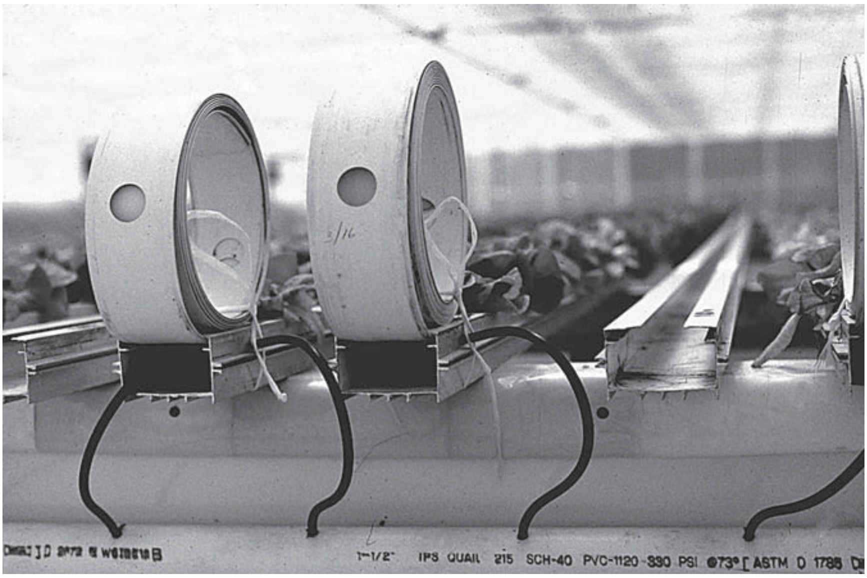

FIGURE 6.21 Inlet ends of NFT channels. Note: The heat-sink ridges at the bottom of the channels, inlet header with a feeder tube to each channel and coil of flexible-tape channel cover supported by ridges in top of channel. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

The cropping schedule for lettuce is from 28 to 38 d, depending on weather conditions, especially sunlight hours and day length, with the shorter period between harvests occurring during the late spring and early summer months. Therefore, about 10 crops are expected annually. Armstrong Ranch harvests on an average 2,200 heads daily. At 6-in. (15 cm) centers, there are approximately 140 plants per 70-ft (21-m) row. About 16 rows are harvested daily. This is based on a 32-d cropping period.

A harvesting machine is used to pull the moveable tape from the NFT channel and roll it up as the operators cut the heads of lettuce from the tape (Figure 6.22).

The lettuce is stored in a mobile refrigeration unit, which then transports it to the packing area (Figure 6.23). The lettuce is packaged individually in a heat-sealed polyethylene bag and shipped as 12 heads per box (Figure 6.24).

The moveable tapes are sterilized in a vat of 10% bleach solution. After rinsing and drying, they are placed one at a time on the transplanting machine and are threaded back into the NFT channels while placing the seedlings into them as described earlier. The sequence is to transplant every third row of channels until the last row is reached. Then repeat and plant every second row, and finally the last row. In this way, smaller plants are next to the older, more mature plants (Figure 6.25). This gives better light to the crop, and during harvest when the tape is pulled, the plants do not brush into one another.

6.8 HORTIPLAN AUTOMATED NFT SYSTEM

Hortiplan N.V., near Mechelen, Belgium (www.hortiplan.com/MGS), has designed and installed fully automated NFT systems. Belgium has over 600 ha (1,500 acres) of greenhouse lettuce production. Of the 600 ha, 500 ha are in greenhouses without central heating, so are termed *cold frames*. The other 100 ha are heated greenhouses. Most of these producers grow in soil. A number of operations in Belgium and Holland

FIGURE 6.22 Use of harvesting–transplanting machine to pull rows of lettuce from the channels. Operators cut the lettuce off at their base as the tape passes to be rolled up below. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

FIGURE 6.23 Mobile refrigeration unit with storage crates. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

FIGURE 6.24 Packing of lettuce in heat-sealed plastic bags. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

FIGURE 6.25 Rows of lettuce showing the sequence of planting dates. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

have converted their soil-growing lettuce operations to the automated "mobile gully system" (MGS) of Hortiplan. They have also installed MGS in Australia, Italy, United Kingdom, and Latvia. The company is presently constructing a greenhouse operation in Chile using the MGS NFT system. One company in the United States, Holandia Greenhouses, Carpenteria, California, has 7.2 ha (18 acres) of lettuce and herbs growing using the MGS.

The seedlings are grown in a special nursery room separate from the automated production area, or in countries that have a large concentration of lettuce growers, this seedling production can be contracted to a specialized nursery company. Sowing is into large peat cubes at a density of 300/m^2 (Figure 6.26). They are grown 3–4 wk before entering the automated production area.

The plants then enter the first part of MGS, the extended nursery. This extended nursery is especially advantageous for growers producing heavy lettuce (large heads). About 7% of the surface area contains more than 32% of the total number of plants in the greenhouse. They are removed and placed in special trays of 100 seedlings per square meter (Figures 6.27 and 6.28) where they can grow under very high density. The peat blocks are spaced 5 cm × 5 cm (2 in. × 2 in.) in summer and 6 cm × 6 cm (2.3 in. × 2.3 in.) in winter (October–March). In winter, the larger blocks are used, as they need fewer irrigation cycles, thus reducing humidity and possible fungal infection. The extended nursery is generally an area at the front of the greenhouses near the growing gullies. These trays move along a bench from the side where they are transplanted to the other side near the NFT gullies. After 10–14 d in winter or after 7 d in summer they are transplanted to the NFT channels (gullies) (Figure 6.29). Transplanting can be done manually or by a plant robot (Figures 6.30 and 6.31).

When the gullies are transplanted, they automatically move on a conveyor underneath the benching to the far end of the benches (Figure 6.32). There they are raised and set

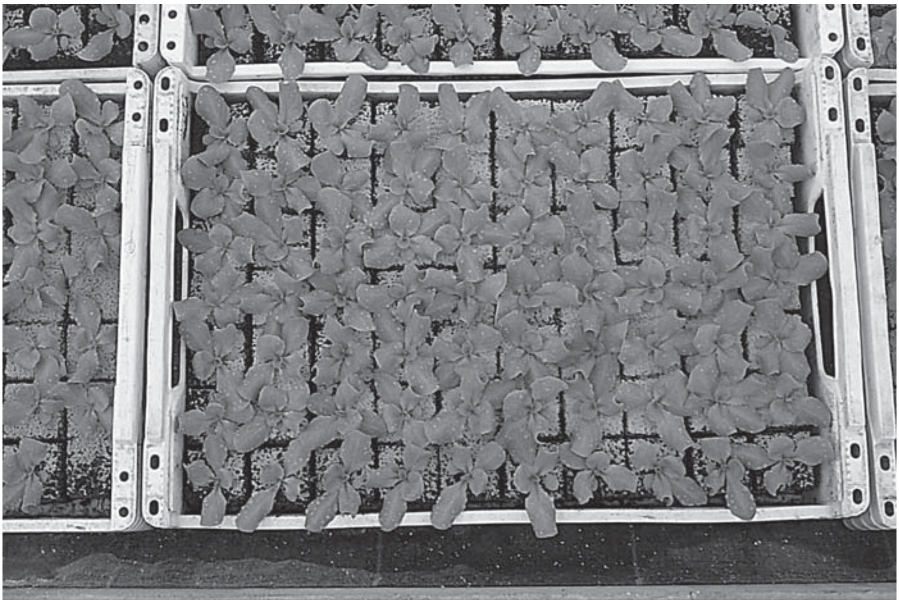

FIGURE 6.26 Lettuce seedlings 3–4 wk old ready to enter the extended nursery. (From Hortiplan N.V., Belgium. With permission.)

FIGURE 6.27 Lettuce seedlings arriving in nursery trays on left and transplanting to the extended nursery on the right. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.28 Transplanting lettuce seedlings to special nursery trays in the extended nursery. Note: The combination of red and green oakleaf lettuces in each block. (From Hortiplan, N.V., Belgium. With permission.)

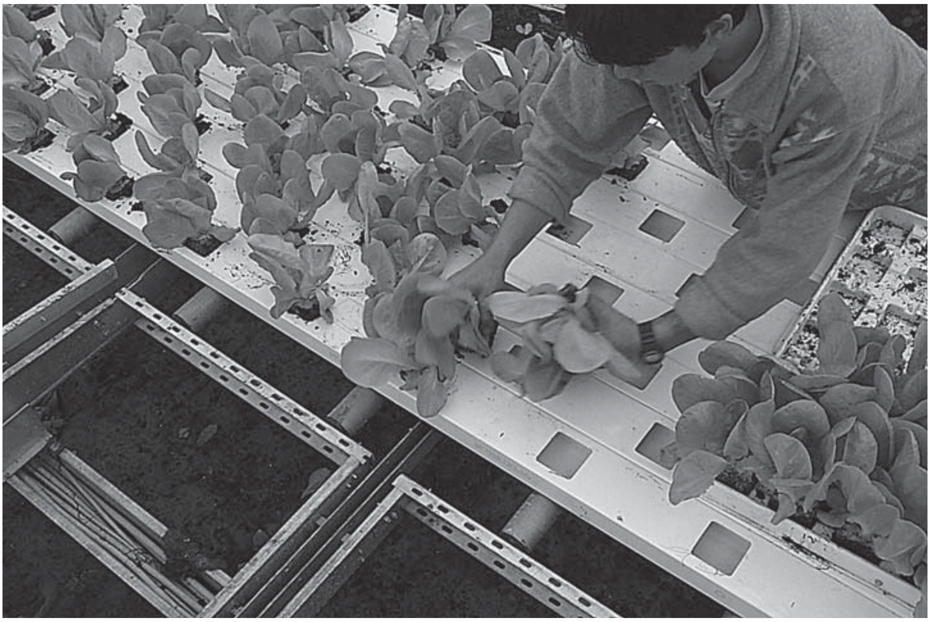

FIGURE 6.29 Transplanting the seedlings from the extended nursery trays to the NFT growing channels. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.30 Automatic transplanting machine takes seedlings and places them into the NFT growing channels. (From Hortiplan, N.V., Belgium. With permission.)

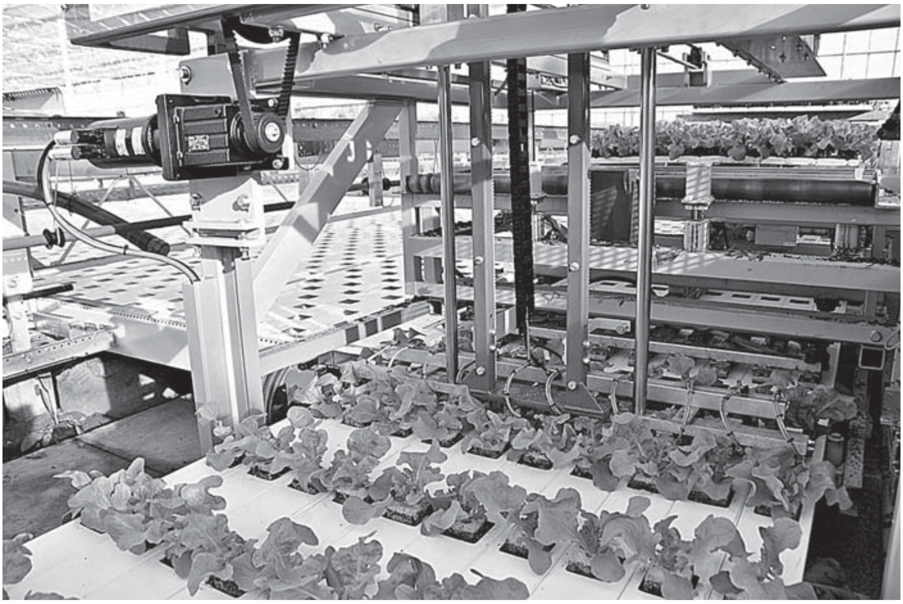

FIGURE 6.31 Plant robot transplanting to the NFT growing channels. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.32 Lettuce in gullies traveling underneath to the far end of the growing bench. (From Hortiplan, N.V., Belgium. With permission.)

up on top of the bench (Figure 6.33). The original spacing of the gullies is 40 plants per square meter.

They are automatically separated over the 5- to 6-wk growing period by a draw bar system underneath (Figure 6.34). While moving along the growing field (bench) the space between the gullies widens through 4–5 spacings as the plants grow, to provide optimum

FIGURE 6.33 The gullies at the far end of the bench are lifted automatically to the top of the growing field (bench). (From Hortiplan, N.V., Belgium. With permission.)

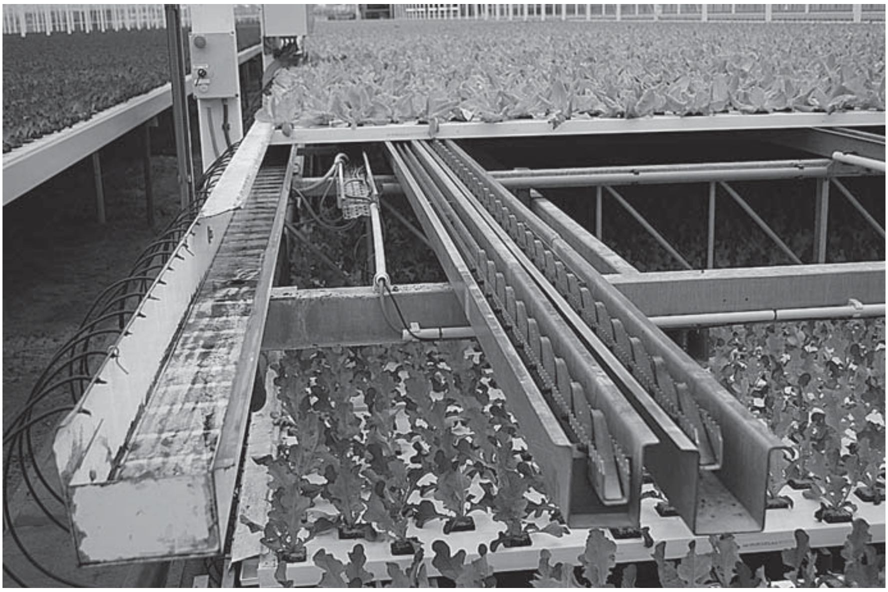

FIGURE 6.34 The drawbar to space the gullies. Note: The inlet lines on the left with the trench under them. The trench collects excess nutrient solution and drains it below to the main drain that returns the solution to central storage tanks where it is treated before recirculation to the gullies. (From Hortiplan, N.V., Belgium. With permission.)

space for the plants in each stage of growth over the 5- to 6-wk period in summer and 8- to 11-wk period in winter (Figures 6.35 and 6.36). They end up at a spacing of 14 plants per square meter (Figure 6.37) to get heads of 400 g (1 lb).

Lettuce gutters are 10 cm (4 in.) wide, and herb gullies are 7 cm (2.75 in.) wide. The length of the gutters depends on the width of the greenhouse bays: 9.6 m (31.5 ft), 12.0 m

FIGURE 6.35 The gullies are initially spaced touching as they are placed onto the growing field. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.36 The gullies are progressively spaced as they grow to a final spacing of 14 plants per square meter. (From Hortiplan, N.V., Belgium. With permission.)

(39.4 ft), or 12.8 m (42 ft). The most common gutter lengths are 12.0 and 12.8 m, as these are the most common house widths. Plant hole size is determined according to the crop and substrate size, such as peat block, rockwool, or others. The most common are 5 and 6 cm. The holes are square, with most common dimensions of 6.5 cm × 6.5 cm or 6.8 cm × 6.8 cm. The depth of the gutter is 5 cm, and holes are spaced within the gullies at 26 cm

FIGURE 6.37 Final spacing with Lollo Rossa lettuce and fennel. This is the catchment trench end of the gullies where the solution is collected and returned via the treatment system. (From Hortiplan, N.V., Belgium. With permission.)

(10.2 in.) centers. The final spacing between gullies to get 14 plants per square meter is 24–25 cm. This spacing is used in Belgium, where large lettuce of over 400 g (almost 1 lb) is grown. The density can be higher for smaller lettuce.

The gullies are irrigated by a trickle feed system. The gullies have open lips on one end to collect the nutrient solution. The trickle feed lines are located at intervals so that they will line up with the gullies as they move. This movement of gullies so that they always end up in front of a feed line is accomplished by draw bars. There is a collection trench immediately below to collect any solution that does not enter the gulley, when emptying the system if overproduction occurs or during maintenance (Figure 6.34). The position of the inlet lines may also be shifted on the cover of the trench. The inlet lines are connected to a main, and the drainage from the collection gutter is piped below, resting on top of the second inlet collection gutter (Figure 6.38). The main drains conduct the nutrient solution to the central part of the greenhouse where water treatment and adjustment processes of the nutrient solution take place before recirculation (Figure 6.39). The lower collection gutter is part of the inlet system for the gullies as they move underneath the growing field to the far end of the greenhouse after transplanting.

There is a 1% slope in the gutters from the inlet to the discharge end. The solution returns to a tank where it is sterilized and stored as treated water, which is then mixed with the injection before going back to the plants (Figure 6.39). There are sand and charcoal filters in each system. There are two formulations, one for young plants, in trays and during the first 10 d in the gutters, and one for older plants, after the initial 10 d in the gutters until harvest. Five different irrigation zones exist on each growing field.

Overhead boom sprayers are located in each range of the greenhouse to apply pesticides when necessary (Figure 6.40). The greenhouse environment is enriched with carbon dioxide by use of burners located overhead. Supplementary high-intensity discharge

FIGURE 6.38 The inlet-catchment trench. Note: The inlet header, trickle feed lines, and return drain main on top of the lower inlet-catchment trench that feeds and drains the gullies as they move from one end of the bench to the other underneath the growing field. Note the drain end of the channels on the right of the pathway that collects the solution at the return end. Lollo Rossa lettuce on the right and Bibb lettuce on the left benches. (From Hortiplan, N.V., Belgium. With permission.)

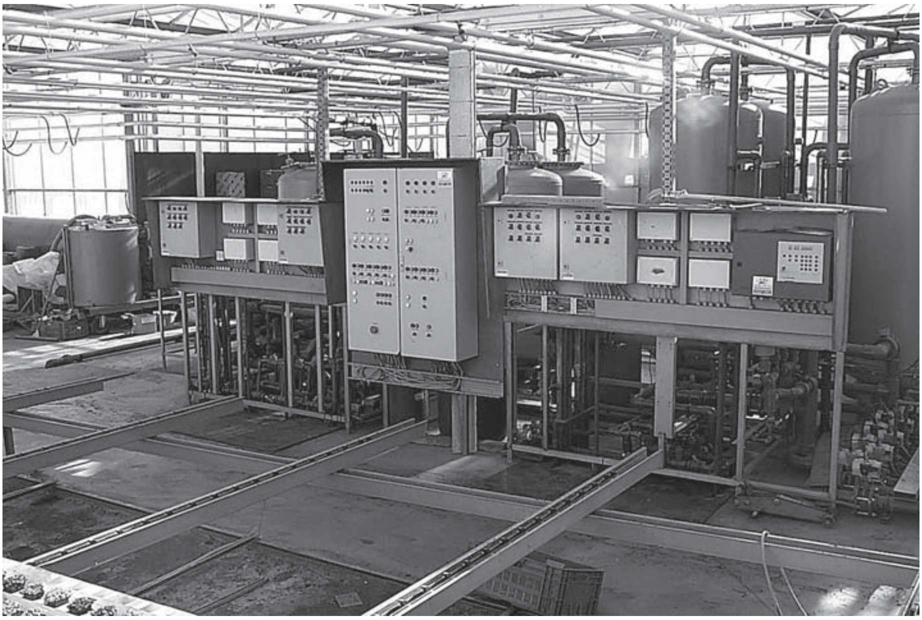

FIGURE 6.39 The central-computer-controlled solution treatment and injection systems with filters (tanks behind). (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.40 Overhead boom sprayer. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.41 HID lighting over a crop of green oakleaf lettuce. (From Hortiplan, N.V., Belgium. With permission.)

(HID) lighting is also installed to improve light during the fall and winter months (Figure 6.41).

During harvesting, the automated system moves the gullies from the growing field to a belt that carries each tray to the packing area where workers remove and package the lettuce. After the lettuce is packed, the plastic bins with the lettuce pass through a misting system to moisten them before going into the refrigerator (Figures 6.42 and 6.43).

FIGURE 6.42 Harvesting lettuce from the NFT gutters as they move along on a conveyor belt. (From Hortiplan, N.V., Belgium. With permission.)

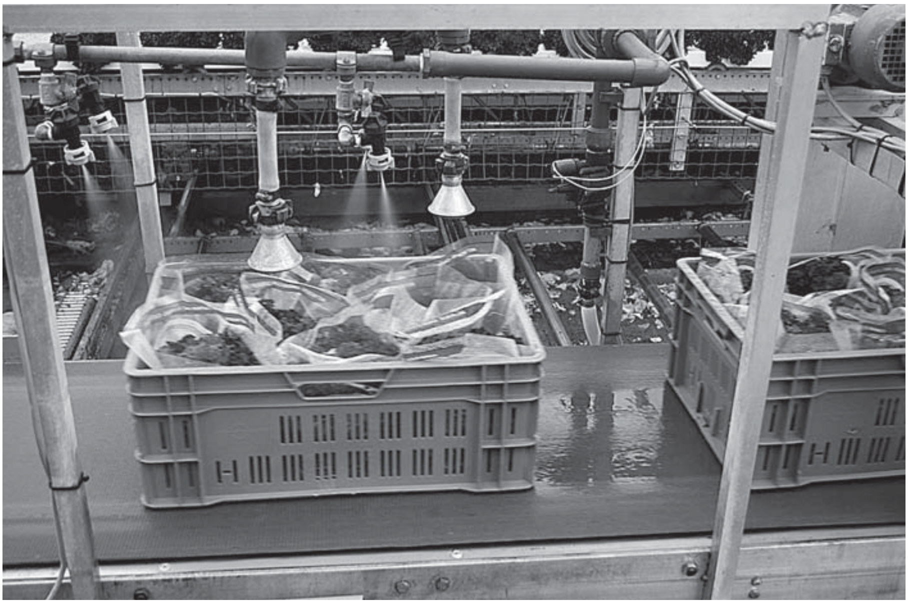

FIGURE 6.43 Packaged lettuce in tote bins moving under a misting system. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.44 Trio combination of leafy lettuces. (From Hortiplan, N.V., Belgium. With permission.)

The lettuce varieties grown include Boston/Bibb, green and red oakleaf, Lollo Rossa, and trios (3 plants per block: red oakleaf + Lollo Rossa + Lollo Bionda). These combinations give diversified products that are in high demand in the market (Figure 6.44). The products are sold with roots on to keep freshness. All products are sold through a Dutch auction system, much of it through electronic bidding online. For this reason, all growers must produce the same consistent quality of product, as purchasers expect the same quality regardless of the grower. The Belgian market demands large heads, of at least 400 g (a minimum of 1 lb) (Figures 6.45 through 6.47).

6.9 OUTDOOR NFT WATERCRESS

An herb grower, California Watercress, Inc., Fillmore, California, farms 60 acres (24 ha) of watercress in conventional field beds, but during 1989–1990, because of drought conditions, had to reduce production to close to half. By 1990, the water table had dropped so low that the irrigation water would percolate below the plant roots before reaching the latter part of the growing beds. This lack of water prompted the company to look for alternative methods of growing that would more efficiently utilize the existing water. The author developed for the company an NFT hydroponic system using beds 9 ft (2.75 m) wide by 500–600 ft (152–183 m) long. This compared to the conventional field beds that measured 50–60 ft (15–18 m) wide by in excess of 1,000 ft (305 m) in length. The field beds were partitioned into 20-ft (6-m) widths using berms.

The hydroponic system was very productive; however, about a year later it was washed out by the nearby Santa Clara River during high flood waters. In 1997, the project was rebuilt on higher ground at another farm site near Fillmore. The site was located near a well with a capacity of 500–600 gpm (32–38 L/s), providing sufficient water to irrigate from 3 to 5 acres (1.2–2 ha) of watercress. The NFT is an open, non-recirculation system.

FIGURE 6.45 Bibb lettuce head ready to harvest. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.46 Crop of Lollo Rossa lettuce ready to harvest. Note: The staggered spacing of the lettuce within the gutters. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.47 Finished product sleeved and packed in plastic tote bins. (From Hortiplan, N.V., Belgium. With permission.)

The site was graded and packed using laser equipment to form a minimum slope of 1% lengthwise and level across the width (Figure 6.48). The underground irrigation system was installed before making the berms or lining the beds with 10-mil black polyethylene (Figure 6.49). Raised berms 1 ft (30 cm) wide by 6 in. (15 cm) high using double disks attached to a tractor (Figure 6.50) formed the sides of the beds. Each section of beds is comprised of four beds and a 10-ft (3-m)-wide roadway for access. Five sections (20 beds) make up the 3-acre (1.2-ha) site.

Polyethylene of 22 ft (6.7 m) width and 100 ft (30.5 m) length covers two beds and their corresponding berms with sufficient overlap on the outside berms to seal the adjoining pair of beds (Figure 6.51). The polyethylene seams are melted together by the use of a heat blower commonly used to remove paint (Figure 6.52). Berms are covered with a 2-ft (61-cm)-wide nursery weed mat to protect the underlying polyethylene from sunlight degradation (Figure 6.53). The weed mat is secured with 6-in. (15-cm) and 9-in. (23-cm) landscape staples (Figure 6.54).

As part of the irrigation system, a main well supplies water to a 10,000-gal (37,850-L) storage tank. A 50-horsepower booster pump located at the storage tank (Figure 6.55) increases water pressure to 60 psi (414 kPa). An 8-in. PVC main carries the water to the corner of the project where it splits into two 4-in. mains. One 4-in. main supplies raw water to the beds, while the other loops through the injector system to provide nutrients.

FIGURE 6.48 Laser leveling 3-acre field. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.49 Irrigation mains at side of field. Four-inch-diameter raw water main and 3-in. nutrient solution main. Note: Risers to solenoid valves of 2-in. submains going across the field. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.50 Berms formed at 10-ft centers with double disks drawn by a tractor. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.51 Covering ground beds with a 10-mil thick black polyethylene liner. (From California Watercress, Inc., Fillmore, CA. With permission.)

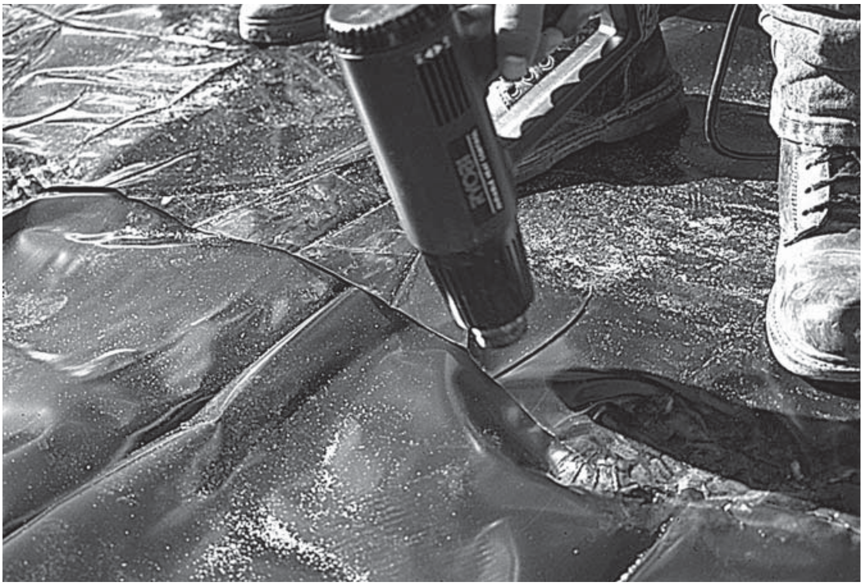

FIGURE 6.52 Melting seams of polyethylene together with a heat gun. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.53 Cover berms with a 2-ft-wide nursery mat to prevent the sun from damaging the black polyethylene. (From California Watercress, Inc., Fillmore, CA. With permission.)

As the growing of watercress requires a constant flow of water, the continuous use of nutrient solution in an open hydroponic system would not have been cost effective. Fertilizers are injected into sections of the project at set intervals. Water from the 4-in. main passes through a filter before entering the injector loop. The loop consists of a 3-in.-diameter pipe connected to the injector, blending tank, and flow control paddle wheel sensor that regulates the injection via a controller (Figure 6.56).

FIGURE 6.54 Author attaching weed mat on top of berm with landscape staples. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.55 Booster pump pressurizes 8-in. main water line from 10,000-gal tank, which is filled from a well. (From California Watercress, Inc., Fillmore, CA. With permission.)

Two 2,300-gal (8,705-L) stock tanks (A and B) supply the injector with a solution 200 times the normal strength, which is diluted back to normal by the injector's dilution rate of 1:200 of stock solution to raw water (Figure 6.57). See Section 3.6.1 for details of the operation of an injector system. A third, smaller plastic tank of 120 gal (454 L) containing nitric or sulfuric acid feeds a smaller fifth injection head to adjust the pH of the nutrient solution. The stock tanks hold a 2-wk supply of solution.

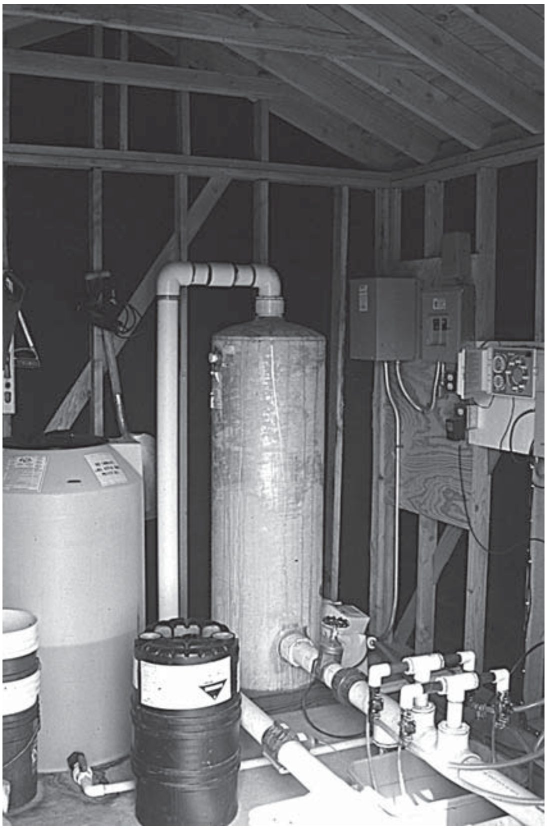

FIGURE 6.56 Injector system with acid tank on left, blending tank in middle, and part of injector system at lower right with irrigation controller above. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.57 Two 2,300-gal stock solution tanks with injector shed on left. (From California Watercress, Inc., Fillmore, CA. With permission.)

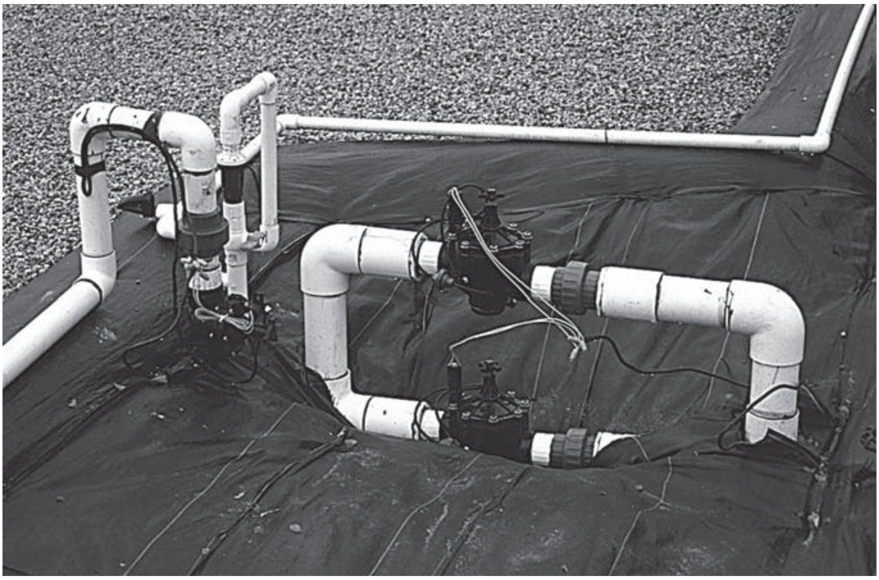

FIGURE 6.58 Mains with 2-in. solenoid valves at each of five sections of the field. Upper solenoid is solution main and lower one is raw water. One-inch riser conducts the irrigation water along the berm as a header from where 0.75-in. black polyethylene tubing runs across the beds. (From California Watercress, Inc., Fillmore, CA. With permission.)

A controller operates the feeding cycles by activating two 2-in. solenoid valves located on the 4-in. mains at each of five sectors running across the 3-acre project (Figure 6.58). The solenoid valves are connected to 3-in. submains going across below all the beds at 100-ft (30.5-m) intervals down the bed length. A normally open solenoid valve on the raw water line allows continuous flow of water to the beds between fertilizing cycles. On a feeding cycle, the controller sends an electrical current to the valves of one station, closing the normally open valve and opening the normally closed valve, stopping the flow of raw water and permitting nutrient solution to enter the beds.

Each cycle operates for 5–8 min as set on the controller, and the nutrient solution sequentially goes down the five sections of the field. The nutrient solution enters only one station at a time during any given cycle, while the other four sections receive raw water. The fertilizing cycles operate every 1–2 h during the day.

A 1-in. riser and header from the 3-in. submain is located in the middle of the berm at one side of the roadway for each sector of four beds (Figure 6.59). From this header, 0.75-in. black polyethylene tubing runs laterally at every 12.5 ft (3.8 m) across the sector beds for the first half of the bed length and at 25 ft (7.6 m) thereafter (Figure 6.60). Small emitter tees located every 18 in. (50 cm) disperse the solution or water into the beds. Plastic ball valves on each riser balance the flow to each section of laterals.

A modified lettuce nutrient formulation is used for growing the watercress, as shown in Table 6.1. Since the raw water is high in boron, calcium carbonate, and magnesium carbonate, a small amount of calcium and magnesium, but no boron is added. Stock A consists of half of the needed potassium nitrate, calcium nitrate, ammonium nitrate, nitric acid, and iron chelate. Stock B includes the other half of the total potassium nitrate, potassium sulfate, monopotassium phosphate, magnesium sulfate, phosphoric acid, and the micronutrients. The pH of the stock solutions is kept near 5.0. A 10% sulfuric acid stock solution

FIGURE 6.59 One-inch riser from each submain feeds each sector. (From California Watercress, Inc., Fillmore, CA. With permission.)

TABLE 6.1
Watercress Nutrient Formulation

Nutrient	Concentration (ppm)
Nitrogen	160
Potassium	200
Magnesium	50
Manganese	0.8
Zinc	0.1
Molybdenum	0.03
Phosphorus	45
Calcium	175
Iron	5
Copper	0.07
Boron	0.3

adjusts the pH of the final nutrient solution to 5.8–6.2 by entering the injector loop downstream from the entrance of stocks A and B.

Individual fertilizers are dissolved separately in large plastic bins of more than 200 gal (750 L). The solution is then pumped into the appropriate stock tank with two submersible pumps attached to hoses (Figure 3.17). Water is added to the stock tank before each addition

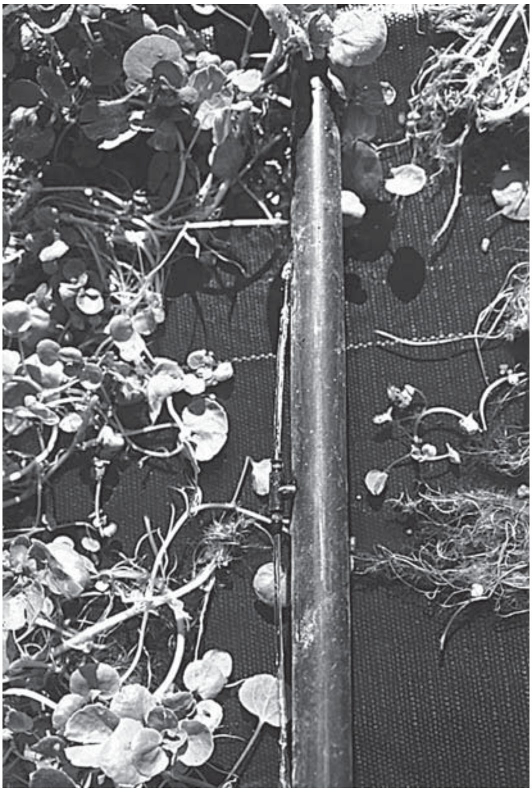

FIGURE 6.60 Black polyethylene laterals with emitters feed the beds. (From California Watercress, Inc., Fillmore, CA. With permission.)

of fertilizer and agitated with a paddle mixer to prevent precipitation. After preparation of the stock solution, the mixers agitate the solution for 15 min every 2 h.

Initially, watercress was grown in a modified NFT system using a 100% polyester capillary mat of 1/8-in. thickness (Figure 6.61). As the black polyethylene bed liner does not provide anchorage for the roots and a thin film of water does not spread across the beds, a medium that will spread the water laterally is required. The capillary mat is also needed to protect the bed liner from degradation by sunlight. With several cropping cycles it was found that the capillary matting impeded the flow of water in the beds causing stagnation, which resulted in oxygen deficit and algae growth. The capillary mat is also difficult to wash between crops. This was resolved by the use of a nursery weed mat placed on top of the black polyethylene liner. Plant roots attach to the weed mat but do not enter it as they do with the capillary mat (Figure 6.62). During crop changes, the plants along with their roots are easily raked away from the weed mat (Figure 6.63). The beds are washed with a hose and large push broom.

While seed or cuttings may propagate watercress, seeding produces new plants that flower less under hot summer temperatures. Two propagation beds 9 ft (2.75 m) × 450 ft (137 m) filled with 2 in. (5 cm) of pea gravel are used to sow seeds using a “whirlybird” hand seeder (Figure 6.64). Overhead sprinklers located on the berms moisten the beds every 10 min for 30 s during germination, which takes from 5 to 8 d. Once the seedlings are established within 2 wk, the sprinklers may be turned off or their irrigation cycles reduced.

FIGURE 6.61 Capillary mat placed on top of polyethylene bed liner. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.62 Plant roots attach to weed mat. (From California Watercress, Inc., Fillmore, CA. With permission.)

The seedlings may be transplanted to the growing beds within 6 wk when they are 2–3 in. (5–7 cm) tall (Figure 6.65).

Transplants are easily pulled from the pea gravel without damaging their roots and transported in plastic crates to the growing beds where they are placed in bunches in lines across the bed. This pattern of planting spreads the water across the beds and keeps all transplants sufficiently moist until they root (Figure 6.66). A 50-ft (15-m) section of propagation bed is

FIGURE 6.63 Raking old plants from weed mat during crop changeover. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.64 Author sowing watercress seeds in pea gravel propagation bed using “whirlybird” seeder. (From California Watercress, Inc., Fillmore, CA. With permission.)

sown daily to supply one of the 18 growing beds. First harvest occurs from 3 to 4 wk after transplanting.

Several harvests are taken from the same plants during the spring and fall seasons, when temperatures are lower than in summer. During winter, when it takes about 45 d between harvests, plants are not changed. Stem cuttings of 7–8 in. (18–20 cm) may be used to propagate the plants, but they tend to lose juvenility sooner than the seedlings. They may be used during the cooler seasons. Owing to the high cost of watercress seed, the beds are

FIGURE 6.65 Watercress seedlings 6 wk old ready to transplant to growing beds. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.66 Placing transplants across beds. (From California Watercress, Inc., Fillmore, CA. With permission.)

allowed to seed during the summer months and the seeds are collected. It is relatively easy to retrieve the seeds from the weed mat on which they grow. The plants are permitted to dry and dehisce onto the mat below. When the stubble is removed after collecting the seed, it serves to directly sow into the production beds. In fact, this saves labor over the traditional seedling propagation method.

FIGURE 6.67 Harvesting watercress by hand 23 d after transplanting. (From California Watercress, Inc., Fillmore, CA. With permission.)

Normal production averages one dozen bundles per lineal foot of bed in the 9-ft (2.75-m)-wide beds. This yield works out to 450–500 dozens per bed. Watercress is cut by hand (Figure 6.67), bundled with "twist-ties" (Figure 6.68), and transported in plastic crates to the packing house where they are washed and packed on top of ice and then placed in cold storage. In comparison to field-grown watercress, hydroponic watercress is taller, has larger leaves, and is more tender and milder in flavor (Figure 6.69). The hydroponic product,

FIGURE 6.68 Watercress tied in bundles with "twist ties" to be transported to the packing house for storage in plastic crates containing 10 dozen bunches each. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.69 Field-grown watercress on left compared to hydroponic-grown on the right. (From California Watercress, Inc., Fillmore, CA. With permission.)

because of its succulence, must be handled more carefully to avoid bruising. Individual packaging instead of bulk shipping helps avoid damage during shipping.

Aphids and fungus gnats are the principle pests of watercress. Pyrenone and M-pede, which can be applied 1 d before harvest, are effective in controlling these pests. A floating weed, duckweed, is a problem introduced by workers not washing their boots or reusing crates that have weeds adhering to them. This problem is resolved by having specific crates for the hydroponic watercress and washing them before entering the beds. Workers are required to wash their boots before entering the beds in a 10% bleach solution. Other challenges include lack of iron, poor aeration, alga growth, and some virus. With good management, crops yield uniform high-quality product (Figure 6.70). A review of this project was presented by Resh in 1993.

6.10 EBB-AND-FLOW (FLOOD) SYSTEMS

The E&F technique is basically a subirrigation method. Nutrient solution is pumped into a shallow bed to a depth of about 1 in. (2–3 cm) for about 20 min and then allowed to drain back to the nutrient tank once the pumps are shut off. E&F benching or flood benching systems are available from commercial manufacturers such as Zwart Systems (Appendix 2). These bench systems are particularly suited for the growing of seedling transplants and ornamental potted plants (Figure 6.71). The bottom of the flood bench has small cross channels perpendicular to deeper channels (Figure 6.72). This allows uniform filling and complete drainage during the irrigation cycles. The deeper channels lead to the inlet–outlet pipes. Tables are irrigated from both ends. The tables are 50 ft (15 m) in length, supported by metal framing with concrete footings to maintain them perfectly level.

Another type of E&F system is the flood floors such as those used by Bevo Agro Inc., Langley, British Columbia, to propagate transplants for commercial greenhouse and field growers. They market to Canada, the United States, and Mexico. Since their incorporation in 1989, they have expanded to their present 34-acre (13.6-ha) facility. They specialize in

FIGURE 6.70 A healthy field of watercress ready to harvest. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 6.71 Ebb-and-flow benches. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

tomatoes, cucumbers, and peppers for the greenhouse industry. However, they also grow many vegetable seedlings for field production and flowers for greenhouse production.

Seeds are sown using automated seeding machines into rockwool substrate in special Styrofoam trays. After the seedlings reach the several-true-leaves stage, they are transplanted to rockwool or "Jiffy" coco coir blocks (cucumbers: 4–5 d; tomatoes: 10–12 d;

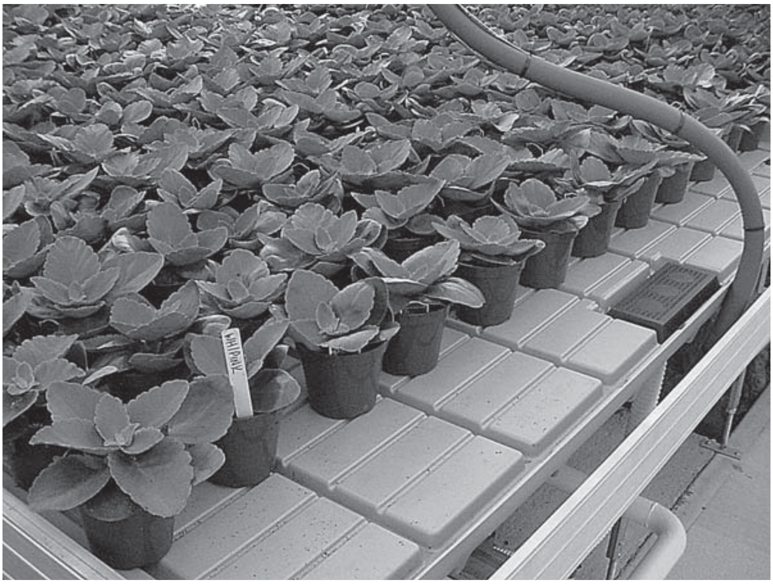

FIGURE 6.72 Fill-drain channels of ebb-and-flow bed. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

peppers: 12–14 d) and spaced 8 in. × 8 in. (20 cm × 20 cm). Tomatoes are also grafted for many clients. Grafting is done in a special grafting room. After grafting, the plants are held in the Styrofoam trays for an additional week or so until the graft union heals before transplanting them to the blocks and placing them in the ebb-and-flood system. Bevo Agro uses a special machine that carries the rockwool blocks to the flood system and spreads them apart as they come off the transport machine onto the concrete floor.

FIGURE 6.73 Tomatoes in rockwool blocks on concrete flood floor. Note: The plant support stackes in the blocks. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

In this type of propagation, the entire floor of the greenhouse is of concrete, which forms the basis of the ebb-and-flood recirculation system. The sides of each bed approximately 20 ft × 100 ft (6 m × 30.5 m) can be constructed using one layer of concrete bricks cemented together on edge. A slight slope from the edge to the center enables flooding and draining to occur from the middle of each bed by way of a sunken drain line (Figures 6.73 through 6.76).

FIGURE 6.74 Peppers in rockwool blocks on concrete flood floor. Note: The floor is draining. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

FIGURE 6.75 Peppers in rockwool blocks on flood floor. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

FIGURE 6.76 Tomatoes growing in an ebb-and-flood system using coco coir blocks. These are Jiffy blocks, and each has two plants. (From Jiffy Products. With permission.)

The center of the "V" is usually 1–1.5 in. lower than the edges. Water is pumped up a buried supply line until the depth at the top of the "V" has been achieved. Drainage is through the same supply pipe back to a cistern. The system requires about 5 min to fill and 7 min to drain. Solenoid valves on the main PVC headers control the irrigation cycles. The nutrient system is fully automated with a computerized controller. The greenhouse is heated with a natural-gas-fired boiler hot-water system with heating pipes buried in the concrete floor. By achieving optimum temperatures for the various crops through combined bottom heating and overhead heating systems, healthy, vigorous tomato, cucumber, and pepper transplants are produced (Figures 6.74 through 6.77).

6.11 A-FRAME NFT SYSTEM

The arrangement of NFT gutters on an A-frame structure to increase the production of low-profile plants such as lettuce, arugula, and herbs has been tested on many occasions on a small scale. Such a system was originally designed for testing these crops in Taiwan in the late 1980s, and the system was shown in one of the previous editions of *Hydroponic Food Production*. However, such systems worked fine on a small scale but were never designed for larger production. In a conference in Costa Rica in April 2011, a company from Colombia, Grupo Tecnico Aponte, presented their A-frame project near Bogota, Colombia (Aponte, 2011).

Bogota, Colombia, at an altitude of 2,600 m (8,530 ft), has a mild climate with night temperatures of about 6°C (43°F) and day temperatures of about 18°C (65°F), with maximum and minimum extremes of 24°C and −5°C (75°F and 23°F). These conditions are quite favorable to the growing of cool-season crops such as lettuce. In a greenhouse, the company constructed A-frames of light-weight metal tubing, 2.1 m (6.9 ft.) tall, 2 m (6.5 ft.) wide at the base, and 20 cm (8 in.) wide at the top. The structures were 6 m (20 ft.) long.

FIGURE 6.77 Tomatoes in Jiffy coco coir blocks in an ebb-and-flood system. (From Jiffy Products. With permission.)

Each frame supports sixteen 2-in.-diameter PVC pipes (Figure 6.78). Plant holes of 5 cm (2 in.) diameter were cut in the pipes at 15-cm (6-in.) centers for the plant sites. There are 40 holes per pipe, giving a total of 640 per A-frame (16 pipes with 40 holes). A 500 m^2 (5,380 ft^2) greenhouse would contain 30 of these A-frames. Irrigation to the pipes is by a drip tube to each pipe. The pipe ends have a cap, and nutrient solution is not recirculated. The solution is pumped from a cistern.

FIGURE 6.78 A-frames with 16 NFT pipes each. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

FIGURE 6.79 Starting lettuce seedlings in plastic pots with coco coir–rice hulls substrate. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

Plants are started in plastic containers of a coco coir and rice hull mixture (Figure 6.79). They are grown in a nursery area of closely spaced pipes with NFT (Figure 6.80) before being transplanted to the A-frames (Figures 6.81 and 6.82). Lettuce is ready for harvest in 7 wk (Figure 6.83). The individual plants are sold as sleeved and retained with their roots in the growing pots.

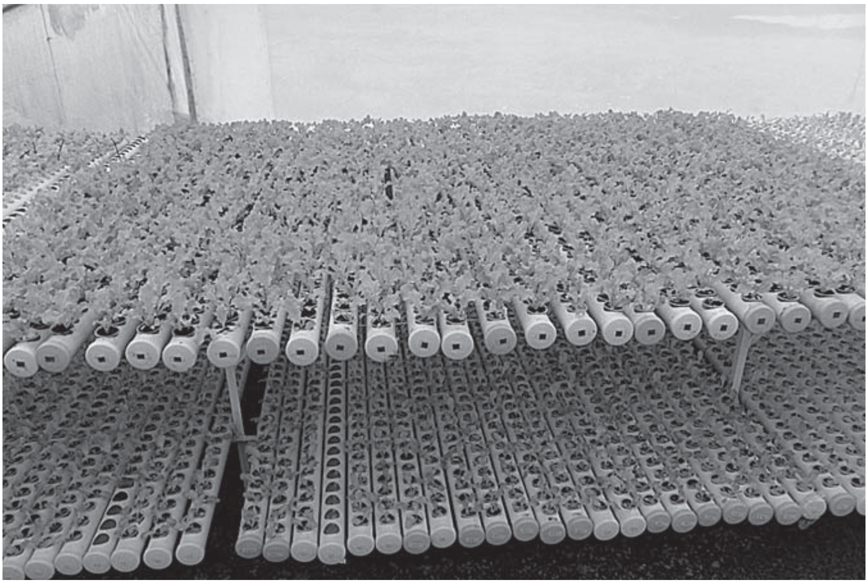

FIGURE 6.80 Nursery area of NFT pipes on two-level bench system. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

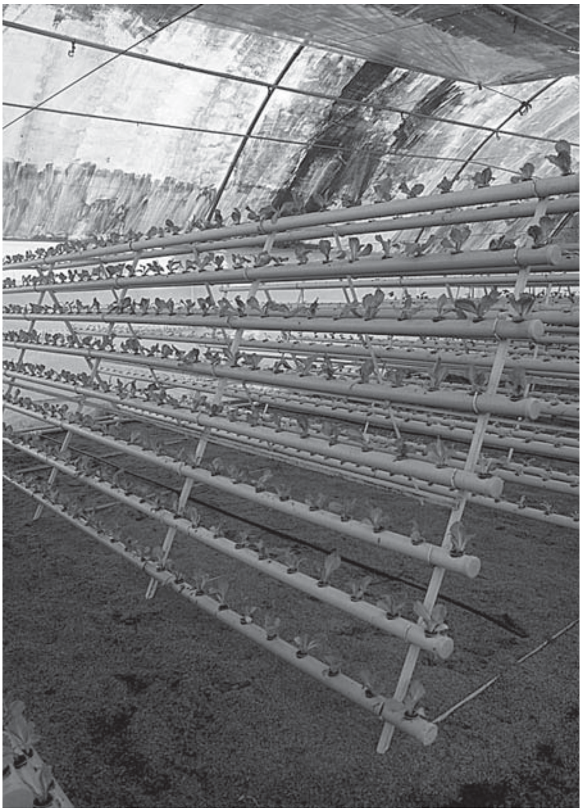

FIGURE 6.81 Lettuce seedlings transplanted to NFT pipes of A-frame. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

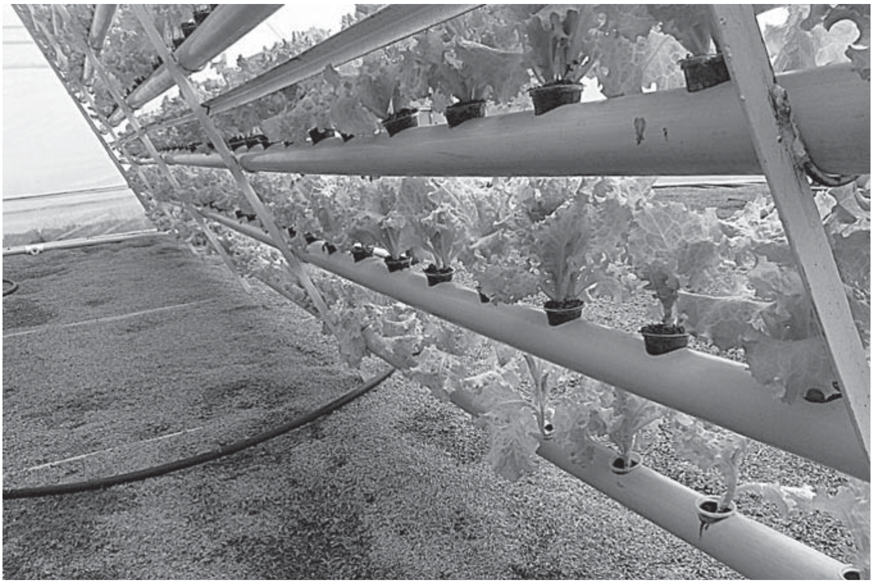

FIGURE 6.82 Lettuce in pots of coco coir–rice hull substrate in NFT pipes. View is from underneath A-frame. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

FIGURE 6.83 Lettuce at 7 wk ready to harvest. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

6.12 SUMMARY

The future of successful hydroponic crop production lies in a universal cropping system in which water and fertilizers can be used efficiently. This is particularly true in arid regions of the world, such as the Middle East, where land is nonarable and water is scarce. In such areas, desalinated sea water can be used, but is very costly. In the past, sand culture was used in many of these areas, but often the sand was of calcareous nature, which caused rapid changes in pH and tying-up of essential elements such as iron and phosphorus. In these areas of high solar energy, efficient use of costly desalinated water is essential.

The NFT is one such hydroponics system that makes efficient use of water and fertilizers and at the same time does not rely on a locally suitable medium such as noncalcareous sand or gravel.

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7 Gravel Culture

7.1 INTRODUCTION

Gravel culture was the most widely used hydroponic technique from the 1940s through the 1960s. During the late 1960s and early 1970s one commercial operation, Hydroculture, near Phoenix, Arizona, had almost 20 acres (8 ha) of greenhouses in gravel culture. Many smaller commercial greenhouses throughout the United States used gravel culture as it was well documented and several companies such as Hydroculture were selling "mom and pop" packages to people interested in setting up their own hydroponic greenhouse.

W.F. Gericke introduced hydroponics commercially using gravel culture. It was used in most outdoor operations established during World War II on nonarable islands, as mentioned in Chapter 1. Gravel culture is still useful in areas having an abundance of volcanic rock, such as the Canary Islands and Hawaii. Today, nutrient film technique (NFT), rockwool, coco coir, and perlite cultures are more widely accepted as they have more consistent properties, are easier to sterilize between crops, and are less laborious to handle, maintain, and manage.

7.2 MEDIA CHARACTERISTICS

Some of the general characteristics that media should possess have been discussed in Chapter 4. The best choice of gravel for a subirrigation system is crushed granite of irregular shape, free of fine particles less than 0.063 in. (1.6 mm) in diameter and coarse particles more than 0.75 in. (1.9 cm) in diameter. Over half of the total volume of particles should be about 0.5 in. (1.3 cm) in diameter. The particles must be hard enough not to break down, able to retain moisture in their void spaces, and drain well to allow root aeration.

The particles should not be of calcareous material—in order to avoid pH shifts. If only calcareous material is available, the amount of calcium and magnesium in the nutrient solution will have to be adjusted according to the levels of these elements released by the aggregate into the nutrient solution. The calcium carbonate in calcareous aggregates such as limestone and coral gravels reacts with the soluble phosphates of the nutrient solutions to produce the insoluble di- and tri-calcium phosphates. This process continues until the surfaces of the calcareous aggregate particles are coated with insoluble phosphates. After they are thoroughly coated, the reaction slows down to a point at which the rate of decrease of phosphates in the nutrient solutions is slow enough to maintain phosphate levels.

A new unused aggregate containing more than 10% of acid-soluble materials calculated as calcium carbonate should be pretreated with soluble phosphates to coat the particle with insoluble phosphates (Withrow and Withrow, 1948). The aggregate is treated with a solution containing 500–5,000 g of treble superphosphate per 1,000 L or 5–50 lb per 1,000 gal. The new gravel should be soaked for several hours. The pH of the solution will rise as its phosphate content decreases. If the phosphate concentration drops below 300 ppm (100 ppm of P) after 1–2 h of soaking, the solution should be drained to the reservoir and a second phosphate addition made to the solution, which is repumped into the beds. This should be repeated until the phosphate level stays above 100 ppm (30 ppm of P) after several hours of exposure to the gravel. When this occurs, it indicates that all of the carbonate particles have been coated with phosphates. The pH of the solution will then remain at about 6.8 or less. The phosphate solution is then drained from the reservoir, and the reservoir filled with fresh water. The beds are flushed with this fresh water several times, and once again the reservoir is drained and refilled with fresh water. The beds may then be planted.

Over time the pH will begin to rise as the phosphates become depleted and free calcium carbonate is exposed on the surface of the aggregate. The process of phosphate treatment will then have to be repeated.

Schwarz and Vaadia (1969) have demonstrated that pretreated calcareous gravel or washed calcareous gravel could not prevent lime-induced chlorosis. The high pH of calcareous gravel also makes iron unavailable to plants. Victor (1973) found that daily addition of phosphorus and iron at the rate of 50 mL of phosphoric acid and 12 g of chelated iron (FeEDTA) per 1,000 gal (3,785 L) of nutrient solution prevented the occurrence of lime-induced chlorosis in tomato plants.

“Haydite” or “Herculite” fired shale, available in a variety of particle sizes, is often used by smaller backyard hydroponic units. It is porous and has given good results in many cases. However, after continued use, the adsorption of fertilizer salts on the surfaces of the particles may cause difficulty. The absorbed salts are not easily removed by washing. Plant roots become lodged in the small pores of the rock surface, making sterilization of the medium between crops difficult. Also, the material fractures and breaks up into small pieces, which eventually form a fine sand and silt that plugs feeder lines and pipes.

If a drip trickle feeding system is used rather than a subirrigation system, a smaller medium must be used. For such a system, “pea” gravel between 0.13 and 0.38 in. (3–10 mm) in diameter should be used. Over half the total volume of gravel should have a particle size of 0.19–0.25 in. (5–6 mm) diameter. No silt or particles larger than 0.38 in. (10 mm) in diameter should be present. Haydite gravel is particularly suitable for a trickle feeding system because its capillary action moves the nutrient solution laterally around the plant root system. However, as plant roots grow laterally they also will intercept the water and cause it to flow laterally.

7.3 SUBIRRIGATION GRAVEL CULTURE

Almost all gravel culture uses a subirrigation system. That is, water is pumped into the beds, which floods them within several inches of the surface, then drains back to the nutrient reservoir. This is similar to the ebb-and-flood system discussed in Chapter 6. Such a system is termed *closed* or *recycled* since the same nutrient solution is used each pump cycle over a period of 2–6 wk. Then the solution is disposed of and a new solution made up.

The frequency and duration of irrigation cycles is important to the success of the system. Each irrigation cycle must provide adequate water, nutrients, and aeration to the plant roots.

7.3.1 FREQUENCY OF IRRIGATION

The minimum frequency of irrigation depends on the following factors:

1. The size of the aggregate particles
2. The surfaces of the aggregate particles

3. The nature of the crop
4. The size of the crop
5. Climatic factors
6. Time of day

Smooth, regularly shaped, coarse aggregates must be irrigated more frequently than porous, irregularly shaped, fine aggregates having large surface areas. Tall crops bearing fruit require more frequent irrigation than short-growing leafy crops, such as lettuce, because of their greater surface area and therefore higher evapotranspirational losses. Hot, dry weather promotes rapid evaporation and makes more frequent irrigation necessary. During midday when light intensities and temperatures are highest, the period between irrigation cycles must be reduced.

For most crops, the aggregate must be irrigated at least three to four times per day during dull winter months, and in summer it is often necessary to irrigate at least every hour during the day. Pumping at night is not necessary. In temperate zones, during the summer, irrigation should be from 6:00 A.M. to 7:00 P.M., while during winter it may be set up from 8:00 A.M. to 4:00 P.M.

Water is absorbed by the plant from the nutrient solution much more rapidly than the inorganic elements. As a result, the films of nutrient solution on the aggregate become concentrated with inorganic salts as absorption takes place. The concentration of the nutrient solution in the aggregate becomes greater as the rate of transpiration of the plants increases, and the rate of water absorption thus increases. By increasing the number of irrigation cycles, the high water demand of the plant is met and the water content within the void spaces of the gravel is maintained at a more optimal level. In this way, the nutrient solution does not become so concentrated between irrigation cycles. It is also necessary to irrigate frequently so that the films of nutrient solution over the aggregate particles in contact with the root tips are not depleted of any nutrient between irrigations.

Immediately following irrigation, the nutrient solution in the aggregate has nearly the same composition as the reservoir solution. As absorption proceeds, the composition of the nutrient solution in the bed continually changes, including the proportion of the various ions, the concentration of the solution, and the pH. If the frequency of irrigation is not sufficient, nutrient deficiencies may develop, even though adequate quantities of nutrient elements may be present in the reservoir solution. If the aggregate does not contain a large proportion of fine particles, it is unlikely that frequent irrigation will cause aeration problems so long as the beds are completely drained between irrigations and the irrigation period is not too long. The more often the beds are irrigated, the more nearly the composition of the aggregate solution approaches that of the reservoir solution.

7.3.2 SPEED OF PUMPING AND DRAINAGE

The speed of pumping and draining the nutrient solution from the gravel determines the aeration of the plant root system. Roots require oxygen to carry on respiration, which in turn provides the energy needed in the uptake of water and nutrient ions. Insufficient oxygen around the plant roots retards their growth or may cause death, which results in plant injury, reduced yields, and eventually plant death.

In a subirrigation system, as the nutrient solution fills the gravel voids from below, it pushes out air that has a relatively low content of oxygen and a high content of carbon dioxide. Then, as the nutrient solution flows from the gravel, it sucks air into the medium. This new supply of air has a relatively high content of oxygen and a low content of carbon dioxide. The greater the speed of solution movement in the gravel medium, the greater is the speed of air displacement. Also, since the solubility of oxygen in water is low, the period of low oxygen supply while the free water is in the gravel is shortened if the speed of filling and draining is rapid.

A 10- to 15-min period each for filling and draining, or a total time of 20–30 min, is generally acceptable. In the removal of the free solution from the bed, nothing less than complete drainage is recommended. Only a film of moisture on the gravel particles is desired. If puddles of solution remain in the bottom on the plant bed, poor plant growth results. This rapid filling and draining of the growing beds can be achieved by the use of large pipes in the bottom of the beds. In summary, proper irrigation cycles should (1) fill the bed rapidly, (2) drain the bed rapidly, and (3) get all the solution out.

7.3.3 Effect of Irrigation Cycle on Plant Growth

By reducing the number of times of nutrient solution pumping, the moisture content in the gravel medium is lowered. This has a concentrating effect on the nutrient ions contained in the water film on the gravel particles. Whenever the osmotic concentration of the nutrient solution is increased, the water-absorbing power of the plant is reduced, also reducing the nutrient ion uptake. Consequently, the rate of plant growth is retarded, and a harder and firmer type of growth develops.

In the greenhouse, during the dark, cloudy, short days of winter, reduction of the number of irrigation cycles per day will help keep the plants reasonably hard and sturdy.

7.3.4 Height of Irrigation

The nutrient solution level should rise to within about 1 in. of the surface of the aggregate. This practice keeps the aggregate surface dry, preventing the growth of algae, and reduces the loss of water and high humidity buildup at the base of the plants. It also prevents the growth of roots into the top inch of the aggregate surface, which, under conditions of high light intensities, may become too high in temperature for satisfactory root growth. The nutrient level in the beds can be regulated by installation of overflow pipes in the plenum. These construction details are discussed in Section 7.3.6.

7.3.5 Nutrient Solution Temperature

In greenhouse culture, the temperature of the nutrient solution should not fall below the night air temperature of the house. The temperature of the solution in the reservoir sump may be raised by the use of an immersion heater or electric heating cable. Be careful not to use any heating elements having lead or zinc sheathing, as these can be toxic to the plants. Stainless steel or plastic-coated cables are the best. Electric heating lamps have also been used successfully. In many locations, the temperature of the outside water used to fill the sump may be as low as 45°F–50°F (7°C–10°C). If a large reservoir needs to be filled, it should be done later in the day after the last irrigation cycle has been completed. Then there will be sufficient time before the next irrigation cycle the following morning for the heating unit to bring the solution temperature to a more optimum level.

In no case should heating cables be placed in the growing beds themselves. This causes localized high temperatures around the heating elements, which injure the plant roots.

7.3.6 GREENHOUSE SUBIRRIGATION SYSTEM

7.3.6.1 Construction Materials

Since fertilizer salts used in making up the nutrient solution are corrosive, any metal parts, such as pumps, pipes, or valves, exposed to the nutrients will wear out in a very short time. Galvanized materials may release sufficient zinc to cause toxicity symptoms in the plants. Copper materials cause the same problem. Plastic pipes and fittings, pumps with plastic impellers, and plastic tanks are noncorrosive and should be utilized. Plant beds can be built of wood and lined with 20-mil vinyl.

During World War II, concrete was used in numerous commercial operations. It has the advantage of permanence and corrosion resistance, but its cost is the highest. Cedar or redwood is the most often used construction material, and direct lining of compacted normal ground substrate is the cheapest for bed construction.

7.3.6.2 Beds

The beds must be designed to provide rapid filling and draining—and complete drainage. The use of a 3-in. (7.6-cm)-diameter PVC pipe and a V-shaped bed configuration will fulfill these watering requirements (Figure 7.1). The beds should have a minimum width of 24 in. (61 cm), a depth of 12–14 in. (30.5–35.5 cm), and a maximum length of 120–130 ft (36.5–40 m). The beds should slope from 1 to 2 in. (2.5–5 cm) per 100 ft (30.5 m). Water enters into and drains from the beds through small 0.3- to 0.5-in. (0.64- to 1.27-cm)-diameter holes or 0.13-in. (0.32-cm)-thick saw cuts on the bottom one-third of the PVC pipe. These holes or saw cuts are made every 1–2 ft (30.5–61 cm) along the entire length of the pipe.

The inclination can be achieved by sloping the sideboards and stacking them. In some cases, growers may pour concrete walkways between these beds. The beds should be constructed using compacted river sand. A jig containing the desired configuration can be used to dig out the bed (Figure 7.2). Once the proper configuration and slope have been compacted, the beds are lined with a vinyl liner of 20 mil thickness commonly used for

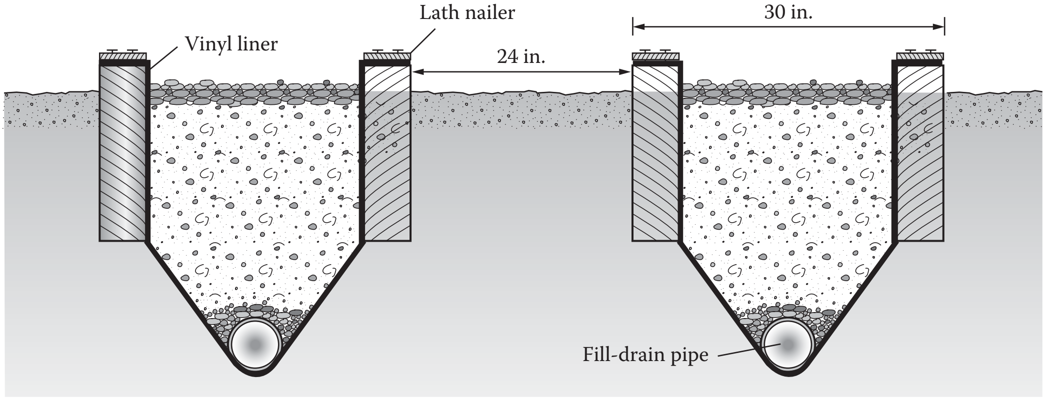

FIGURE 7.1 Cross section of a subirrigation gravel bed. (From George Barile, Accurate Art, Inc., Holbrook, NY. With permission.)

FIGURE 7.2 Digging bed configuration in compacted river-sand fill.

swimming pools (Figure 7.3). The 3-in.-diameter PVC fill-drain pipe is then set in place with holes or cuts facing downward to prevent roots readily growing into the pipe. The vinyl is held on the sides of the beds by folding it over the rough 2-in.-thick cedar side planks and nailing with a wooden strip on top of its entire length.

The PVC pipe allows water to flow rapidly along the bottom of the beds, and fills and drains the beds equally and vertically along the entire length. With this rapid filling and draining, old air is pushed out of the aggregate and new air is sucked in as discussed earlier.

The beds should be filled with gravel to within 1 in. of the top at the end near the nutrient tank and within 2 in. at the far end. To prevent uneven near-surface moistening during the irrigation cycles, level the top surface of the gravel. Remember that the beds are not level, but water remains level; so, with the top surface of the gravel leveled, the water level in the flooded beds will be parallel to the gravel surface. If the gravel were placed to within 1 in. of the top of the bed along the entire length, it really would have a 1-in. slope and therefore if during the irrigation cycle the beds were filled to within 1 in. of the gravel surface at the reservoir end of the beds, it would be 2 in. from the top at the far end. This would cause uneven watering of the plant roots from one end to the other end of the beds. Recently transplanted seedlings might suffer a water stress at the far end because of insufficient height of water in the bed. If the water level were within 1 in. at the distant end, it would come to the surface at the reservoir end, creating problems of algae growth.

FIGURE 7.3 Vinyl liner placed into beds and PVC drain pipes location.

The 3-in. PVC pipe should have a 45° elbow and project above the gravel surface with a cap at the far end from the tank to allow for cleaning of the pipe. Usually the pipes are cleaned of roots every year or so with a “snake” rooter machine. The end of the pipe at the reservoir drains into a plenum.

7.3.6.3 Plenum

Filling and draining times can be greatly decreased by the use of a plenum rather than solid plumbing from the pump(s). The plenum is simply a trough into which the water is pumped from the tank. The 3-in. PVC pipes running along the bottom of the beds open into this plenum (Figures 7.4 through 7.6). The bed pipes must be sealed into the plenum, or water will leak behind the tank, resulting in loss of nutrient solution and buildup of water under the greenhouse and tank.

Either a sump or submersible pumps may be used to pump the nutrient solution from the reservoir into the plenum. The pump is activated by either a time clock or a feedback mechanism attached to a moisture sensor in the beds. The water level in the beds is regulated by an overflow pipe in the plenum. The plenum and beds will fill to a level that corresponds to 1 in. below the gravel surface in the beds. A dump valve, activated by the same time clock or feedback mechanism as the pumps, closes the drain holes of the plenum while the pumps are operating (Figure 7.4). The operation is as follows:

1. The moisture sensor in the bed signals the feedback mechanism to turn on the pumps (or the preset time clock strikes an irrigation cycle) and activates the plenum valves.
2. The pumps are activated; the dump valves of the plenum close.
3. The plenum and beds begin to fill.
4. They continue filling until excess solution spills back into the tank via the overflow pipes.

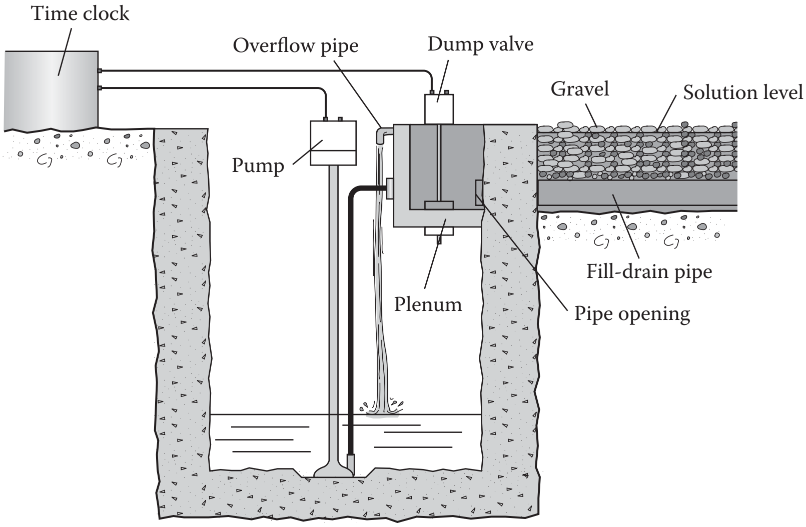

FIGURE 7.4 Cross section of plenum and nutrient tank. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

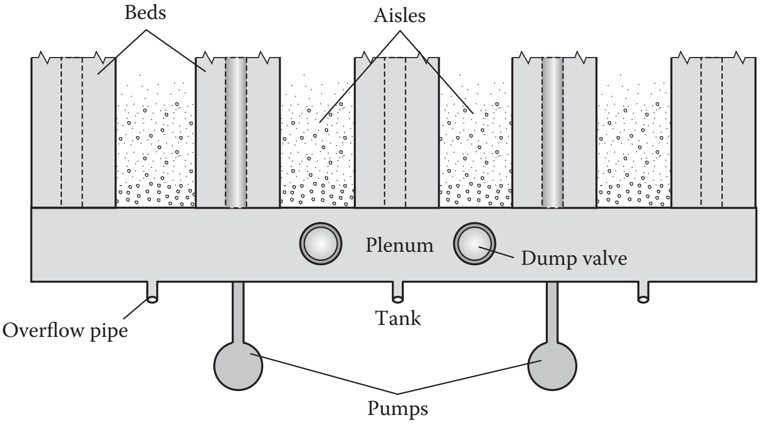

FIGURE 7.5 Plan view of plenum and nutrient tank. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

5. The preset irrigation period terminates; the beds are full of solution.
6. The pumps stop, the dump valves fall open, the nutrient solution drains from the beds back to the plenum, and finally falls into the tank, being well aerated.
7. The whole cycle of pumping and draining should be completed within 20 min.

7.3.6.4 Nutrient Tank

The nutrient tank must be constructed of a watertight material. Steel-reinforced concrete 4 in. (10 cm) thick, coated with a bituminous paint to make the concrete watertight, is the most long-lasting material. The plenum should be a part of the tank so that leakage cannot occur between them. The volume of the tank must be sufficient to completely fill the gravel beds, based on the amount of void space in the gravel. This can be determined by

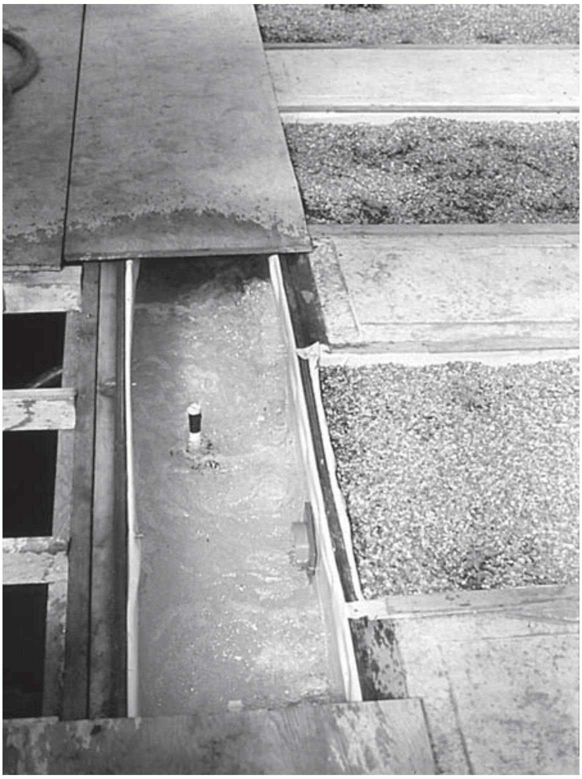

FIGURE 7.6 Bed fill-drain pipe entering plenum.

taking a sample of the rock (about a cubic foot) and filling it with water, then measuring the volume of water required to fill the void spaces. Then extrapolate to calculate the total void space in all the beds. The tank should hold a volume 30%–40% greater than the total volume required to fill the beds. For example, a tank of about 2,000 Imp. gal (9,092 L) would be required to supply five beds 2 ft (61 cm) wide × 12 in. (30.5 cm) deep × 120 ft (36.5 m) long (Figure 7.7).

An automatic float valve could be attached to a water refill line in order to maintain the water level in the tank. In this way, water lost during each irrigation cycle through evapotranspiration by the plants would immediately be replaced. The nutrient tank should have a small sump in which the pumps sit in order to facilitate complete drainage and cleaning of the tank during nutrient changes (Figure 7.4).

The tank plenum could be changed somewhat in structure to reduce its size. This can be done (as shown in Figure 7.8) by dividing the plenum into two parts, each servicing three beds. A three-way automatic valve would discharge the nutrient solution alternately into one plenum on activation of the pumps and dump valve, filling three beds during each cycle (Figure 7.9). In this case, a time clock, rather than a moisture-sensor feedback system, must be used, with shorter intervals between irrigation cycles than those required for one larger plenum as described earlier.

The pump could also be piped into a discharge line, which could be connected to the outside drainage system. Gate valves would be used to control the direction of flow of the nutrient. When the nutrient solution is changed, the gate valve in the waste line is opened and the solution is pumped out to waste. Normally during regular feeding cycles, this waste

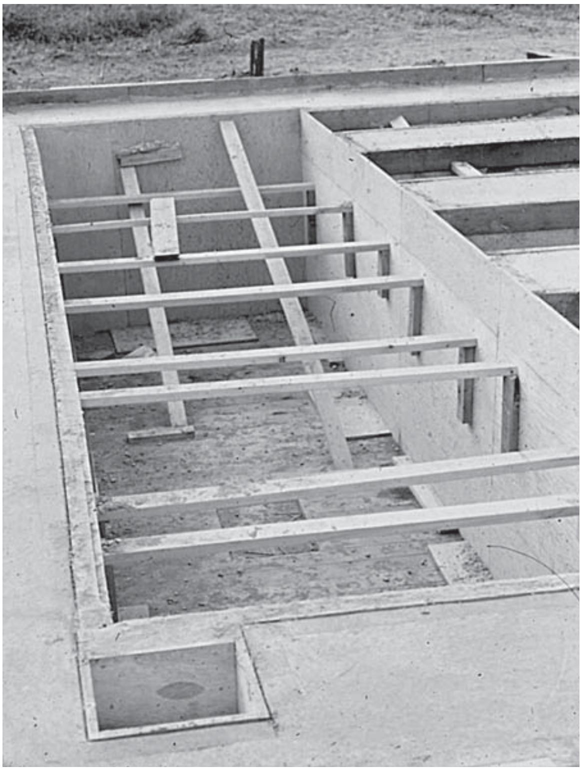

FIGURE 7.7 Nutrient tank construction.

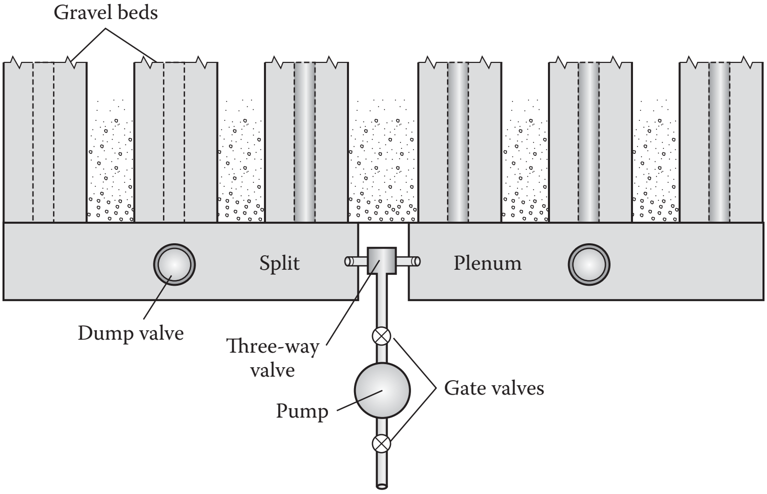

FIGURE 7.8 Plan view of nutrient tank with a split plenum. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

valve is closed and the valve between the pump and the three-way valve is open. The three-way valve is available commercially.

By using such a split plenum, the tank capacity can be reduced to almost half the volume of one large enough to fill all six beds at once. Thus, a tank of 1,200 Imp. gal (5,455 L)

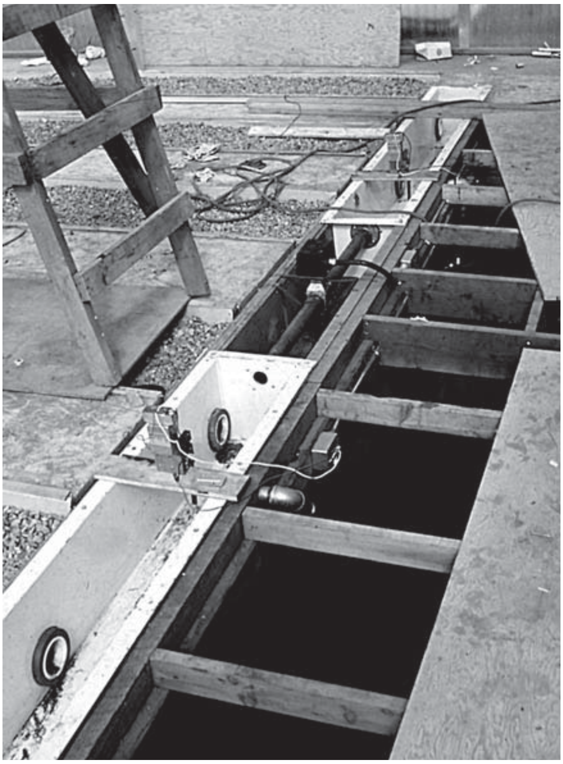

FIGURE 7.9 Three-way automatic valve used with a split-plenum design.

should easily supply three gravel beds 24 in. (61 cm) wide × 12 in. (30.5 cm) deep × 120 ft (36.5 m) long.

An overall plan of a gravel culture system having six beds and the attached plenum and nutrient tank is illustrated in Figure 7.10. Successful crops of high productivity can be grown with a subirrigation gravel system, as illustrated in Figures 7.11 and 7.12.

7.4 TRICKLE IRRIGATION DESIGN

The bed design and construction of trickle irrigation systems are similar to that of subirrigation systems, but a smaller tank (cistern) is needed as the beds do not need to be filled with solution. This is a closed, recycling system similar to subirrigation gravel culture. The nutrient solution is applied to the base of every plant by a drip line or ooze hose. The solution percolates through the gravel and plant roots and is returned to the cistern through a large drainage (3-in. PVC) pipe similar to subirrigation. The bed drain pipes connect to a main return line that conducts the solution back to the nutrient tank. The nutrient tank should therefore be placed at a lower end of the greenhouse so that all drain pipes can slope to that point. The use of smaller gravel (0.13–0.25 in. in diameter) with the trickle system is essential to facilitate lateral movement of the nutrient solution through the medium. Lateral distribution of the solution also occurs along the lateral roots of the plants.

A modified recirculating pea gravel system was constructed at California Watercress to grow baby salad greens and later mint. A greenhouse 20 ft (6 m) × 120 ft (37 m) with four beds, each 4 ft (1.2 m) wide, was constructed. The irrigation system was set into the

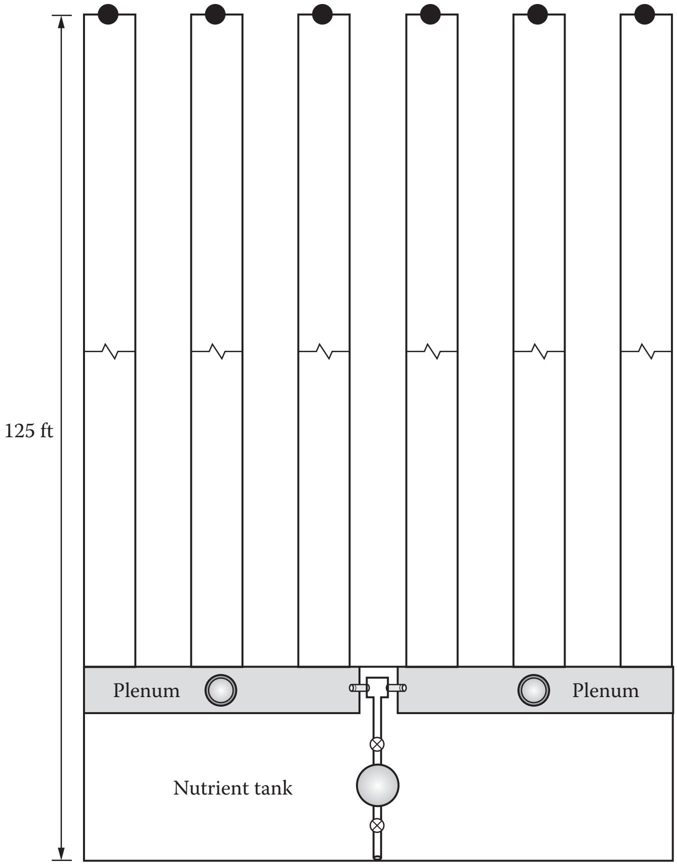

FIGURE 7.10 Plan of a greenhouse with six gravel beds. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 7.11 Crop of tomatoes growing in a gravel culture system. Note: The three-way valve in the lower right corner.

FIGURE 7.12 Crop of mature tomatoes ready for harvesting.

ground before covering the floor with a nursery weed mat to prevent any weed growth and to produce a sterile barrier between the underlying soil and the greenhouse environment. A closed recirculating hydroponic system was set up using a 2-in.-diameter main from a 2,500-gal cistern tank. From the main, 1-in. submains were installed under the aisles along the length of the greenhouse. Three 0.75-in. risers entering at 40-ft (12-m) intervals of the bed length were joined to a 0.75-in. black polyethylene hose having 0.25-in. tees every 12 in. (30.5 cm) along its length to supply the nutrient solution. The solution was returned to the cistern by 4-in.-diameter PVC catchment pipes placed as a collection gutter at the lower side of the beds (Figures 7.13 and 7.15). These catchment pipes joined onto a 3-in.-diameter common return pipe to the cistern.

Beds 4 ft (1.2 m) wide by 110 ft (33.5 m) long constructed of 2 in. × 4 in. treated lumber and 0.63-in.-thick plywood were set on top of 8 in. × 8 in. × 16 in. (20 cm × 20 cm × 40 cm) concrete blocks (Figure 7.14). The beds were sloped 3 in. (7.6 cm) toward the catchment pipe (across the 4-ft width). The tables were covered with a 10-mil black polyethylene liner after applying two coats of paint. A pea gravel substrate 1.5 in. (4 cm) in depth was used as the medium.

Irrigation cycles, using a modified herb nutrient formulation as shown in Table 7.1, were repeated every 2–3 h for a 15-min period. An overhead misting system (Figure 7.15) was installed above each bed to provide adequate moisture for the germination of seeds directly

FIGURE 7.13 Raised beds set on concrete blocks. On the left, plants in the foreground are 18 d and those in the background are 15 d. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 7.14 Baby salad greens in beds with mist lines above. The beets in the foreground of the middle bed are 19 d and lettuce mixes 10 d in the right bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

TABLE 7.1
Herb Nutrient Formulation

Nutrient	Concentration, ppm	Nutrient	Concentration, ppm
N	150	P	40
K	182	Ca	230
Mg	50	Fe	5
Mn	0.5	Zn	0.1
Cu	0.035	Mo	0.05
B	0.5		

FIGURE 7.15 Mist system to assist seed germination in pea gravel beds. Note: The catchment pipe is under the poly cover at the center of the bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

sown into the beds. During germination, mist was applied every 10 min for 15 s with a mist controller. Once seedlings had fully expanded cotyledons, the mist cycles were set to every 30 min for 45 s.

After estimating the market demand, trials with many varieties of lettuce and other baby green crops were undertaken to decide on growing the following mixes in each of the beds of 100 ft × 4 ft (30.5 m × 1.2 m).

Bed 1 contained beets only, of the variety Bull’s Blood. Two sowings per week of an 8-ft (2.4-m) section of bed created a cropping cycle of 6 wk. The beets were ready to harvest 3 wk after sowing and were harvested twice before changing the crop. This provided several harvests per week, which are two 8-ft sections.

Beds 2 and 3 had lettuce mesclun mixes containing Tango (20%), Red Oak (20%), Green Romaine (20%), Red Romaine (20%), Mizuna (5%), Tah Tsai (10%), and Broadleaf Cress (5%). The cropping period for lettuce is 3 wk. Therefore, with two beds of 100 ft (30.5 m) each, the total bed length for this crop is 200 ft (61 m). Sowing twice a week gave several harvests per week on a continual basis. The crop is changed after each harvest.

The twice-weekly sowing schedule is as follows: six crops in 200 ft of bed; 200/6 = 33 ft (10 m) per sowing; Tango, Red Oak, Green Romaine, Red Romaine—6 ft 7 in. (1.25 m) each variety (20% × 33 ft); Tah Tsai—3 ft 4 in. (1 m); Mizuna and Broadleaf Cress—20 in. (51 cm) each.

Bed 4 contained dill (Delikat), arugula, spinach, and fennel. With one sowing per week, 3 wk per crop, and one harvest per crop, 33 ft (10 m) of bed is sown each week as follows: dill—16 ft (4.9 m), arugula—8 ft (2.4 m), spinach—5 ft (1.5 m), and fennel—4 ft (1.2 m) of bed length.

Plant spacing for red items is 3 in. (7.6 cm) between rows and about 0.13 in. (3 mm) between seeds within rows. For green vegetables, the spacing is 3 in. (7.6 cm) and almost touching within the rows. The wider spacing for red vegetables is to allow more light to enter the crop, which assists in producing a red color. Seed was sown by hand using a wooden stick (lathe) as a guide.

Seeds are sown directly onto the pea gravel surface and maintained moist during daylight hours by the automatic application of mist for the first 10 d. The mist provides sufficient moisture for imbibitions and subsequent growth of the seed. At the same time, it moves fine seeds into the void spaces of the gravel, protecting it from drying between misting cycles. Once the plants reach about 1 in. (2–3 cm) in height, the mist is turned off, as continued use causes white stains on the leaves because of the high calcium and magnesium carbonates in the hard water. The plants are then irrigated with the recirculating nutrient system every 2 h for 15-min periods during daylight. At the end of the 3-wk cropping period, the plants should be no higher than 2 in. (5 cm), because if they are permitted to grow taller they become less tender with age.

Pests and disease problems associated with a short-term crop such as baby greens is less severe than with long-term crops. However, aphids, white flies, squash beetles, and various moth and butterfly larvae are common pests. These can be controlled with Pyrenone and Dipel or Xentari.

The most difficult problem was to remove the excess roots from the pea gravel between crops, as only the tops of the crop are cut with a knife. Do not use gravel culture for growing mesclun mixes when other cultures, such as the ebb-and-flood systems discussed in Section 6.10, are now available. In the ebb-and-flood system, the crop can be grown in trays or on a capillary mat, and after harvesting the capillary matting can be simply changed to reseed. Also, Section 5.6 presents a better method that can be applied for growing mesclun mixes.

Mesclun mixes are available from seed companies, already made up as mixes, so it is easier to sow as one instead of many different varieties separately and later upon harvesting mixing them. Mesclun mixes are best packaged in a ready-to-eat form that does not require washing, so a washing–packing facility of the most up-to-date standards is required.

7.5 ADVANTAGES AND DISADVANTAGES OF TRICKLE IRRIGATION

The advantages of the trickle system over the subirrigation system are as follows:

1. Fewer problems of roots plugging the drain pipes.
2. Better aeration to the roots, since at no time are they completely submerged in water. Also, water trickles down past the roots, carrying fresh air with it.
3. Lower construction costs, since smaller nutrient tanks are needed and no valves or plenums are required.

4. A much simpler system with fewer chances of failure. Coordination of valves, pumps, and so on, is not involved. It is simple to install, repair, and operate.
5. The nutrient solution is fed directly to each plant.

The following are some disadvantages of the system:

1. Sometimes “coning” of water movement occurs because of the relatively coarse particles of gravel. That is, water does not move laterally in the root zone but flows straight down. This results in water shortage to the plants and roots growing along the bottom of the beds where most water is present, eventually plugging drainage pipes. A subirrigation system uniformly moistens all plant roots and the medium.
2. The trickle lines sometimes get clogged or pulled out by workers. The use of filters in the main header lines will reduce clogging. The use of sweat hoses or emitters can reduce problems of workers accidentally pulling out lines.

7.6 STERILIZATION OF GRAVEL BETWEEN CROPS

The sterilization of gravel between crops can easily be done with household bleach (calcium or sodium hypochlorite) or hydrochloric (muriatic) acid used for swimming pools. A 10,000 ppm of available chlorine waste solution is made up in the nutrient tank, and the beds are flooded several times for 20 min each time. The chlorine solution is then pumped to waste, and the beds rinsed several times with clean water until all bleach residues are eliminated. The greenhouse then should be allowed to air out for 1–2 d before planting the next crop. An alternative is Zerotol, a form of hydrogen peroxide.

In a trickle system, the drain-pipe exit must be plugged to allow the beds to fill up, and the sterilizing solution can be pumped through the trickle lines. This will take time, so it is helpful to use an auxiliary pump and hose to flush the beds from above until they fill up. The same procedure is followed in rinsing the beds with clean water.

With each successive crop, some roots will remain in the medium. Over the years, chlorine sterilization will become less effective unless the roots are removed. Removal would be very costly; therefore, eventually a more powerful sterilant will have to be used, such as steam sterilization or chemicals such as Vapam or Basimid. It is inevitable that at some point the roots will plug the drain pipes and a “snake” type rooter will have to be run through the pipes to remove them. If that does not work, the pipes will have to be dug up and cleaned before replacing them in the beds.

7.7 ADVANTAGES AND DISADVANTAGES OF GRAVEL CULTURE

Gravel culture initially is blessed with many advantages, but over time some of these advantages are lost.

The following are the advantages:

1. Uniform watering and feeding of plants
2. Can be fully automated
3. Gives good plant root aeration
4. Adaptable to many types of crops

5. Has proved to be successful on many commercial crops grown both outdoors and in greenhouses
6. Can be used in nonarable areas where only gravel is available
7. Efficient use of water and nutrients through a recycling system

The following are the disadvantages:

1. Costly to construct, maintain, and repair.
2. With automatic valves and so on, failures occur often.
3. One of the biggest problems is the root buildup in the gravel, which plugs drainage pipes. Each crop leaves some roots behind, and the moisture-holding capacity of the medium increases. Consequently, watering frequency may be reduced each year. Watering and aeration stresses occur. Over the years, this root buildup results in a graveled soil, and the advantages over a soil system will be lost. Eventually the gravel will have to be cleaned of roots, if not completely changed. Sterilization between crops by the use of chlorine alone becomes ineffective.
4. Some diseases such as *Fusarium* and *Verticillium* wilts can spread through a cyclic system very rapidly.

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8 Sand Culture

8.1 INTRODUCTION

Sand culture was the most common form of hydroponics in areas of the world having an abundance of sand. It was particularly well suited to desert regions of the Middle East and North Africa. Now, however, nutrient film technique (NFT) and rockwool systems have replaced sand culture because of their ability to recirculate the nutrient solution and to automatically control nutrition through the use of computerization.

Since high-quality water is rare in most of these desert locations, some form of purification through distillation or reverse osmosis is imperative for success. Recirculating hydroponic systems that efficiently utilize the costly purified water are essential from an economic standpoint.

Some of the larger sand-culture operations in the past include the following:

Superior Farming Company, Tucson, Arizona (11 acres) (4.4 ha)
Quechan Environmental Farms, Fort Yuma Indian Reservation, California (5 acres) (2 ha)
Kharg Environmental Farms, Kharg Island, Iran (2 acres) (0.8 ha)
Arid Lands Research Institute, Sadiyat, Abu Dhabi, United Arab Emirates (5 acres) (2 ha)
Sun Valley Hydroponics, Fabens, TX (10 acres) (4 ha)

The Environmental Research Laboratory, a branch of the University of Arizona, worked with these projects. They were instrumental in proving the use of sand culture in these areas (Fontes, 1973; Hodges and Hodge, 1971; Jensen et al., 1973; Jensen and Teran, 1971).

8.2 MEDIUM CHARACTERISTICS

In Mexico and the Middle Eastern countries where greenhouse projects were established on the seacoast, normal beach sand was used as the medium (Jensen and Hicks, 1973; Massey and Kamal, 1974). Once the growing medium (sand) was leached free of excess salts, vegetables were either seeded directly in the sand or planted as transplants. In the U.S. Southwest, concrete river-wash sand is used, not mortar sand, as it is too fine and will puddle. Puddling is indicated by water coming to the surface on vibration of the sand. It is a result of a high percentage of silt and fine sand. The aggregate must be washed free of fine silt and clay. It should also be relatively free of particles of diameter over 0.0625 in. (2 mm) and under 0.025 in. (0.6 mm). A properly screened sand-culture aggregate will drain freely and not puddle after application of a large amount of water.

Aggregates that are soft and tend to disintegrate should be avoided. However, it may not be possible to avoid using soft particles in areas where only limestone sand is available. In such cases, nutrients should be added and the pH adjusted daily, as discussed in Chapter 7.

8.3 STRUCTURAL DETAILS

Two methods of utilizing sand as a growing medium have proved satisfactory. One is the use of plastic-lined beds; the other involves spreading sand over the entire greenhouse floor.

8.3.1 Beds with Plastic Liner

Growing beds may be built as above-ground troughs with wooden sides (Figure 8.1) similar to those described for gravel culture in Chapter 7. Six-mil black polyethylene can be used for the liner, but 20-mil vinyl is more durable. The bottom of the trough should have a slight slope of 6 in. (15 cm) per 200 ft (61 m), so that it can be drained or leached when necessary. The drain pipe should be placed in the entire length of the bed. A 2-in. (5-cm)-diameter pipe is large enough, since in sand culture only excess solution (about 10% of that added) is drained. Connect the drain pipes from all beds to a main at one end, which collects the waste water and conducts it away from the greenhouses.

Similar to gravel culture, drainage holes are crosscut with a saw one-third the distance through the pipe at every 18 in. (46 cm). The cuts must be against the bottom of the bed so that plant roots are discouraged from entering the pipes. As in gravel culture, one end of each pipe should be left above the ground so that a Roto-Rooter can be used to clean them. An alternative to making these drain pipes, which is very laborious, is to purchase the black-coiled plastic drainage pipe from an irrigation supplier. This drain pipe is prepunched with holes.

The width of the beds may be 24–30 in. (61–76 cm) and the depth 12–16 in. (30.5–40.6 cm). The bottom of the bed may be level, round, or V-shaped with the drainage pipe in the middle.

8.3.2 Greenhouse Floors Lined with Polyethylene

Construction costs can be reduced in areas where lumber is expensive or difficult to obtain by lining the greenhouse floor with black 6-mil polyethylene and filling it with 12–16 in. (30.5–40.6 cm) of sand (Jensen, 1971). The floor should have a slight grade of 6 in. (15 cm)

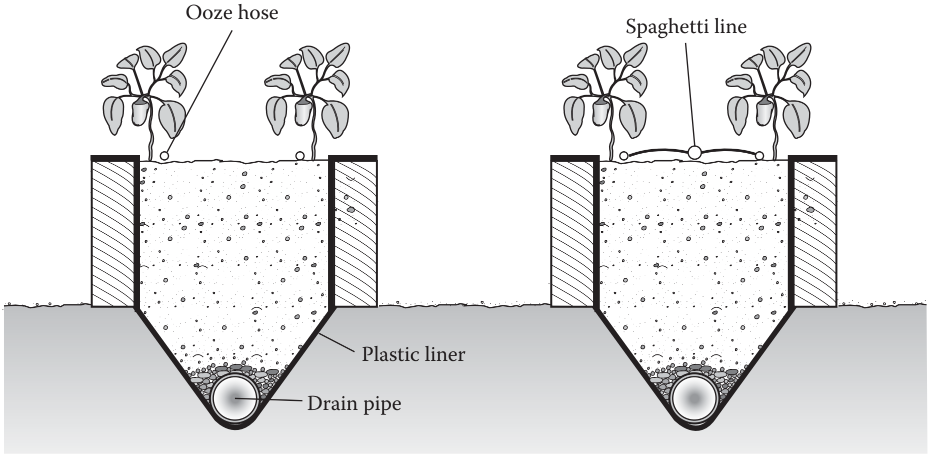

FIGURE 8.1 Cross section of sand-culture beds. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

per 100 ft (30.5 m), so that the area may be drained or leached when necessary. Generally, two layers of 6-mil plastic are used to cover the entire floor.

Before installing the polyethylene, the floor should be graded and packed. Polyethylene sheets should be overlapped several feet (0.6 m) when more than one sheet is required in wide houses. The drain pipe, 1.25–2 in. (3.1–5 cm) in diameter, or black drainage pipe as mentioned above, is then placed on top of the polyethylene at a uniform spacing of 4–6 ft (1.2–1.8 m) between pipes, depending on the nature of the sand. The finer the particles, the closer the pipes will have to be spaced. These drain lines must run parallel to the slope down into a main drain running across the low end of the greenhouse grade. Once the drain pipes are in place, sand is spread over the entire area to a depth of 12 in. (30.5 cm) (Figures 8.2 through 8.4).

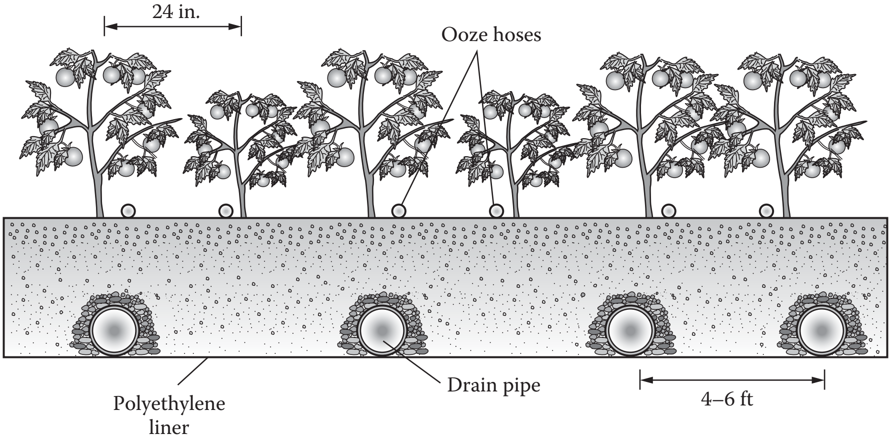

FIGURE 8.2 Cross section of greenhouse floor design for sand culture. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 8.3 The laying of a polyethylene liner and drain pipes.

FIGURE 8.4 Back filling with 12 in. of sand.

If the medium is spread shallower than 12 in. (30.5 cm), there will be a problem in obtaining uniform moisture conditions and a greater chance of roots growing into the drain pipes. The surface of the bed should be graded to the same slope as the floor.

8.4 DRIP (TRICKLE) IRRIGATION SYSTEM

A drip irrigation system must be used with sand culture. Waste nutrients (approximately 10% of that applied) are not recycled. Such a system is termed an *open system*, as opposed to the recycled or closed system of gravel culture. The drip irrigation system feeds each plant individually by use of emitters and drip feed lines, or sweat (ooze) hoses (Figure 8.5).

If the ooze hose is used, a 4-in. (10-cm) spacing between outlets is recommended. If the surface of the bed is level, the tube should not be over 50 ft (15 m) long. If the surface is sloped 6 in. (15 cm), the tube can be 100 ft (30.5 m) long, with the supply manifold at the high end.

On a level bed, the supply manifold may run down the center of a 100-ft (30.5-m) bed, with 50-ft (15-m) lines off either side. The objective of a greenhouse drip irrigation system is to apply uniform water at optimum levels to all plants.

8.4.1 PLANNING A DRIP IRRIGATION SYSTEM

Divide the total greenhouse area into equal or similar crop sections or into individual houses. Plan irrigation systems so that each house or section can be irrigated independently (Figure 8.6). Piping to each section should be capable of distributing 1.6–2.4 gal/min (6–9 L/min) for each 1,000 ft^2 (93 m^2), or 8–12 gal/min (30–45 L/min) for each 5,000 ft^2 (465 m^2) of growing area.

The rate and duration of each irrigation cycle will be a function of the type of plant, its maturity, weather conditions, and the time of day. In all cases, a tensiometer system should

FIGURE 8.5 The installation of ooze hoses for an automated drip irrigation feeding system.

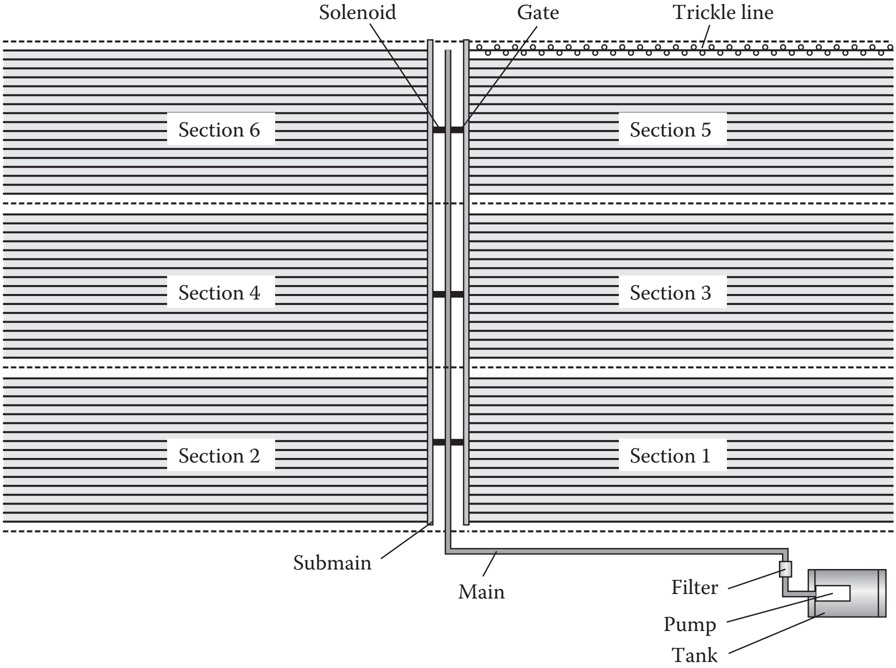

FIGURE 8.6 A typical drip (trickle) irrigation system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

be set up so that no more than 8%–10% of the nutrient solution applied at any irrigation cycle is wasted. This can be determined by measuring the amount of water passing through the main supply line and that flowing out of the main collector drain line.

The volume of water that can enter each greenhouse section should be regulated by a flow-control valve that is sized and selected according to plant water requirements of that greenhouse section. Flow valves are usually available in 1- and 2-gal/min (3.8- and 7.6-L/min) size increments and fit 0.75- and 1-in. (1.9- and 2.5-cm) pipe connections. The flow valve should be located upstream from the solenoid valve where the irrigation cycle is automatically controlled. While a minimum water supply pressure of 15 psi (pounds per square inch) (103.5 kiloPascals or kPa) is required for proper operation of most flow-control valves, for best performance the main water supply line should be maintained at a pressure between 20 and 40 psi (138 and 276 kPa). The flow-control valve assures a constant quantity of water and reduces water pressure in the irrigation system piping to 2–4 psi (13.8–27.6 kPa), which is optimum for low-pressure drip irrigation emitters.

The main line piping should be 2- to 3-in. (5- to 7.5-cm)-diameter PVC, depending on the area of the largest greenhouse section or number of sections watered at any one time. Since all sections are not irrigated at the same time, the total volume capacity of the main line needs to satisfy only the maximum number of sections operating at a time. Header lines should be 1-in. (2.5-cm)-diameter PVC pipe for a 5,000-ft^2 (465-m^2) section. Larger sections should use a larger pipe. The header line is connected to the main line with a tee at its center to equally divide the water supply (Figure 8.6). A gate valve with a solenoid valve downstream on this connection between the main and submain (header) operates the irrigation cycle. From this header line, a 0.5-in. black polyethylene pipe is run along the inside of each plant row. The emitters are placed in these lateral lines at the base of each plant. Flexible polyethylene pipe (usually 80–100 psi) is normally used for these emitter laterals. Where manufactured emitters are used, a 0.5-in. pipe will provide equal water distribution and uniform water application throughout 100- to 150-ft (30.5- to 46-m) greenhouse irrigation runs.

Most drip emitters can deliver water at a rate of 0.5–3 gal/h (2–11 L/h), depending on the water pressure in the lateral line. A greenhouse drip irrigation system should be designed so that each emitter applies 1–1.5 gal/h (4–6 L/h).

While spaghetti tubing is more economical than manufactured emitters, more labor is required for its installation and maintenance. Perforated (ooze) hose is installed more easily but is not as durable (it must be replaced between crops).

Emitters, pipes, and fittings should be black to prevent algae growth inside the piping system.

Water must be filtered before flowing into a drip irrigation system. Y-type, in-line strainers, containing at least 100 mesh screens and equipped with clean-out faucets, should be installed with the screen housing and flush valve down. The filter(s) should be installed downstream from the fertilizer injector in the main supply line. It is wise to also install a filter in the main supply line upstream from the fertilizer injector.

The fertilizer injector or proportioner automatically proportions the right amount of stock solution into the main supply line during every irrigation cycle. Positive-displacement pump injectors, venturi proportioners, and forced-flow batch tanks are some of the types of fertilizer injectors available commercially (Figure 8.7).

Alternatively, a nutrient solution can be pumped into the drip irrigation system directly from a large storage tank. Today most growers use injectors and stock solution tanks.

Irrigation is now controlled by the use of sensors with a feedback system to a central computer. These control the solenoid valves and the activation of the fertilizer injector or tank pump, which allow one section of the greenhouse to be irrigated at one time.

If calcareous sand is used, the amount of chelated iron going to the plants must be increased, as discussed earlier. When fertilizer proportioners are used, two stock solutions are prepared. One is a calcium nitrate and iron solution, and the other contains magnesium

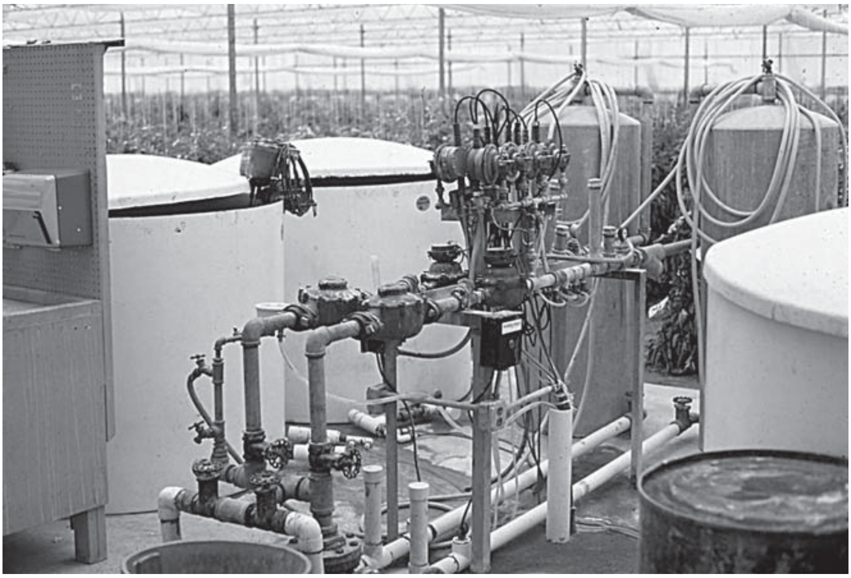

FIGURE 8.7 Automatic proportioner fertilizer-injector system.

sulfate, monopotassium phosphate, potassium nitrate, potassium sulfate, and the micronutrients. The proportioner must be of a twin-head type. For example, if each head injects 1 gal (3.785 L) of stock solution into each 200 gal (757 L) of water passing through the water line, then the stock solution will be 200 times the final concentration that reaches the plants. In this case, the proportioners would have a ratio of 1:200. Two manufacturers of proportioners in the United States are Anderson and Smith.

8.5 WATERING

If a time clock is used, water the crop two to five times per day, depending on the age of the plants, weather, and time of the year. As mentioned earlier, enough water is added during each cycle to allow 8%–10% of the water applied to drain off. Twice a week a sample of this drainage should be tested for total dissolved salts (TDS). If the TDS reaches 2,000 ppm, the entire bed should be leached free of salts by using pure water. However, if no extraneous salts such as sodium are found, pure water may be irrigated onto the crop until the plants themselves, over a few days, lower the salt level down to a point at which nutrients can again be added to the irrigation water.

When using a proportioner, the TDS of the nutrient solution going to the plants should be checked daily to be sure that the injector is functioning properly. Most injector systems have a pH and electrical conductivity (EC) meter in the main line, so monitoring is automatic. Also, check whether each injector pump is injecting the proper amount of stock solution to the irrigation water.

If a nutrient tank is used to store the nutrient solution, it must be large enough to supply water to all the plants in the greenhouse for at least 1 wk. Its size therefore will depend on the total greenhouse area. If several crops having very different nutrient requirements are grown, two storage tanks should be used, each having its specific formulation suitable to the crop it is feeding. The entire irrigation system connected to one tank must be independent of the other.

Since a sand-culture system is an open system in which excess nutrient solution goes to waste, there will be little change in the formulation of the nutrient solution in the storage tank. The pH, however, should be checked daily, especially in areas having highly alkaline waters.

The nutrient solution in the storage tank does not have to be changed regularly as was necessary in gravel culture. The tank need only be cleaned periodically of any sludge and sediment due to inert carriers in the fertilizer salts. To help prevent this, use some type of agitation or aeration of the solution in the tank. Make up a new batch when the existing solution is almost depleted.

Fertilizer injectors have several advantages over a storage tank: (1) they require less space and (2) they are capable of making rapid changes in the nutrient solution formulation to compensate for changes in plant requirement under changing weather conditions. For instance, during a period of dull weather, the concentration of nitrogen can be easily reduced, whereas in a storage-tank system the entire volume of nutrient would have to be altered.

8.6 STERILIZATION OF SAND BEDS BETWEEN CROPS

The best method of eliminating disease-causing organisms and nematodes in the sand is to use steam sterilization. If the greenhouse is heated with a hot water boiler, the boiler should be assembled with a steam converter, which can produce sufficient steam for sterilization (pasteurization) of the growing beds. The steam may be put through the drain system provided the drain lines will not be damaged by the high temperature. Alternatively, pipes can be placed within the top few inches of the sand and the beds covered with heavy canvas or polyethylene before releasing the steam. Pipes are moved along the beds as sterilization is completed for each section of the bed.

8.7 SAND CULTURE OF HERBS

Chives, basil, sage, and mint have been grown successfully in sand-culture beds at California Watercress, Inc., Fillmore, California. In one greenhouse of dimensions 30 ft × 156 ft (9 m × 47.5 m), 17 beds 8 ft × 12 ft (2.4 m × 3.65 m) on one side and 17 beds 8 ft × 14 ft (2.4 m × 4.27 m) on the other side were constructed using 1 in. × 6 in. treated lumber. The 6- to 8-in. (15- to 20-cm)-deep beds were lined with 6-mil black polyethylene. The bottoms of the beds were sloped 2 in. (5 cm) from one side to the other to assist in drainage.

At a second location, a greenhouse of one-half acre (0.2 ha) was erected to grow herbs. In that greenhouse, one range of 30 ft × 165 ft (9 m × 50 m) was used to grow sage and mint in sand. Before building the beds, the irrigation system was installed. A 2-in. PVC main with a 0.75-in. riser to each bed was set in place. A solenoid valve on the main line operated by an irrigation controller activated the feeding cycles from an injector system. The entire floor of the greenhouse was covered with a nursery weed mat to prevent weed growth (Figure 8.8). The underlying soil was very sandy with many rocks, which provided excellent drainage. The beds, of the same dimensions as in the other greenhouse, were placed on top of the weed matting and staked in position. However, unlike the other beds, these were not lined with polyethylene. The treated boards making up the beds were simply set on top of the weed-mat covering, as the weed mat allows water to move through it freely while roots cannot easily penetrate.

A coarse river-wash sand of granitic origin was used as the medium. In the larger greenhouse, the beds of sand were covered with 1 in. (2.5 cm) of peat–perlite mix to improve

FIGURE 8.8 Greenhouse floor covered with a weed mat. (From California Watercress, Inc., Fillmore, CA. With permission.)

lateral movement of the solution. It was found later that the sand had too much silt in it as crusting occurred with the hard water of the area. To improve the sand, approximately one-third was removed and replaced with the peat–perlite mix, which was incorporated in the sand. The other beds in the smaller greenhouse had a better quality of sand from a different source, and chives and basil grew well.

Drip irrigation lines were placed along the length of the beds from the 0.75-in. header at 12-in. (30.5-cm) centers (Figure 8.9). “T-tape” having small holes every 12 in. (30.5 cm)

FIGURE 8.9 Drip irrigation system of sand-culture beds growing herbs. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.10 Attaching T-tape drip line to polytube adapter. (From California Watercress, Inc., Fillmore, CA. With permission.)

provided 38 gph (gallons per hour) per 100 ft at 10 psi pressure, which is equivalent to 144 L/h per 30.5 m at 69 kPa pressure. The T-tape was secured with an adapter attached to a 0.25-in. black poly drip emitter line, which in turn was inserted into the 0.75-in. header via a hole and sealed with silicone rubber (Figure 8.10). The ends of the T-tape were sealed, folding them several times and taping them with pipe tape.

Sage was seeded in a peat-lite medium in 98-celled trays and later transplanted to the beds (Figure 8.11). Mint cuttings were rooted in 2.25-in. × 3-in. deep (6 cm × 7.5 cm) plastic

FIGURE 8.11 Transplanting sage into sand-culture beds. (From California Watercress, Inc., Fillmore, CA. With permission.)

pots with a peat-lite medium before transplanting. Chives were transplanted from the field after washing the soil from their roots. The basil was grown from seed. The mint was ready for first harvest after 6 wk (Figure 8.12), with continued harvests every 4–5 wk depending on the season. The basil was harvested every 3 wk. Chives were harvested on a 30- to 35-d cycle depending on day length and light conditions (Figures 8.13 through 8.15). Two to four

FIGURE 8.12 Sage and mint in beds. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.13 Chives 7 d after harvesting. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.14 Chives 33 d after cutting, ready for another harvest. Note: The space heater in the foreground. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.15 Chives just harvested on the right. (From California Watercress, Inc., Fillmore, CA. With permission.)

beds were cut each day over a 2-wk harvesting period. Similar to watercress, these herbs are bundled with elastic bands or twist ties and sold as dozens of bunches.

8.8 ADVANTAGES AND DISADVANTAGES OF SAND CULTURE

Advantages of sand culture over gravel culture are as follows:

1. It is an open system, that is, the nutrient solution is not recycled, and so the chances of disease organisms such as *Fusarium* or *Verticillium* spreading in the medium are greatly reduced.
2. There are fewer problems with drain pipes getting plugged with roots since the denser medium of sand favors lateral root growth.
3. The finer sand particles allow lateral movement of water through capillary action so that solution applied at each plant becomes evenly distributed throughout the root zone.
4. With the right choice of sand combined with a drip irrigation system, adequate root aeration is achieved.
5. Each plant is fed individually with a new complete nutrient solution during each irrigation cycle—no nutrient imbalance occurs.
6. Construction costs are lower than for a subirrigation gravel system.
7. The system is simpler, easier to maintain and service, and more foolproof than a subirrigation gravel-culture system.
8. Owing to the smaller particle size of sand, water retention is high, and only a few irrigations are required each day. If a failure occurs, there is more time available to repair the system before the plants will use up the existing water in the medium and begin to experience water stress.
9. Smaller, centrally located nutrient reservoirs or injectors can be constructed away from the actual growing area of the greenhouse.
10. Sand is readily available in most locations. When using calcareous sand, the formulation can be adjusted to compensate for daily pH changes and shortages of iron and/or other elements.

Disadvantages of sand culture compared with gravel culture are as follows:

1. One of the major disadvantages is that either chemical or steam sterilization methods must be used to fumigate between crops. However, such methods are thorough, even if they are a little more time consuming than the use of bleach with gravel culture.
2. Drip irrigation lines can become plugged with sediment. This, however, can be overcome by the use of in-line 100- to 200-mesh filters, which can be easily cleaned daily.
3. Some claims are made that sand culture uses more fertilizer and water than a cyclic gravel-culture system. Again, this can be overcome by good management. The waste should be monitored and feeding adjusted so that no more than 7%–8% of the solution added is actually drained out. Even in gravel culture, the waste can be equally as great, if not greater, because of the need to change the nutrient solution periodically.

4. Salt buildup may occur in the sand during the growing period. This can be corrected, however, by flushing the medium periodically with pure water. Again, proper management with monitoring of salt accumulation from the drainage water is important to prevent excess salt problems.

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9 Sawdust Culture

9.1 INTRODUCTION

Sawdust culture was particularly popular during the introduction of soilless culture in the 1970s in British Columbia, Canada. This was due to the large forest industry in the West Coast of Canada and the Pacific Northwest of the United States. Sawdust was, at that time, a waste material of sawmills and was burnt to dispose of it. The sawdust had no value and could be obtained from sawmills for the cost of trucking it to the greenhouse site. In British Columbia, Canada, the Canada Department of Agriculture Research Station at Saanichton carried out extensive research for a number of years to develop a sawdust-culture system for greenhouse crops (Maas and Adamson, 1971; Mason and Adamson, 1973). The need for a soilless-culture system became evident with increased soilborne nematode infestations and diseases coupled with poor soil structure, which made the profits from greenhouse crops very marginal. Over the next few decades in British Columbia, over 90% of all greenhouses used some form of soilless culture for vegetable and flower production. Vegetable growers usually used sawdust culture, while flower producers used a peat–sand–perlite mixture.

Sawdust culture began to decline in the early 1980s as rockwool culture was introduced. Today, very few, if any, growers still use sawdust culture, as now sawdust is used as a by-product in making fiber-board products used in house and furniture construction. As a result, it is no longer a cheap substrate, if at all available.

9.2 GROWING MEDIUM

Sawdust was adopted as a growing medium in the coastal region of British Columbia because of its low cost, light weight, and availability. Moderately fine sawdust or one with a good proportion of planer shavings is preferred, because moisture spreads better laterally through these than in coarse sawdust.

Sawdust from Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) was found to give best results (Maas and Adamson, 1971). Western red cedar (*Thuja plicata*) is toxic and should never be used.

While other media such as sphagnum peat, ground fir bark, and mixtures of sawdust with sand and/or peat were tested successfully, they are more expensive and therefore might be used if sawdust is unavailable.

One precaution that should be taken with sawdust is that of determining its sodium chloride content. Logs are floated in barges on the ocean and often remain in the water for many months before going to a sawmill. They absorb sea water over this time and thus acquire salt (sodium chloride) levels toxic to plants. Therefore, as soon as the sawdust is received, samples should be taken and the sodium chloride content tested. If any significant amount of sodium chloride is found (greater than 10 ppm), the sawdust should be thoroughly leached with pure fresh water once it is placed in the beds, but before planting.

This leaching process may take up to a week in order to reduce the sodium chloride to an acceptable level.

9.3 BED SYSTEM

Growing beds are usually constructed of rough cedar and lined with 6-mil black polyethylene or 20-mil vinyl similar to those designs under sand culture (Figure 9.1). Rough cedar boards of 1 in. × 8 in. (2.5 cm × 20 cm) can be used for the sides. Either a V-bottom or round-bottom bed configuration is suitable (Figure 9.1). The depth of the beds should be 10–12 in. (25–30.5 cm). A 2-in. (5-cm) diameter drain pipe is placed on the bottom of the bed.

Beds are usually 24 in. (61 cm) wide; however, 20-in. (51-cm)-wide beds (inside dimension) are adequate with 32-in. (81-cm) pathways between the beds. Studies by Maas and Adamson (1971) have shown that even somewhat narrower and shallower beds, with a volume of 0.33 ft^3 (0.009 m^3) of medium per plant, are satisfactory. If narrower beds are used, the pathways should be widened to provide the same total amount of greenhouse area for each plant, as light requirements for the plants are the same regardless of the ability of the volume of medium required to provide adequate nutrition.

An alternative to these standard bed designs is the use of sloped-bottom beds (Figure 9.1). In this case, the beds are constructed of rough cedar, 1 in. × 8 in. (2.5 cm × 20 cm) on one side and 1 in. × 12 in. (2.5 cm × 30.5 cm) on the other. The 1 in. × 12 in. lumber is covered

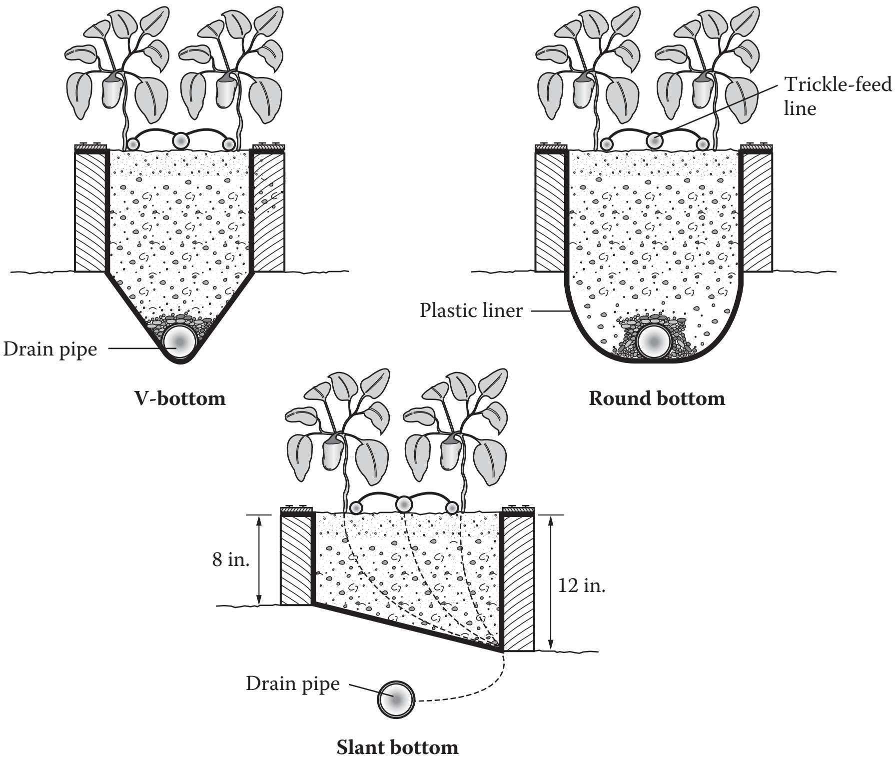

FIGURE 9.1 Cross sections of sawdust-culture beds. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

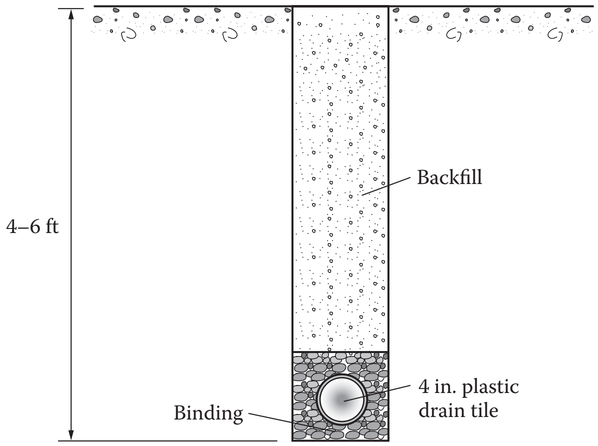

FIGURE 9.2 Cross section of a drainage ditch and 4-in. perforated drain pipe. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

with the liner on the inside face and around the top and bottom edges. The 1 in. × 8 in. lumber is covered with the liner on one face and extends on a slope toward the wide side. But a small gap (0.5 in.) (0.6 cm) between the end of the poly liner and the wide side allows drainage of excess solution to a drainage pipe located several feet (61 cm) below the beds (Figure 9.1).

Drain pipes are installed when the site is leveled before the construction of the greenhouse. In this case, a standard perforated plastic drain pipe is used. It is placed in a ditch dug by an automatic ditch-digging machine (Ditch Witch). When fine-texture (clay loam) soil is present, a filtering material (binding) placed above and around the pipe will prevent clogging of the holes in the pipe (Figure 9.2). The best material is a composition of varied particle sizes: coarse sand to fine sand, pea gravel. The material should be placed at a depth of approximately 6–8 in. (15–20 cm) above and around the tile.

9.4 BAG SYSTEM

The most common system is to use long plastic bags similar to those of rockwool slabs. These are aptly termed *slabs*. The slabs are made from 6-mil thick white-on-black polyethylene “layflat” plastic, which is heat sealed on one end. They are filled with the medium using a hopper and chute that fits into the top of the bags. Once filled, the other end of the bag is closed with a heat-sealing machine. The process can be fully mechanized to reduce labor. Finished bags are approximately 8–10 in. (20–25 cm) wide by 3 ft (90 cm) long by 3–4 in. (8–10 cm) thick, as shown in Figure 9.3. Up to six tomato plants may be grown in one bag.

Seedlings are started in rockwool cubes, which are transplanted into rockwool blocks, which are then placed into the sawdust bags, similar to rockwool culture. For an early crop (crops seeded by mid-December), the growing blocks are placed on top of the sawdust bags, but not allowed to root out until one flower truss sets fruit. Then holes are cut below the blocks in the plastic bag and the blocks set into the holes.

In British Columbia, where light is limited during the winter months, when tomato seedlings are started it is advisable to use high-intensity discharge (HID) 400-W sodium vapor

FIGURE 9.3 Sawdust slabs with six plants. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 9.4 Sawdust culture with hot water heating pipes and carbon dioxide tube next to left pipe. (From Gipaanda Greenhouses Ltd., Delta, B.C., Canada. With permission.)

lights to give 5,500 lx (510 ft-c) intensity at the plant surface with a 20-h photoperiod. Seedlings should be grown under this propagation section of the greenhouse until they are ready for transplanting into the bags. Seedlings are generally sown in mid-December and transplanted in mid-January.

The greenhouse floor is lined with white polyethylene to prevent contact of the roots growing from the bags with the underlying soil. The white polyethylene also serves to reflect light (much needed during the winter months) and seal out insects and disease organisms present in the underlying soil. Similar to rockwool culture, the floor is sloped to create a swale between each set of two rows of bags for drainage of excess solution out of the greenhouse. Hot water heating pipes conducting heat from a central boiler are laid in the aisles between the double rows of bags (Figure 9.4). The heating pipes also serve as a track for a mobile harvesting plant maintenance cart to run on (Figure 9.5).

Each plant is fed individually using a spaghetti trickle-feed line placed on the rockwool block in the sawdust bag. The irrigation line runs the length of the rows along one side of the slabs (Figure 9.6). The nutrient solution is pumped from a central injector system using stock solution tanks. Carbon dioxide enrichment is also distributed to the plants by a small polyethylene conduction tube running the length of the rows next to the irrigation line (Figures 9.4 and 9.6). The carbon dioxide is generated as a by-product of combustion of natural gas from the central boilers and is piped to each greenhouse (Figure 9.7).

FIGURE 9.5 Mobile harvesting working cart runs on heating pipes. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

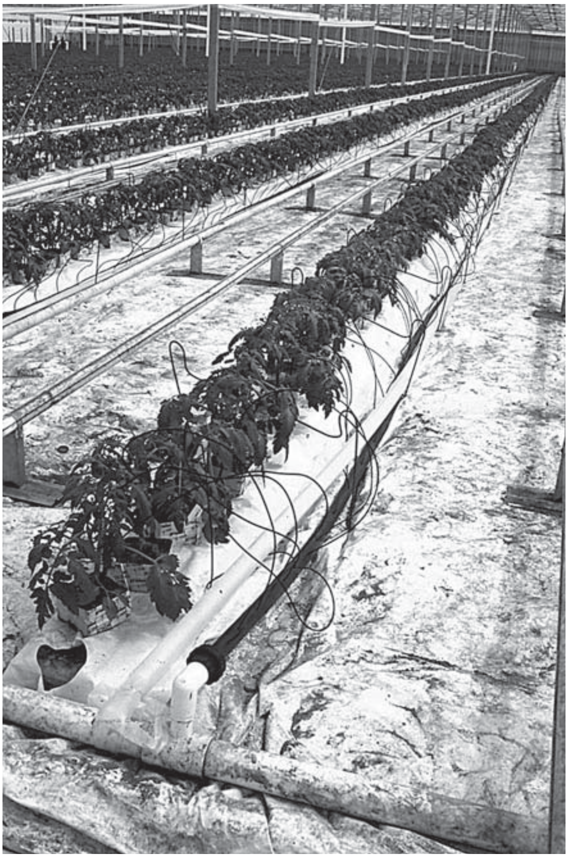

FIGURE 9.6 Sawdust culture with drip irrigation lines and heating pipes. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

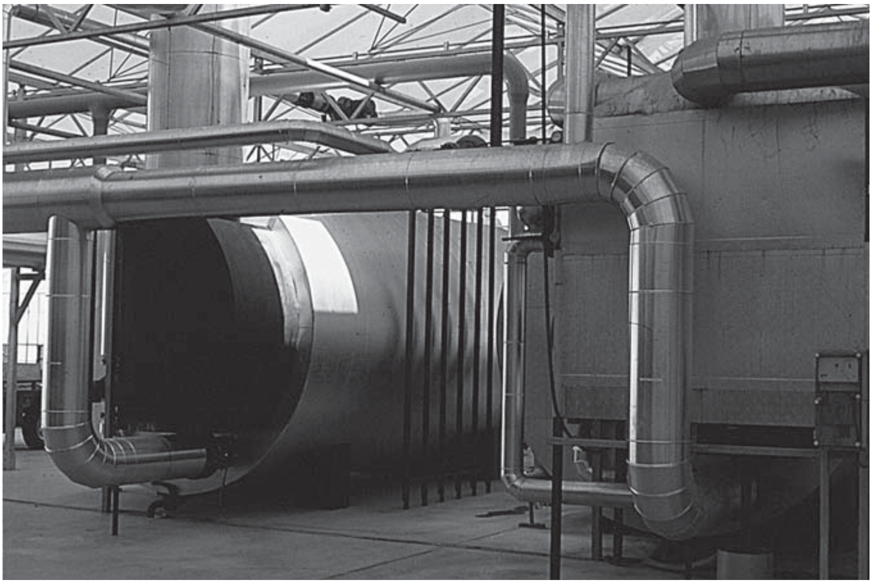

FIGURE 9.7 Carbon dioxide recovery unit attached to central boiler.

Tomatoes are harvested into 25-lb (11-kg) plastic tote bins using mobile carts running on the heating pipes, and, with tomatoes on vines (TOVs), are boxed in the greenhouse (Figures 9.8 and 9.9). Activities such as pollination, suckering, and tying string supports are made easier by the use of a mechanically raised platform running on the heating pipes, as shown in Figure 9.5. Harvested tomatoes in tote bins or boxes are moved using a pallet jack, a fork lift, or trailers pulled by a tractor (Figure 9.9).

FIGURE 9.8 Tomatoes are harvested into plastic tote bins. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 9.9 A tractor with carts transports the harvested product. (From Eurofresh Farms, Wilcox, AZ. With permission.)

With the sawdust-culture system in British Columbia, generally one crop of tomatoes a year is grown. Seeding is in mid-December, with production beginning by late March and continuing until November.

Many northern U.S. and Canadian growers have now established subsidiary operations in the southwestern United States. Houweling Nurseries Oxnard, Inc., located in Camarillo, California, constructed 20 acres (8 ha) by 1997 and has continued to expand to a total of 126 acres (50 ha) by 2009. More on this operation is discussed in Chapters 10 and 11.

They grew tomatoes in the first year in a foam substrate set up similar to rockwool and sawdust cultures using a drip irrigation system. Problems with nonuniform distribution of moisture in the foam slabs prompted them to return to their conventional sawdust culture. On expansion, they turned to growing a large percentage of TOV using the variety Tradiro.

This southern location enables the greenhouse company to focus on winter production when prices are highest and their Canadian operation has less or no production. Tomatoes are seeded in July and transplanted in August to begin production by October. Harvesting takes place until June.

Sawdust-filled slabs (bags) similar in dimensions to rockwool slabs are transported from Canada (Figure 9.10). Before setting out the slabs, the floor is covered with a 6-mil white-on-black polyethylene barrier to prevent contact of plant roots with the underlying substrate (Figure 9.11). The slabs are 8 in. (20 cm) wide by 3 in. (7.5 cm) thick by 39 in. (1 m) long. Seed is sown in rockwool cubes, which after several weeks are transplanted to large rockwool blocks (double blocks) 6 in. × 3 in. × 2.5 in. (15 × 7.5 × 6.5 cm) (length × width × height). Two seedlings are transplanted per double block. Many growers buy their seedlings from a specialized transplant grower such as Bevo Agro as mentioned in Chapter 6. The transplants are set into the slabs when they are 4–5 weeks old, about 6 in. (15 cm) high (Figure 9.12). Each slab contains six plants that are trained in a V-cordon fashion strung alternatively to overhead support wires (Figure 9.13). V-cordon training also makes more light available for intercropping a young crop between the rows.

FIGURE 9.10 Sawdust slabs shipped from Canada. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

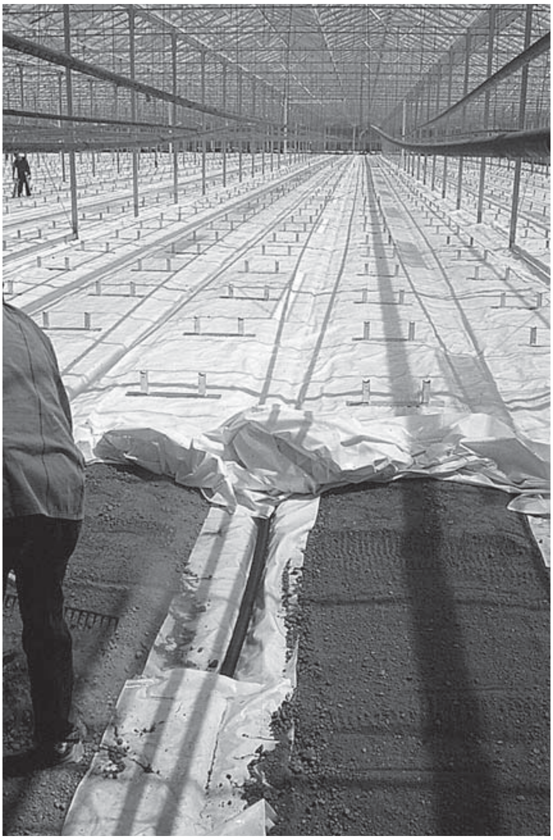

FIGURE 9.11 White-on-black polyethylene floor barrier. Note: The drainage pipe under the polyethylene floor barrier located in what will be the middle of the plant rows. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 9.12 Transplants set onto sawdust slabs. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 9.13 V-cordon training system of tomato-on-vines (TOV). (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

Each plant is irrigated with a drip line secured by a small stake. Several slits are cut in the polyethylene wrapper of each slab to permit good drainage. The drainage (leachate) flows to the underground drainage pipes through slits in the ground cover.

9.5 NUTRIENT SOLUTION DISTRIBUTION SYSTEM

In both the bed and bag systems of sawdust culture, a drip irrigation system is used to supply the water and nutrient requirements of the plants. As pointed out in Chapter 8, adequately sized main headers and valves are needed to balance the flow to the row headers. Row headers are usually made of 0.75-in. plastic black poly hose, which can handle 200 (1.66-mm diameter) feeding tubes. Row headers of 0.5- and 1-in. sizes can supply 100 and 300 feeding tubes, respectively. The trickle lines are attached to the black poly headers with 0.5-gal/h (2-L/h) flow rate compensating emitters.

Plants are supplied with nutrient solution directly from a dilute-solution storage tank or through a fertilizer proportioner from containers of concentrated stock solutions as described for sand culture (Section 8.4). The dilute-solution system needs a storage tank, a pump, filters, and a distribution system.

Determine the capacity of the tank from the number of plants to be fed at one time. The tank should be able to supply at least 1 qt (1 L) of solution per feeding for each plant for total feeding requirements for 1 wk. The total volume needed depends on the number of irrigation cycles required, which in turn is a function of weather conditions, plant maturity, and the nature of the plant. Some growers install more than one tank so that they can prepare the nutrient solution at least a day in advance of the estimated time of depletion of the other tank. In this way, the recently made nutrient solution can be heated for at least 12 h by an immersion heater to bring its temperature to an optimum level of 65°F–70°F (18°C–21°C) before it is applied to the plants.

This system of using regular-strength nutrient solution in large storage tanks has now given way to the use of stock solutions and injectors, as was described in Chapter 3. With stock solutions, large plastic storage tanks are also used. The tanks and injection system should be located in header houses near water supply and have close access to fertilizers.

The distribution system consists of a main supply line, submain headers, laterals, and drip lines with emitters, fittings, and controls (Figure 8.6). Gate valves and solenoid valves should be installed in the submain lines so that there is the option of controlling the feed supply to each greenhouse section. In this way, the flow to each section can be varied if there are differences in the volume requirements of the plants. The submain header is connected to the main header and located underground close to the main header. It is best to position the main supply line so that the walkway is unobstructed (Figure 9.14).

Pipe sizes must be selected by taking into consideration the flow rates and frictional loss (head) in feet per 100 ft of pipe length of the specific diameter of pipe. The use of a Williams and Hazen formula table will assist in determining the correct pipe size. Otherwise, when laying out a plan of the irrigation system, a qualified person from an irrigation supply store may be asked do these calculations. The total frictional loss in the system will then determine the size of the pump needed to supply the water.

Most growers now use emitters of 0.5- to 1-gal/h (2- to 4-L/h) volume instead of spaghetti lines (Figure 9.15). The emitters are inserted directly into the 0.5- or 0.75-in. black polyethylene lateral with a special punch. A drip line is attached to the other side of the emitter and placed at the base of each plant with a special stake that directs the solution down its length to its base as shown in Figure 9.15. The emitters produce a uniform volume of solution and are also available as "pressure-compensating" ones should there be differences in the level of the greenhouse floor. Pressure-compensating emitters are more expensive than the regular ones, but their output is constant regardless of elevation differences or location along the poly lateral line.

When using these trickle tubes and stakes, check them periodically to determine if any salt buildup or root growth into them that causes plugging occurs. This can be avoided if

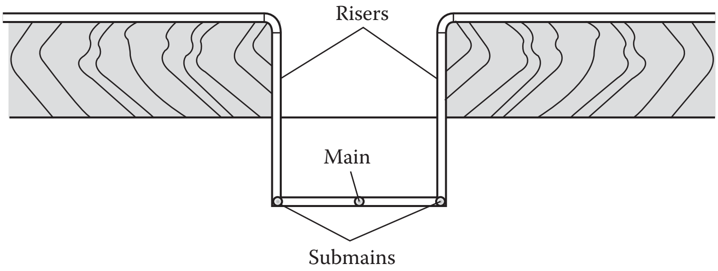

FIGURE 9.14 Main header with submain headers placed underground. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 9.15 Emitters, drip lines, and stakes. (From CuisinArt Resort & Spa, Anguilla. With permission.)

there are adequate number of irrigation cycles so the plant does not seek moisture and by keeping the stakes pushed into the substrate only about one-quarter of its length. Any root growth plugging trickle lines or stakes can be removed by soaking them in 10% bleach solution for several hours to dissolve the roots. At the end of the season, thoroughly flush the whole system with an acid solution to dissolve any salt deposits.

9.6 ADVANTAGES AND DISADVANTAGES OF SAWDUST CULTURE

The advantages of sawdust culture are as follows:

1. Since sawdust culture, like sand culture, is an open system, there is less chance of spread of diseases such as *Fusarium* and *Verticillium* wilts, especially in tomatoes.
2. There is no problem of plugging of the drainage pipes with roots.
3. There is good lateral movement of nutrient solution throughout the root zone.
4. Plants have good root aeration.
5. A new nutrient solution is added during each irrigation cycle.
6. The system is simple and easy to maintain and repair.
7. The high water retention capacity of sawdust reduces any risk of rapid water stress should a pump fail.
8. It is adaptable to fertilizer injectors, and therefore less space for tanks is required.

The disadvantages of sawdust culture are as follows:

1. Sawdust culture is applicable only to areas having a major forest industry; therefore, it is not feasible to use this method in arid desert countries. It is also now becoming unavailable because of the use of sawdust in lumber by-products such as chip board.
2. Sawdust must be steam or chemical sterilized.

3. Initially, there can be problems of sodium chloride toxicity to plants if the medium is not well leached before planting.
4. Over the cropping season, salt accumulation can occur in the medium to levels toxic to the plants. This toxicity can be reduced by leaching adequately with the nutrient solution during irrigation cycles.
5. Plugging of trickle-feed lines may occur if proper filters are not used or if cleaning of these filters is neglected.
6. If the sawdust used is very coarse, coning of water may occur, causing roots to grow downward rather than laterally.
7. As sawdust is organic in nature, it decomposes with time. Between crops it must be rototilled and a proportion of new sawdust added to make up for that decomposed and that lost on plant roots during the pulling of the plants at the end of each crop.

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Mason, E.B.B. and R.M. Adamson. 1973. *Trickle Watering and Liquid Feeding System for Greenhouse Crops*, Can. Dept. Agric. Publ. 1510, Information Services, Agriculture Canada, Ottawa, Canada.

10 Rockwool Culture

10.1 INTRODUCTION

Over the past 30 yr, rockwool culture became one of the principal techniques for growing vine crops, especially tomatoes, cucumbers, and peppers. Commercial stone wool production started in Denmark in 1937 with the Rockwool Group. In 1949, they started manufacturing rockwool in the Netherlands. Grodan, a subsidiary of the Rockwool Group, was founded in 1969 to research the potential use of stone wool as a substrate in horticulture industry. In 1979, Grodan began commercial production of rockwool for horticultural use in the Netherlands. Grodan is now established in over 60 countries worldwide.

In a 1986 study by C.J. Graves of the Glasshouse Crops Research Institute in Littlehampton, England (Graves, 1986), the total area (in hectares) of tomato production in Great Britain using rockwool in 1978 was less than 1 ha (2 acres). This increased to 77.5 (197 acres), 126 (320 acres), and 148 ha (376 acres) during 1984, 1985, and 1986, respectively. Similarly, the area of rockwool culture of cucumbers increased from less than 1 ha (2 acres) to 68 ha (173 acres) over the period from 1978 to 1986. In 1991, Desmond Day stated that the estimated rockwool production in the United Kingdom was 230 ha (575 acres) for cucumbers and 160 ha (400 acres) for tomatoes. In the Netherlands, where rockwool manufacture began, the area of greenhouses using rockwool as a substrate for hydroponic culture is much larger. Rockwool culture is now the most extensively used form of hydroponics in the world, with more than 2,000 ha (5,000 acres) of greenhouse crops being grown using this system in the Netherlands.

Stone wool is made from basalt rock (solidified lava) that is molten in furnaces at a temperature of 1,500°C (2,732°F). The liquid basalt is then spun into threads and hardened in a kiln using hot air at 230°C (446°F) and compressed into wool packets, which are then cut into slabs, blocks, or plugs and wrapped with a plastic cover. One cubic meter of basalt can produce about 90 m^3 of stone wool.

Most of the rapid expansion of the greenhouse industry over the past 15 yr has been with rockwool culture. However, over the past decade there has been concern about the disposal of rockwool, as it does not break down in landfills. Now many growers are turning to an alternative substrate that is natural and environmentally friendly and is sustainable in the form of coco coir (Chapter 11). An example of the now rising use of coconut coir as a substrate is pointed out in the following statistic for the greenhouse industry in Ontario, Canada, where the growing medium for greenhouse vegetable crops is 57% rockwool and 39% coco coir (Statistics Canada, 2008).

Grodan, in an effort to avoid losing market share, offers a recycling program for the spent rockwool. They claim that as a part of their "sustainable business policy" they have set up a recycling service for its growers in specific countries. Grodan recycles the used stone wool into raw material for the production of new stone wool products or other products, such as bricks for construction.

10.2 NORTH AMERICAN GREENHOUSE VEGETABLE INDUSTRY

The following statistics indicate the expansion of the North American greenhouse vegetable industry. Certainly a similar growth has occurred in Europe, but it is important to concentrate on North America, with which the reader may closely relate. Most of the expansion has been with rockwool culture, but as mentioned earlier, coco coir is increasingly used as a substrate.

In 1998, the industry in British Columbia and Ontario, Canada, was reported at 1,140 acres (456 ha). The Ontario marketing board claimed that in 1999 there were more than 800 acres (320 ha) of greenhouse vegetables compared to 600 acres (240 ha) the previous year. In 1998, British Columbia Ministry of Agriculture and Lands reported 310 acres (124 ha) of greenhouse vegetable production. This increased over the next 4 yr (2002) to 510 acres (204 ha). The latest figures from Statistics Canada for 2008 and 2009, respectively, are 2,775 acres (1,110 ha) and 2,852 acres (1,141 ha). These figures are broken down into the area per crop in Table 10.1.

The latest figures for the greenhouse area of the United States and Mexico were those of 2007, where the following information was given by the U.S. Census of Agriculture, 2007, and for Mexico by Cantliff and Vansickle (2003); Steta (2004); and Cook and Calvin (2005), as published in *Greenhouse Vegetable Production Statistics* by Gary W. Hickman in 2011.

Production Area—Hectares (Acres)

	Canada	USA	Mexico	North America
Tomato	432 (1,068)	408 (1,009)	1,951 (4,820)	2,841 (7,019)
Cucumber	282 (696)	105 (259)	330 (815)	634 (1,566)
Pepper	296 (733)	61 (150)	550 (1,360)	785 (1,940)
Total	1,010 (2,500)	574 (1,418)	2831 (6,995)	4,260 (10,525)

Over half of the greenhouse vegetable production area in the United States is produced by seven companies. They have 355 ha (888 acres) of the total production of 574 ha

TABLE 10.1
Greenhouse Vegetable Production Area—Canada—2008–2009

Province	Tomatoes, Acres (ha)	Cucumbers, Acres (ha)	Peppers, Acres (ha)	Lettuce, Acres (ha)	Totals, Acres (ha)
			2008		
British Columbia	272 (109)	110 (44)	303 (121.2)	28.2 (11.3)	685 (274)
Ontario	746 (298)	537 (215)	512.5 (205)	6 (2.4)	1,801.5 (720.4)
Others	172 (69)	66 (26)	18 (7.2)	4 (1.6)	260 (104)
Canada	1,190 (476)	713 (285)	833.5 (333.4)	38.2 (15.3)	2,774.7 (1,110)
			2009		
British Columbia	279 (111)	100 (40)	307.6 (123)	NA	686.6 (274.6)
Ontario	782 (313)	561 (224)	525.4 (210.2)	NA	1,868.4 (747.4)
Others	167 (67)	62 (25)	22.8 (9.1)	NA	251.8 (100.7)
Canada	1,228 (491)	723 (289)	855.8 (342.3)	45.4 A (18.1)	2,852.2 (1,141)

Source: Statistics Canada-Greenhouse, Sod and Nursery Industries 2009, Catalogue no. 22-202-x.

(1,418 acres) as reported in 2008. That is, they operate 65% of the greenhouse area in the United States. The following is a list of these large greenhouse operations.

Eurofresh—129 ha (318 acres) (2008), Arizona
Wijnen—56 ha (138 acres) (2009), California
Houwelings—50 ha (124 acres) (2008), Oxnard, California
Village Farms—49 ha (122 acres) (2009) + 12 ha (30 acres) (2011), Texas
Sunblest—36 ha (90 acres) (2008), Colorado.
Intergrow—25 ha (63 acres) (2011), New York
Backyard Farms—17 ha (42 acres), Maine
Windset Farms—12.5 ha (32 acres) (2011), California

10.3 WORLD GREENHOUSE VEGETABLE INDUSTRY

While there are many statistics reporting areas of greenhouse vegetable production throughout the world, it is important to recognize that often such statistics include all protective structures, such as high plastic tunnels, shade structures, and any structures that will extend the growing season of plants. Many of these are not greenhouses with environmental control systems such as heating, cooling, nutrient systems with drip irrigation, protection against pests, and other components to modify the internal environment to achieve optimum conditions for the crop grown. In addition, greenhouses in many countries may still use soil and not a soilless or hydroponic system. Subsequent information presented focuses on soilless or hydroponic greenhouse facilities growing vegetables (Table 10.2). This information is summarized from numerous sources, which was compiled by Gary W. Hickman (2011).

As noted above, however, not all operations in this list of the largest greenhouse operations in the world may use hydroponic culture. I know from personal experience that Desert Glory, Guadalajara, Mexico; Petro Veg. Co., Canada; and Eurofresh Farms, Wilcox, Arizona, use only hydroponic culture. The list presented in Table 10.3 shows the area of soilless or hydroponic culture in greenhouses in some countries.

TABLE 10.2
Large World Greenhouse Vegetable Operations

Country	Name	Hectares	Acres
Morocco	Group Azura	751	1,856
Mexico	Desert Glory	405	1,000
Mexico	Melones	350	865
China	Le Gaga	263	649
Mexico	Agricola la Primavera	162	400
Russia	Yuzhny	148	366
Canada	Petro Veg. Co.	135	334
Mexico	Divemex	135	334
Mexico	Bioparques de Occidente	130	321
United States	Eurofresh	129	318
Russia	Agrikombinat Moskovsky	120	300
Mexico	Grupo Batiz-Wilson Batiz	115	284
Netherlands	Royal Pride	102	252
Israel	Gilad Desert Produce	100	250

TABLE 10.3
Soilless/Hydroponic Greenhouse Vegetable Production Area

Country	Hectares	Acres
China	1,250	3,100
Japan	1,500	3,700
Turkey	500	1,235
Italy	4,000	10,000
Morocco	426	1,053
Netherlands	4,600	11,300 (Some of this area is not soilless)
Mexico	4,305	10,638 (Some of this area is not soilless)
New Zealand	688	1,700 (95% is soilless culture)
United States	574	1,418
United Kingdom	89	220
South Africa	75	185
Taiwan	35	86
Singapore	30	74
Canada	1,141	2,852

Source: Gary W. Hickman, 2011, *Greenhouse Vegetable Production Statistics*.

10.4 ROCKWOOL COMPOSITION

As mentioned above, rockwool or stone wool is derived from basaltic rock. It is an inert fibrous material produced from a mixture of basalt, limestone, and coke, melted at 1,500°C–2,000°C. It is extruded as fine threads and pressed into loosely woven sheets. Surface tension is reduced by the addition of a phenol resin during cooling. While the composition of rockwool varies slightly from one manufacturer to another, it basically consists of silica dioxide (45%), aluminum oxide (15%), calcium oxide (15%), magnesium oxide (10%), iron oxide (10%), and other oxides (5%).

Rockwool is slightly alkaline, but inert and biologically nondegradable. It has good water-holding capacity, with about 95% pore spaces. All fertilizers must be added to the irrigation water for plant growth. Rockwool has about 80% water-holding capacity. The pH of rockwool is between 7 and 8.5. Since it has no buffering capacity, the pH can easily be reduced to optimum levels of 6.0–6.5 for tomatoes and cucumbers by the use of slightly acidic nutrient solution.

Rockwool culture in the past was generally an open, nonrecycling hydroponic system, with nutrients fed to the base of each plant with an emitter and drip line. Approximately 20%–30% excess solution was supplied during each watering to leach minerals from the rockwool slabs to prevent salt buildup. Today, with the emphasis on the environment and the reduction of the environmental "footprint" of any operation, recirculation of nutrient solution from the leachate of the rockwool system has become imperative. Now, the rockwool is supported by channels that collect the leachate and recirculate it back to the central injection area where it is treated for disease control and its pH and electrical conductivity (EC) adjusted by injectors. This is discussed in more detail later in this chapter.

Information on growing vegetables using rockwool culture is presented in a number of articles and manuals (Bijl, 1990; Hochmuth, 1992; Marlow, 1993; Smith, 1986).

10.5 ROCKWOOL CUBES AND BLOCKS

Tomatoes and peppers are seeded in rockwool cubes of 1.5 in. × 1.5 in. × 1.5 in. (3.75 cm × 3.75 cm × 3.75 cm) (Figure 10.1) or in granular rockwool in Styrofoam trays of 240 cells. Cucumbers may be seeded in rockwool cubes or directly into blocks (Figures 10.2 and 10.3).

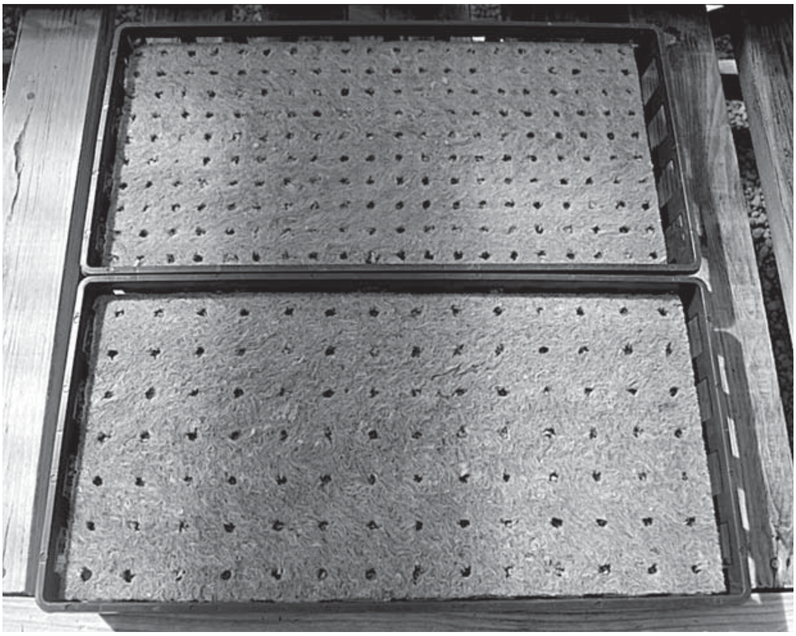

FIGURE 10.1 Rockwool cubes. Background: 1 in. × 1 in. × 1.5 in. deep (200 cubes/flat). Foreground: 1.5 in. × 1.5 in. × 1.5 in. deep (98 cubes/flat).

FIGURE 10.2 Cucumbers seeded in rockwool cubes.

FIGURE 10.3 Cucumbers seeded in rockwool blocks.

After sowing the seed in cubes or blocks, the seed may be covered with coarse vermiculite to maintain moisture during germination and to assist the plant in removing its seed coat, but this is not a standard practice as it is time consuming. It is very important to soak the rockwool well before sowing seeds. This is usually done with a dilute nutrient solution of EC 0.5 mS (milliSiemens) to assist in adjusting the pH.

The trays are watered with raw water until germination takes place and then with a dilute nutrient solution until the first true leaves begin to unfold. Tomato seedlings are usually transplanted to rockwool blocks within 2–3 wk, depending on their growth rate. Cucumbers are transplanted to the blocks earlier, usually between 6 and 10 d. The seedlings with their cubes are transplanted into rockwool blocks having large holes (Figures 10.4 through 10.6). Presoak the blocks with nutrient solution of EC 2.5 mS and pH of 6.0 at 23°C (73°F).

Rockwool blocks are available in a number of sizes, 7.5 cm × 7.5 cm × 6.5 cm (3 in. × 3 in. × 2.5 in.); 7.5 cm × 7.5 cm × 10 cm (3 in. × 3 in. × 4 in.); 10 cm × 10 cm × 6.5 cm (4 in. × 4 in. × 2.5 in.); and 10 cm × 10 cm × 8 cm (4 in. × 4 in. × 3 in.) (length × width × height). The growing blocks are manufactured in strips, each block being individually surrounded by a plastic wrapping. The choice of the growing block is determined by the plant being grown and the stage at which the grower wishes to transplant to the final rockwool slabs. Many growers transplant two plants per double rockwool block, which is 6 in. × 3 in. × 2.5 in. high (15 cm × 7.5 cm × 6.5 cm), or one per large block, which is allowed to form two stems. Transplant six plants per slab or in high light areas, four blocks, each with one seedling that is permitted to branch to give an equivalent of eight plants per slab.

The longer the grower wishes to hold the plants in a seedling area, the larger the blocks he should use (Figures 10.3 through 10.6). While the smaller blocks are good for tomatoes and peppers, the larger ones are more suitable for cucumbers, which grow rapidly. By placing the blocks on wire-mesh benches, roots that grow out of the bottom of the blocks are air pruned. This keeps the bulk of the roots inside the block and lessens transplant shock.

FIGURE 10.4 Tomato plants transplanted into rockwool blocks after 3 wk. Note: If the plants are not grafted they can be laid on their sides in the blocks.

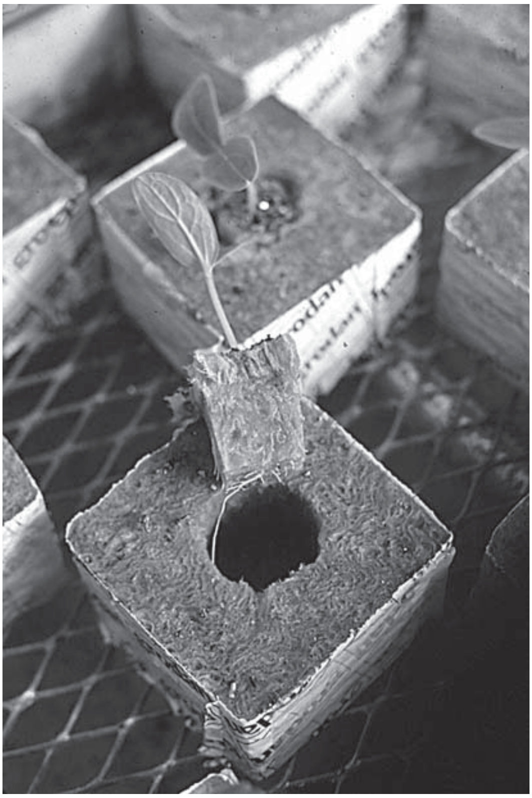

FIGURE 10.5 Cucumber seedling in rockwool cube is transplanted to rockwool block with a large hole.

FIGURE 10.6 Author transplanting cucumber seedlings. (From Environmental Farms, Dundee, FL. With permission.)

10.6 ROCKWOOL SLABS

Slabs are enclosed in a white polyethylene sheet cover. They are available in a number of sizes, 90 cm × 30 cm × 5 cm (35.5 in. × 12 in. × 2 in.); 90 cm × 15 cm × 7.5 cm (35.5 in. × 6 in. × 3 in.); 90 cm × 20 cm × 7.5 cm (35.5 in. × 8 in. × 3 in.); 90 cm × 30 cm × 7.5 cm (35.5 in. × 12 in. × 3 in.); and 90 cm × 45 cm × 7.5 cm (35.5 in. × 18 in. × 3 in.) (length × width × thickness).

Slabs that are 15–20 cm (6–8 in.) wide are generally recommended for tomatoes and peppers, those that are 20–30 cm (8–12 in.) wide for cucumbers, and those that are 30 cm (12 in.) wide for melons. Wider slabs for tomatoes can lead to excessive vegetative growth if only two or three plants are grown in each. The trend now is to use the wide slabs and grow four to six plants in them. Slabs are also available in several densities. Higher density slabs will maintain their structure when used for several crops over a period of 2–3 yr and especially when steam sterilized between crops.

Owing to their cost, it is more cost effective to use the same slabs for 2–3 yr (crops) by steam sterilizing between crops or changing the crop. For example, if a greenhouse operation grows tomatoes, cucumbers, and peppers, the tomatoes can be grown in the new slabs, which are subsequently used for cucumbers and peppers. There will be some structural breakdown resulting in a 10%–15% loss, but this may be reduced by using the higher density slabs.

To sterilize the slabs, they must be stacked on pallets after removing the plastic wrapping. They should be stacked with each layer in opposite directions, with some air spaces between so that the steam will penetrate the entire pile. They are covered with canvas and steam piped into the pile under the covering. The center slabs must reach a temperature of 60°C–80°C (140°F–180°F) throughout for 30 min to be assured of complete sterilization. The slabs are rewrapped after sterilization.

Grodan now makes five kinds of slabs in an attempt to better suit specific crop needs. The Grodan Classic M/Y is for use for several cropping seasons. Its water content (WC) can easily be modified for seasonal differences in crop demand for water to facilitate crop steering (vegetative vs. generative phases) (Chapter 14). Grodan Vital is a single-season slab and is suitable for tomatoes, peppers, cucumbers, and eggplants. They claim that the WC can fluctuate with no problems, within a safe range between 55% and 78% (day level). The slab can be resaturated quickly if it contains insufficient water. The others, Grotop Expert, Grotop Master, and Grotop Master Dry, all have different WC percentages to assist in steering plants toward being more vegetative or generative.

10.7 ROCKWOOL LAYOUT

Rockwool culture was first designed as an open, nonrecycling hydroponic system. More recently, the use of recycling systems with rockwool culture is emphasized as the awareness of the environment and conservation of water is becoming more important. Such recycling systems are discussed later. Nutrients are fed to the base of each plant with a drip irrigation line and emitter. Approximately 15%–20% excess solution is supplied during each watering to allow leaching of minerals from the rockwool slab.

A typical layout for an open-system rockwool culture is shown in Figure 10.7. Before placing the growing slabs out, the greenhouse floor area should be disinfected and the soil surface (floor) leveled. Beds consist of two rockwool slabs set 60–75 cm (2–2.5 ft) apart for cucumbers. With tomatoes and peppers the slabs may be closer, generally 40–45 cm (16–18 in.), depending on the specific plant row spacing required. Soil or sand makes the best floor as it can be easily formed to obtain good drainage. A slight slope toward the center between the two slabs will provide adequate drainage away from the slabs. The entire greenhouse floor area is covered with a white-on-black polyethylene of 6 mil thickness

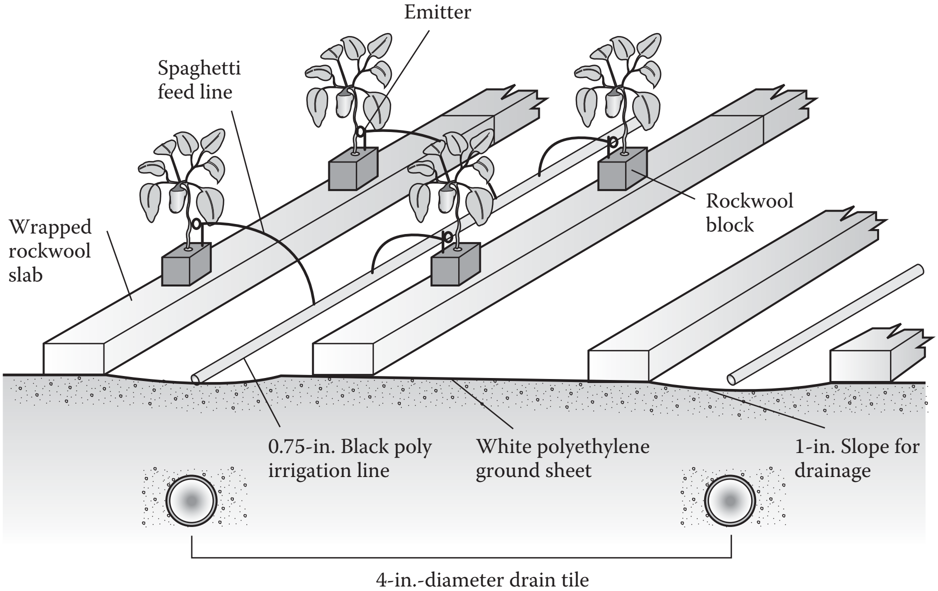

FIGURE 10.7 Sketch of an open system of rockwool culture. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

to provide light reflection and good hygiene (Figure 9.11). If the drainage conditions in the greenhouse are poor, it is necessary to lay a drainage pipe in the middle of the bed. The drainage pipe should be covered with pea gravel and/or coarser sand, and the white ground sheet placed on top of it. If this method is used, the ground sheet should have small holes punched in it to allow percolation of the excess nutrient solution to the drainpipe. Alternatively, the unpunched polyethylene sheet will act as a drainage channel to conduct excess solution to a drainpipe at the far end of the greenhouse. However, problems with algae may develop if stagnant water remains in the channel, which also promotes an environment for fungus gnats. To avoid algae and fungus gnats, it would be better to use a nursery weed mat on top of the underlying substrate. The weed mat would permit water to pass through it to the substrate underneath.

In more northerly latitudes where the ground temperature is cold, it is advantageous to place the slabs on top of 1-in. (2.5-cm) to 4-in. (10-cm)-thick Styrofoam sheets. Today, almost all growers use collection channels in which the slabs are set to collect the drain water and return it to a central treatment area. This will be discussed in detail later.

Most growers now use high-density rockwool slabs placed in a single row and V-cordon train the plants. Five to six plants are set on each slab. This reduces the cost of slabs and still provides sufficient growing space for the plant roots.

10.8 IRRIGATION SYSTEM

A drip irrigation system with a fertilizer injector as shown in Figure 10.8 provides nutrients to each plant individually. A drip emitter of 0.5 gal/h (2 L/h) feeds each plant via a drip trickle line. A PVC main line must be of sufficient diameter (minimum of 3 in.) to supply the area of the greenhouse section to be irrigated at a given time. From the main, submains or headers distribute solution to subsections. Risers (usually of 1 in. diameter) join the 0.75-in. black poly lateral of each row to the header. These diameters may be increased to 1.5 and 1 in., respectively, with long laterals up to 200–300 ft. If the emitters are punched directly into the lateral line at the plant spacing rather than putting them at the end of the drip line, less plugging will occur, as they do not dry out between watering cycles. Spitter-type emitters should not be used, as they will moisten the base of the plants and promote diseases. Special small ribbed stakes are attached to the end of the emitter trickle line and support the drip line on the rockwool blocks or slabs (Figure 10.9).

The rockwool slabs must be soaked with nutrient solution of EC 2.5–3.0 mS and pH 6.0 before transplanting (Figure 10.10). The slabs will be soaked with nutrient solution for 24–48 h. This will adjust the pH and uniformly moisten the slabs. To do this, place the slabs in their final position, with three drip lines entering a small slit on top of each slab at equal spacing. Operate the nutrient system until the slabs swell as they fill with solution. Do not cut drainage holes in the slabs until they have been soaked. Check that all the slabs are soaked. Usually, a few slabs have holes in their wrappers, and they do not soak properly. If this happens, the growth of the plants on such a dry slab will be greatly restricted.

Following the first irrigation after transplanting, the slabs should again be checked for dry spots between the drip lines, as the slabs must be fully saturated to ensure sufficient solution reserves for the plant during the initial posttransplant period. Drainage holes must be cut on the slab sides at the bottom edge (Figure 10.11). They should be in the shape of an inverted “T” or an angled straight cut approximately 4–5 cm (2 in.) in height. Two or three holes should be made in each slab on the inside face. Make the cuts between plant locations,

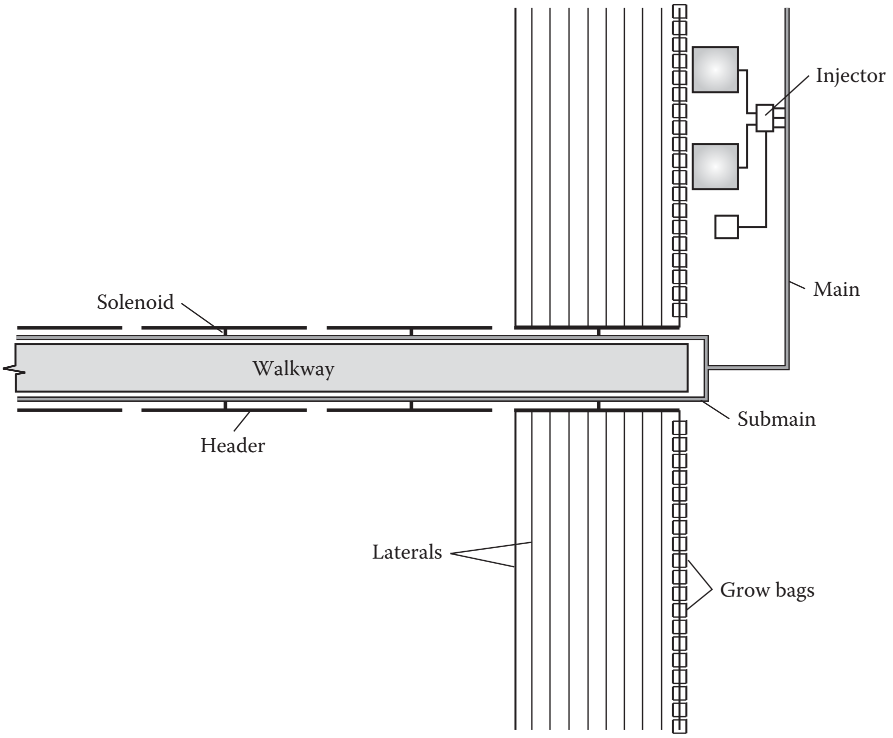

FIGURE 10.8 Rockwool irrigation system plan. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 10.9 Drip line with ribbed stake placed at the edge of the block.

not directly under them, or the solution will run immediately out of the holes and not be forced to flow laterally.

Cut holes in the polyethylene wrap at the top of the slabs in the locations where the transplants are to be set. While transplanting, simply set the rockwool blocks growing the seedlings on top of the slabs through the holes cut in the plastic sleeve. Place a drip line at

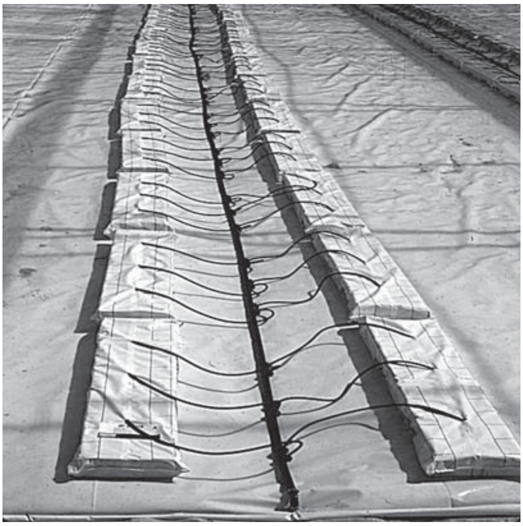

FIGURE 10.10 Soaking of slabs before transplanting.

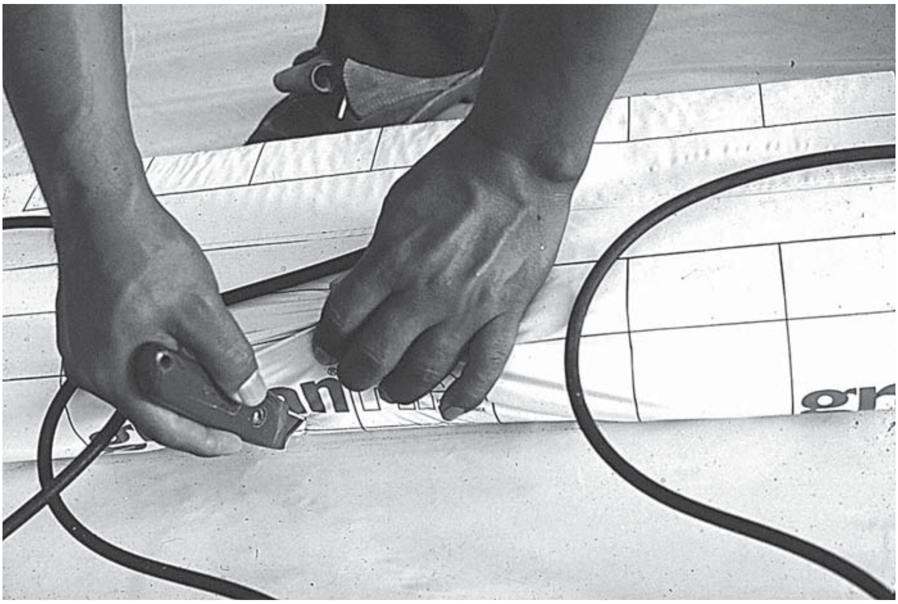

FIGURE 10.11 Cutting drainage slits on the inside bottom face of the slabs.

the edge of the block with a stake. Use the ribbed stakes to prevent any spray onto the crown of the plant to reduce disease infection. Push the stakes not more than about one-third of their length into the block, because if they are pushed too deep into the block or slabs, plant roots may grow up into them. Little transplant shock is encountered by the plants using this rockwool system of blocks. The roots will grow from the blocks into the slabs within several days.

Before transplanting, all support strings should be strung to the overhead wires. When transplanting, attach the string to the plant, with a plant clip located under the first set of true leaves. Do not pull the string too tight, so that it can easily be wound around the plant as it grows.

More frequent irrigation is necessary immediately after transplanting until the plants become established. Later, a frequency of five to eight times per day should be adequate, with rates varying according to plant stage of growth and environmental conditions.

Irrigation cycles in large greenhouse operations are controlled by a computerized system that monitors ambient weather conditions and moisture levels in the slabs and regulates the cycles accordingly. In this case, a slab, representative of all slabs growing the crop, is selected and placed in a “start tray” (Figure 10.12). The start tray monitors the amount of solution present in a slab growing healthy plants. The bottom of the wrapper is removed from the slab placed in the start tray so that excess solution drains easily. A V-shaped groove in the bottom of the stainless steel tray conducts the solution to one end where an electrode is positioned. As long as there is adequate solution present, the solution is in contact with the electrode and the circuit complete. The signal then prevents an irrigation cycle from being initiated. As soon as the circuit is broken, as the solution falls with the drying of the slab due to uptake by the plants, an irrigation cycle begins and will continue for the preset time interval set in the irrigation controller or computer. Smith (1987) stated that watering should be done before the slabs have lost more than 5%–10% of their water-holding capacity. The moisture level in the slabs may be raised or lowered by raising or lowering the probe in the start tray. That is, if a higher moisture level is to be maintained between irrigation cycles, the probe may be raised, and as a result, more frequent irrigation cycles will occur.

The duration of an irrigation cycle should be long enough to get a 20%–25% runoff from the slabs. The drainage from the slabs may be determined by setting up a special collection tray under one of the slabs having healthy plants (Figure 10.13). A pipe outlet at the lower end of the collection tray directs the waste solution to a container below, buried in

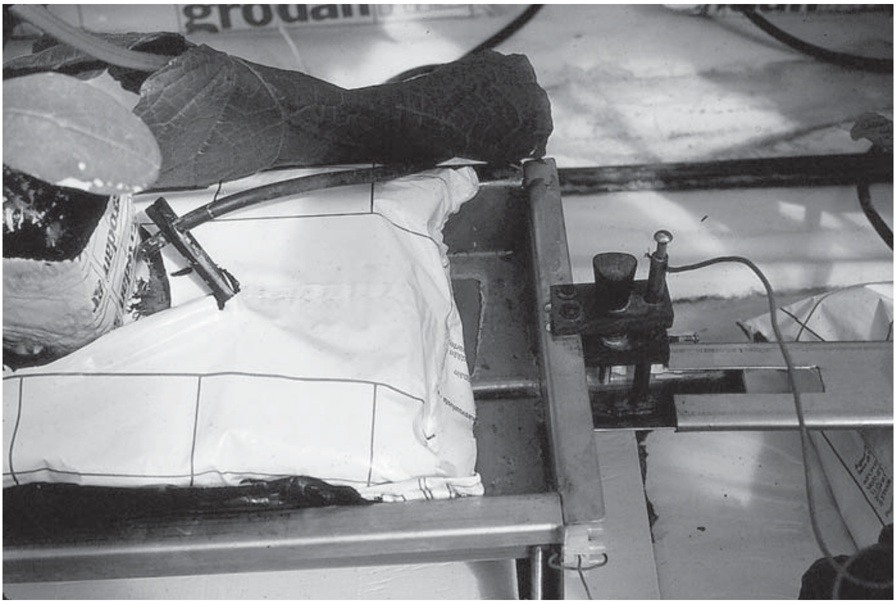

FIGURE 10.12 Start tray monitors the amount of solution present in the slab. (From Environmental Farms, Dundee, FL. With permission.)

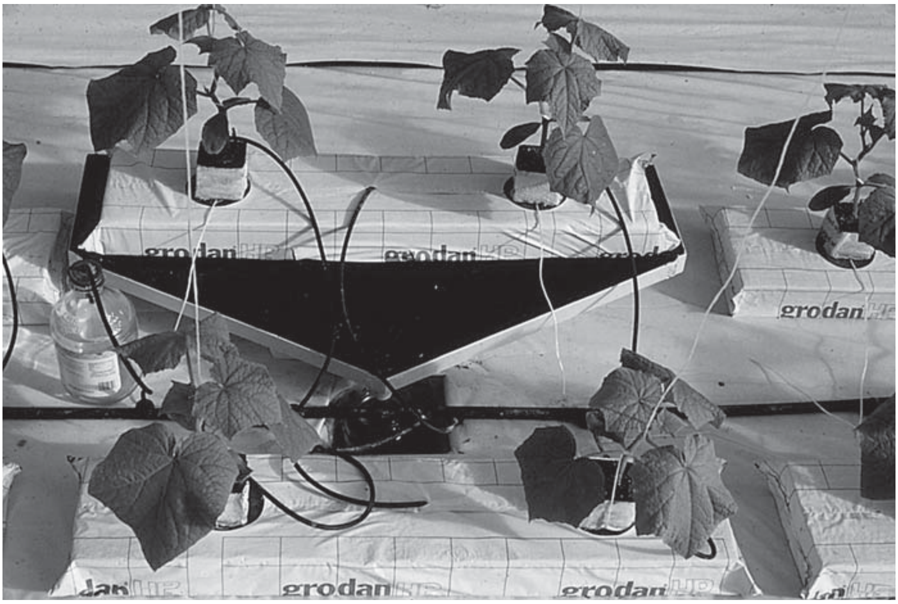

FIGURE 10.13 Collection tray to monitor amount of solution runoff from the slab. (From Environmental Farms, Dundee, FL. With permission.)

the floor. A second container collects the solution from one emitter. This gives the amount of water that actually came out of each emitter, assuming they are all equal. If pressure-compensating emitters are used, the flow through each should be the same. To get the volume of solution that entered the slab, multiply the volume collected from one emitter by the number of emitters in each slab. Divide the waste volume from the collection tray by this inlet volume from the emitters. It is easiest to use milliliters as a volume measurement. A graduated cylinder will suffice to measure the liquids.

Systems of root zone monitoring that are more advanced than these start and collection trays are now used. Good root growth, which avoids diseases and waste of water and fertilizers and steers crops to optimize yields and quality, can be achieved by tightly controlling root zone conditions. To do this, irrigation quantity, frequency, EC, and pH must be controlled and adjusted to achieve ideal root conditions. The media must be allowed to dry down somewhat overnight and rapidly wet up in the morning. The media leachate must be sufficient to avoid salt buildup (excessive EC) while at the same time keeping it satisfactorily moistened.

An automatic data logging system, such as that of Autogrow (www.autogrow.com), uses a moisture probe that remains embedded in the media. Their “Minder” system measures the irrigation quantity (from one dripper) together with the EC and pH, the moisture level, media temperature, and runoff quantity, including its EC and pH. It calculates the runoff ratio and displays it as a graph together with ECs, pHs, media moisture, and temperature. In addition to the root zone parameters, a solar sensor measures the sunlight received. This information is sent to a computer that controls the irrigation cycles and duration according to preset levels. This type of feedback control optimizes irrigation cycles according to existing conditions within the root zone and available light (Broad, 2008). Other computer controllers that perform similar functions include Argus Controls (www.arguscontrols.com) and Priva (www.priva.nl).

Salt levels in the rockwool slabs should be monitored at least every other day. Greenhouses having computers may have a number of EC and pH sensors in slabs at several locations

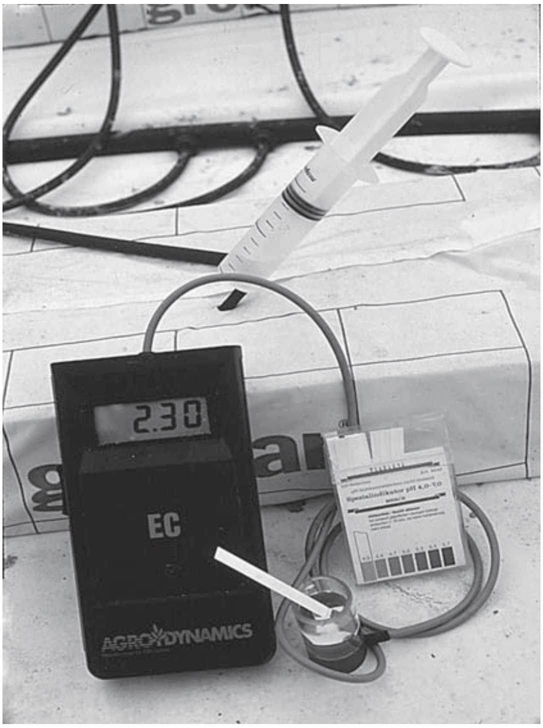

FIGURE 10.14 Testing the slab solution EC and pH with EC meter and pH paper.

in the house, giving continuous monitoring. Otherwise, a sample must be taken from the slab with a small syringe and tested for its pH and EC (Figure 10.14). Values should be close to those of the nutrient solution provided to the plants. If significantly high levels of conductivity or nonoptimal pH levels are detected, the slabs must be irrigated more often until their solution concentration approaches that of the input solution. “Clear” raw water should not be used as it often contains sodium, calcium, and magnesium. These ions will accumulate in the slabs, and other nutrients such as potassium, nitrates, and phosphates will be depleted, causing an imbalance in the slab nutrition.

10.9 CUCUMBERS IN ROCKWOOL

Cucumbers were grown at Environmental Farms, Dundee, Florida. An existing greenhouse of 1.5 acres (0.6 ha) that had been previously a citrus nursery was converted to rockwool culture of cucumbers. The floor was filled with 6 in. (15 cm) of sand after drainage tiles were installed. The floor was contoured for the rockwool slabs and a white polyethylene liner placed on it. A drip irrigation system was installed and the cucumbers seeded in rockwool cubes and transplanted to blocks (Figures 10.2, 10.5, and 10.6). Fourteen days from seeding they were transplanted to the slabs (Figure 10.15). They became established in the slabs within 2–3 d and grew close to 6 in./d (15 cm/d). Eighteen days from transplanting (32 d from seed), they reached 5 ft (1.5 m) in height (Figure 10.16).

European cucumbers are trained using the “renewal umbrella” system. All of the small stem fruits have to be removed up to at least the seventh or eighth leaf. All of the side shoots are removed except the top two nearest the support wire that are permitted to grow

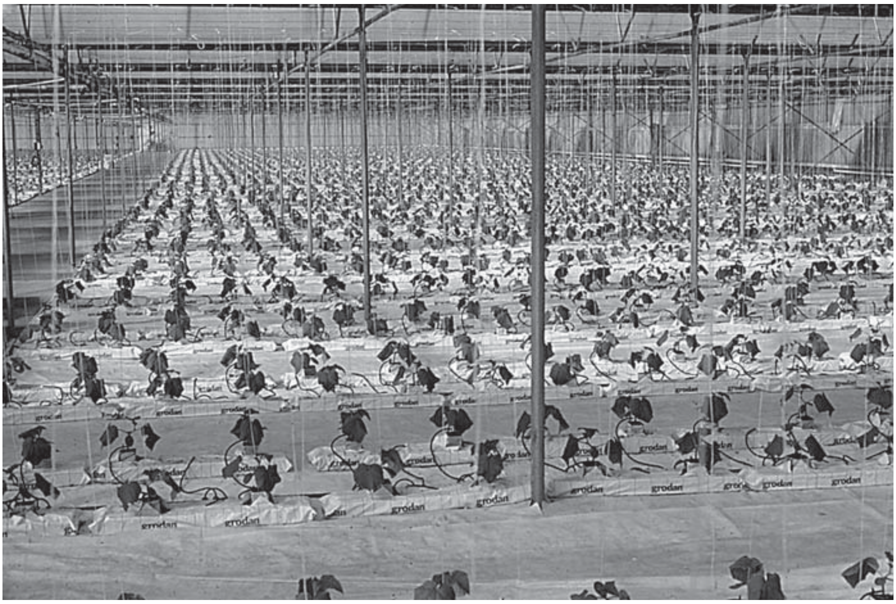

FIGURE 10.15 Fourteen days after seeding, cucumbers have been transplanted to the slabs. (From Environmental Farms, Dundee, FL. With permission.)

FIGURE 10.16 Cucumbers 31 d after seeding (18 d after transplanting). (From Environmental Farms, Dundee, FL. With permission.)

over the wire and hang down as the top of the main stem of the plant is cut just above the wire. For more details on plant training, refer to Chapter 14. Harvesting began at 40 d from seeding (Figure 10.17). The fruit was harvested in the late morning after the plants had dried out. Plastic tote bins were used to harvest the fruit and were transported to the packing area by a tractor and trailer (Figure 10.18). The cucumbers were shrink-wrapped with an L-bar sealer and oven (Figure 10.19). Larger operations, such as Houweling Nurseries,

FIGURE 10.17 Beginning of harvest, 40 d after seeding. (From Environmental Farms, Dundee, FL. With permission.)

FIGURE 10.18 Fruit is harvested in plastic tote bins. (From Environmental Farms, Dundee, FL. With permission.)

FIGURE 10.19 Cucumbers may be shrink wrapped with an L-bar sealer. (From Environmental Farms, Dundee, FL. With permission.)

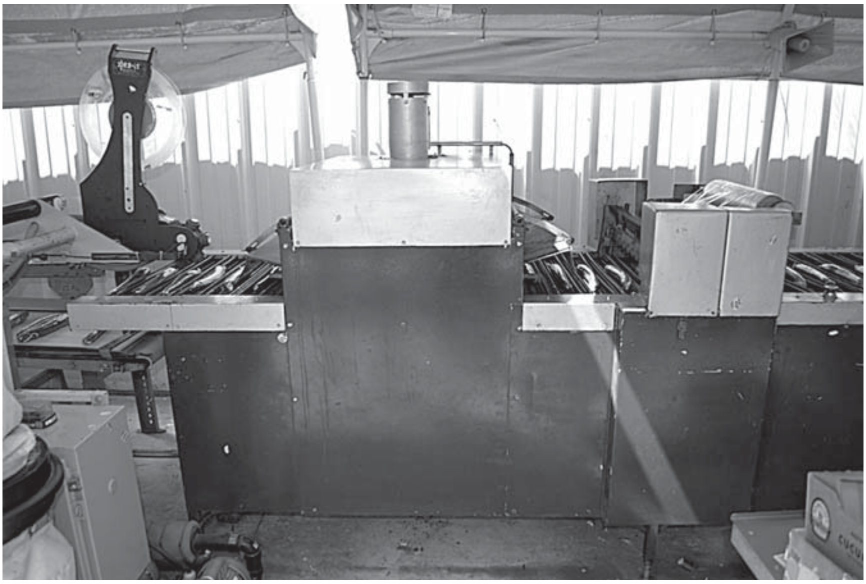

FIGURE 10.20 Large commercial shrink wrapping machine. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

Camarillo, California, use a large oven shrink wrapper (Figure 10.20). The cucumbers are packed 12 fruits to a case, palletized, and placed in cold storage at 50°F–55°F (10°C–13°C) (Figure 10.21). Environmental Farms had three grades, regular, large, and jumbo, which were determined by the length of the fruit. Most of the product was shipped to the northeastern United States and Canada.

As with any agricultural crop, pest and disease problems arose. The most troublesome pests included aphids, whiteflies, and thrips. With the humid conditions of Florida, gummy stem

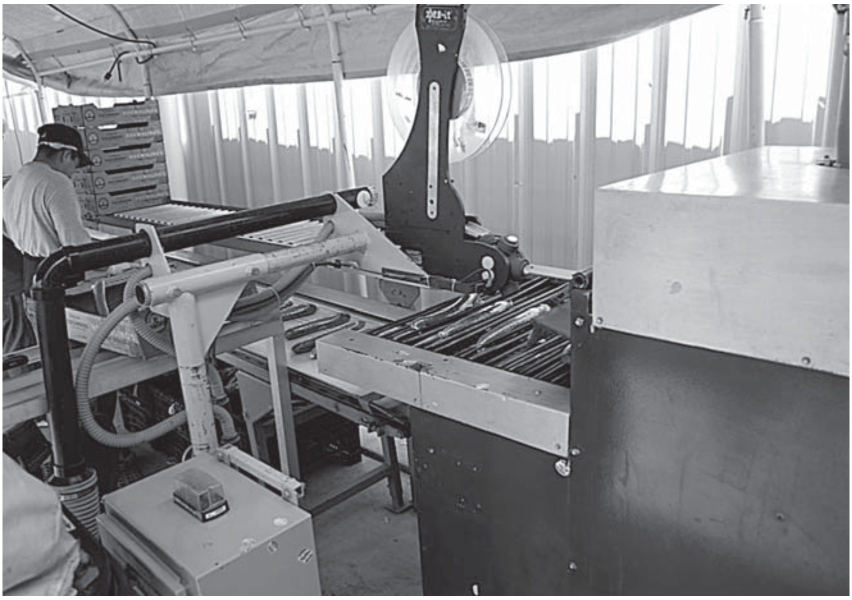

FIGURE 10.21 After labeling, the cucumbers are packed 12 fruits to a case. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

blight and mildew diseases were present. Powdery mildew was overcome by use of a resistant variety, Marillo. Gummy stem blight was prevented by painting a fungicide on the base of the plant stem. Viruses were the most challenging. Aphids and whiteflies were the vectors. Control of the viruses depended largely on control of the insect vectors. The spread of viruses during pruning, training, and harvesting by the workers was prevented by dipping tools in a milk bath carried by the workers. This dip was necessary before touching each plant.

A fogger was used to apply pesticides (Figure 10.22). It dispersed a suspension of fog through the crop canopy as it was pushed on a cart down every row (Figure 10.23).

Modified renewal umbrella training with only one leader growing over the wire was adopted as the cucumbers in Florida are extremely vigorous with the amount of sunlight present. With the existence of high insect populations and disease inoculums because of the semitropical conditions of Florida, most cucumber growers change their crops every 3–4 mo as diseases and insects eventually infect the crop severely enough to substantially reduce yields.

Houweling Nurseries Ltd., Delta, British Columbia, grows two crops of European cucumbers annually. The first crop is seeded on December 1 and transplanted in late December, with the first harvest by early February. Production continues until June. A second crop is seeded in June in a separate seedling range. Three-week-old plants are transplanted, and production commences within 3 wk and continues until mid-November.

Cucumbers are planted at a density of 1.2–1.4 plants per square meter (10.76 ft^2), which is 5,000 plants per acre (12,500 plants per hectare). While the industry average annual production was 110 cucumbers per square meter in the late 1990s, this operation produced over 140 cucumbers per square meter. This is equivalent to 10–13 fruits per square foot or 73–93 fruits per plant. Growers today produce an average of 120 fruits per year per plant. This is partly due to improved varieties that yield higher because of disease resistance, more vigor, and improved growing techniques.

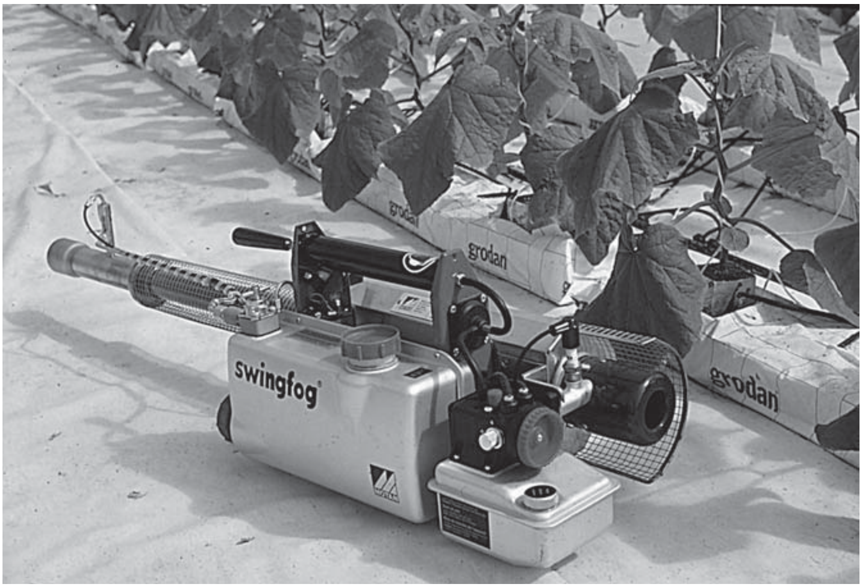

FIGURE 10.22 A fogger can apply pesticides effectively to high-density crops. (From Environmental Farms, Dundee, FL. With permission.)

FIGURE 10.23 It is important to use protective clothing when applying pesticides. (From Environmental Farms, Dundee, FL. With permission.)

10.10 TOMATOES IN ROCKWOOL

In 1993, Gipaanda Greenhouses Ltd., Surrey, British Columbia, grew 5.25 acres (2.1 ha) of tomatoes in rockwool. They started the seedlings in flats of 1-in. rockwool cubes and after 12–14 d transplanted them to 3-in. (7.5-cm) rockwool blocks. It is now common practice to seed tomatoes in rockwool cubes and transplant to the blocks following this procedure.

Gipaanda Greenhouses Ltd. has now moved to Delta, British Columbia, where they have constructed a new 18-acre (7.2-ha) facility. This is discussed in Chapter 11 on coco coir production, as they have now converted to that substrate. The seedlings are transplanted to 4 in. × 4 in. × 3 in. (10 cm × 10 cm × 7.5 cm) rockwool blocks. The larger blocks are used so that the plants will not dry out as quickly when placed on top of the rockwool slabs before positioning them inside the slab wrapper.

To overcome *Fusarium* crown and root rot disease, a resistant rootstock variety is used in the absence of a commercially resistant variety. For tomato-on-vine (TOV) cultivars, such as "Tricia" and "Success," a "Maxifort" rootstock is used. This same rootstock is commonly used for other TOV varieties and for beefsteak varieties such as "Caramba." "Beaufort" rootstock is used with cherry tomato varieties such as "Favorita." Both varieties (scion and rootstock) are germinated at 79°F (26°C). The scion is the upper part of the plant, which is the desired variety, such as Tricia, Success, Caramba, Favorita, and so on. After germination, the two seedlings are grown in separate sections of the greenhouse under different temperature regimes. The rootstock is grown at 64°F (18°C), and the scion variety at 72°F (22°C). To obtain a thicker stemmed rootstock, the rootstock variety is sown 2 d earlier than the scion variety. The rootstock variety is grown for 14 d and the scions for 12 d before grafting. This is termed *green grafting*. The procedure is discussed in Chapter 14. Most growers now contract to a specialized grower of transplants who grafts the seedlings. Bevo Agro Inc., Langley, British Columbia, and Houweling Nurseries Ltd., Delta, British Columbia, are two such operations.

A typical cropping schedule in British Columbia is to purchase 6-wk-old grafted seedlings from a nursery grower and transplant in the first week of January. There are two plants in each rockwool block (Figure 10.24). When transplanting, the blocks with the seedlings are placed on top of the slabs, but not in them until the first flower truss opens. The plants are allowed to bifurcate at the first truss. This is done around January 17 in British Columbia. This bifurcation will increase plant density from 1.65 to 3.3 stems per square meter, which is equivalent to 6.5–3.26 ft^2 per plant. In high sunlight areas, such as southern California and Arizona, tomatoes are allowed to bifurcate early in their growth (Figure 10.25). In northerly areas, such as British Columbia, bifurcation is practiced later so that there is sufficient light with increasing day length in the subsequent months as the plants grow with two stems. This procedure increases production. Beefsteak tomato annual yields average between 50 and 75 kg/m^2 (10–15 lb/ft^2 or 33–50 lb per plant).

This unique training system was adopted to save on rockwool blocks and slabs. Two blocks, each with two plants, instead of the conventional three blocks with one plant each, were set onto each slab. Slabs and plants were spaced to get centers of 75 cm (30 in.) within rows by 45–50 cm (18–20 in.) between rows. That is, two rows of slabs were used for two rows of plants. Now, they use only one row of slabs and double the number of plants and blocks on the slabs. The plants are V-cordon trained upward to the support wires. This gives the same area per plant, but utilizes half the slabs. This is equivalent to 0.6 m^2 (6 ft^2) per plant. This is reduced to the normal final spacing of tomatoes of 0.3 m^2 (3 ft^2) per plant by mid-April when light has improved. Plant density is increased by letting each plant form two shoots. By the end of February, one-sixth of the plants were allowed to form a second shoot by letting one healthy sucker grow. This procedure is continued over a period of 2 mo, so that by the end of April every plant has two stems and therefore the plant density is doubled.

Gipaanda Greenhouses has done trials on TOV varieties at a spacing of 1.8 going up to 3.6 stems per square meter (6–3 ft^2 per plant). Resulting yields have reached 63 kg/m

FIGURE 10.24 Two grafted tomato seedlings per rockwool block. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

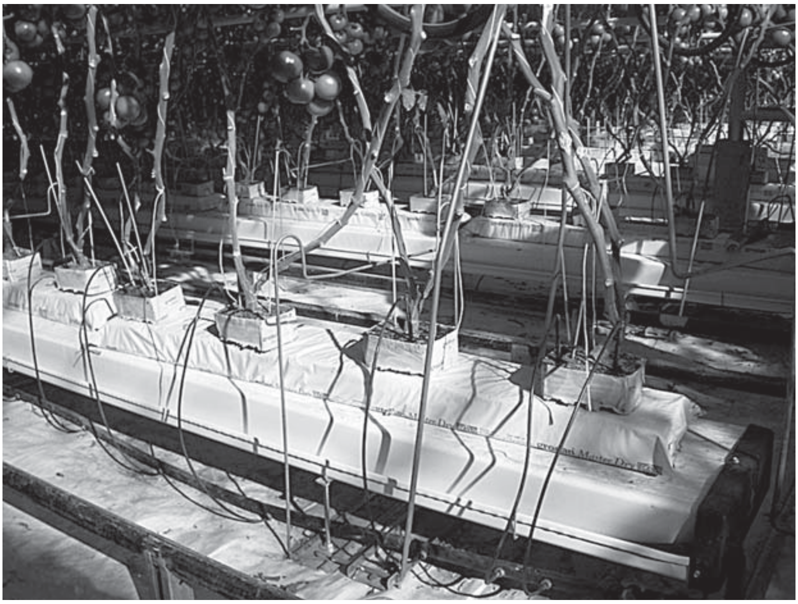

FIGURE 10.25 Bifurcation of tomato plants at an early stage in high light areas. (From Eurofresh Farms, Wilcox, AZ. With permission.)

(13 lb/ft^2 or 38.6 lb per plant). Other specialty tomatoes (cherry, Japanese berry, and grape) spaced at 3–6 stems per square meter (3.6–1.8 ft^2 per plant) yield between 25 and 30 kg/m^2 (5.5–6 lb/ft^2).

Plants are supported by polyethylene twine about 30 ft (9 m) long for each plant. The string is wound around double hooks, which hang from the overhead wire support (Figure 10.26). The plant vines reach 25–30 ft (7.6–9 m) by the end of the season. Plants are lowered by untying the string from the hooks (tomahooks). Plant stems are looped around the ends of each bed by the use of a 3-in.-diameter plastic drain-tile pipe or other wire supports to prevent breakage (Figure 10.27). The stems are laid along the top of the slabs. Wire hoops of about 0.19 in. diameter placed across the slabs support the plant stems (Figure 10.28). This method has now been updated to using the small pipe support frame of the raised trays to support the stems (Figure 10.29). Raised trays, now used for rockwool and coco coir cultures, are discussed in detail in Chapter 11.

Keeping the bare stems supported above the floor and slabs permits good ventilation and maintains the stems dry so that fungal infection is avoided. It also keeps the scions above the slabs so that they will not root into the blocks.

Gipaanda Greenhouses Ltd. has found that the management of irrigation is important in rockwool slab oxygenation (Ryall, 1993). The last irrigation is done 2.5–3 h before sunset to reduce solution retention in the rockwool slabs to 65% of their capacity. This drying of the slabs to create a water deficit overnight allows better oxygenation of the roots. Active root

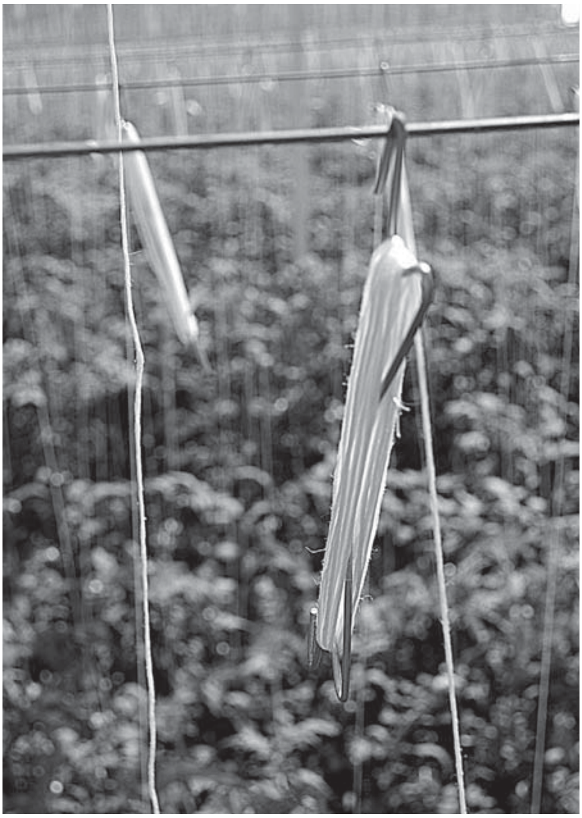

FIGURE 10.26 Tomahook with string to support plants. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 10.27 Plants are bent around the end of the row using a 3-in. pipe. (From Gipaanda Greenhouses Ltd., Delta, BC, Canada. With permission.)

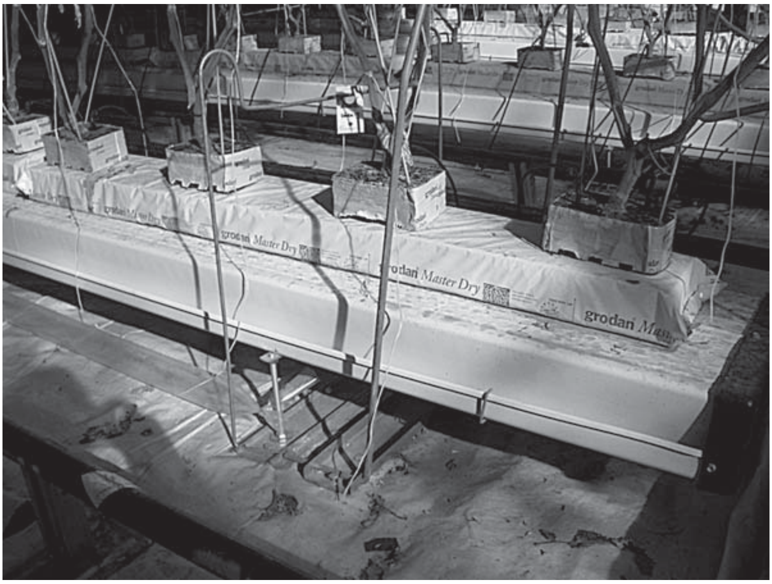

FIGURE 10.28 Wire hoops support the plant stems above the floor. Note: The slabs are set on top of FormFlex trays. The collection lip on the sides of the trays recycles the solution. (From Eurofresh Farms, Wilcox, AZ. With permission.)

growth is encouraged by the overnight water deficit in the slabs. The first irrigation occurs about 2 h after sunrise. Subsequent irrigations are initiated by the computer according to light availability. On a bright sunny day it may irrigate up to 20 times. Overall, the slabs are irrigated to give a 40% leachate during irrigation cycles. During heavy demand for water during midday, the over drain may be increased to 60%.

FIGURE 10.29 New stem support used with raised beds. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

This management of irrigation has been further substantiated by Jeff Broad (2008) as irrigation techniques are used to steer crops (to correctly balance vegetative and generative plant phases). He pointed out that watering stop time is used to steer the plants. Stopping earlier will cause greater dry down of the rockwool slabs and steer them toward being generative. However, he points out that if the slabs are allowed to dry too much, it will be difficult to wet them up the next day. The watering start time he recommends is close to sunrise and not later than 2 h after sunrise. Too close to sunrise or before sunrise may cause fruit splitting in tomatoes. Too far after sunrise may make it difficult to wet up the slabs as the crop takes water from the media before irrigation commences.

10.11 LARGE GREENHOUSE OPERATIONS IN NORTH AMERICA

As examples of large greenhouse operations and their growing procedures, Eurofresh Farms and Houweling Nurseries Oxnard, Inc., Camarillo, California, are described. Eurofresh Farms has five 53-acre (21-ha) complexes for a total of 265 acres (106 ha) in Wilcox and another 53-acre (21-ha) facility in Snowflake, Arizona. All the greenhouses are glass Venlo Dutch structures having 6-m (19.7-ft) gutters (sidewalls). They grow mainly TOV tomatoes, with one complex (site) of cucumbers. They also grow cherry and other specialty tomatoes. The greenhouses have cooling pads, with fans drawing air from the interior passageway between ranges. The rows of plants are 114 m (374 ft) on either side of the central passageway within the greenhouse.

In 2007, Eurofresh Farms were using a De Ruiter (Monsanto purchased De Ruiter in 2008) TOV variety, “Brilliant,” grafted to a “Maxifort” rootstock. Other TOV varieties they use include “Campari,” “Lorenzo,” and “Balzano,” grafted to “Maxifort.” They also grew “Conchita” (cherry) and “Savantas” (roma/plum) varieties. For more detailed information on tomato varieties, refer to Chapter 14.

They intercrop plantings as discussed earlier. The plants are pinched at 40 wk and removed at 47 wk. Before their removal, another crop is intercropped and allowed to reach about 3 ft (1 m) in height by the time of the removal of the previous crop. The new intercrop plants are set on new slabs beside the existing slabs by pushing them over on the collection tray. They plant four plants per slab, but each plant is allowed to bifurcate to get the correct spacing of 3.3 plants per square meter (1 plant per 3.3 ft^2) and later increase stems to get 3.8 plants per square meter (1 plant per 2.8 ft^2).

A recirculating rockwool system is designed to take the leachate back to a storage tank where it is sterilized with ultraviolet (UV) lights, the EC and pH are monitored, and stock solutions are injected according to computer settings (Figure 10.30). The standard recycling trays by FormFlex are raised about 10 in. (25 cm) above ground level by a steel frame that allows the bed to be adjusted to get an even slope to the return end without low spots along the channel (Figure 10.28). The rockwool slabs lay on top of the FormFlex trays. Wire plant supports are placed over the gutters. A single row of channel is set for each plant row. Each rockwool slab contains four bifurcated tomato plants that are trained in a V-cordon fashion to the above support cables via plastic twine. This enables each row in effect to have an equivalent number of plants as the normal two rows. This method saves on the number of rockwool blocks, slabs, and raised gutters compared to two rows of single-stemmed tomato plants.

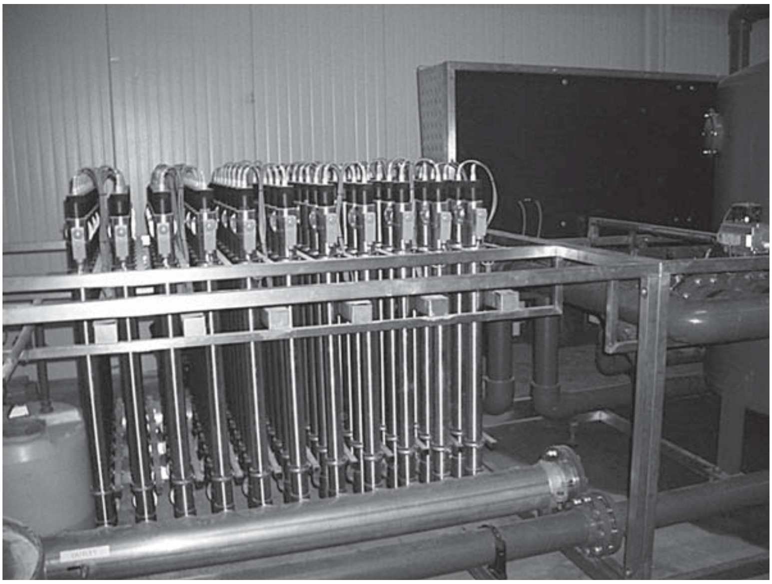

FIGURE 10.30 UV sterilizers on return solution. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FormFlex, a company in The Netherlands, has distribution centers in the United States and Canada. Their website is www.formflex.nl for The Netherlands and www.formflex.ca for Canada. FormFlex was a pioneer in developing cultivation gutters that are formed on-site. They introduced the "AG plateau gutter," with suspension cables to reduce light interception. These systems resulted from the need for recirculation growing systems to conserve water and fertilizers. Leachate from the rockwool or coco coir slabs is collected by the raised gutters and conducted to a central system for treatment of disease control and nutrient and pH adjustment before returning to the crop. These raised gutters also offer advantages of optimum air circulation through the crop; improved working conditions for employees, with resultant increased labor productivity; and even water distribution between plants. They offer a complete range of gutter designs to best suit the specific crop grown.

Eurofresh Farms in Wilcox, Arizona and Houweling Nurseries Oxnard, Inc., Camarillo, California, use these FormFlex raised gutters for rockwool and coco coir systems. The raised gutter system is described in detail in Section 10.14.

Eurofresh Farms was one of the first greenhouse operations to introduce raised trays by FormFlex (Figure 10.31). They started a large trial in 2007 with rockwool culture. This system is now common in North America and Europe using coco coir slabs. They also introduced the principle of positive pressure cooling system by fans at one end of the greenhouse pulling air through a cooling pad and distributing the air under the plateau trays via a poly convection tube (Figures 10.31 and 10.32). The fans move cool air from the cooling pad or heated air from a heat exchanger charged by hot water through the convection tube. It also serves to inject carbon dioxide into the greenhouse by the convection tube. With this system, they can heat or cool a greenhouse up to 200 m (656 ft) in length. The plateau trays collect the leachate from the slabs and return it for sterilization and EC and pH adjustment in the central injection room.

FIGURE 10.31 Plateau gutters by FormFlex. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.32 Positive pressure cooling/heating greenhouse system. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.33 FormFlex plateau trays, with supports, convection tube, and irrigation line. (From Eurofresh Farms, Wilcox, AZ. With permission.)

The drip irrigation lines are located next to the raised trays (Figure 10.33). The irrigation system can be doubled so that one system feeds the young plants and the other feeds the mature plants. The raised trays also have supports for the plant stems as they are lowered, so that the stems remain at or above the tray level (Figure 10.31). Heating pipes, even if not necessary for heating, are still placed in the aisles as “tracks” for the electric carts. This system is discussed further in Chapter 11.

10.12 HARVESTING, GRADING, AND PACKING

Loose tomatoes are harvested in tote bins, whereas TOV are harvested directly into the packing boxes and transported down the aisles on wheeled carts that run on the heating pipes. A very modern facility of packing is exemplified by Eurofresh Farms. If the tomatoes are sold as TOV, they are harvested into the final cardboard boxes and placed on a picking cart and transported down the central greenhouse passageway (Figure 10.34). The cart

FIGURE 10.34 Picking carts transporting tomatoes in boxes to packing facility. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.35 Picking carts lined up in the packing facility. (From Eurofresh Farms, Wilcox, AZ. With permission.)

passes over an electronic scale to weigh the tomatoes. The picking carts are towed by an airport baggage car that allows many carts to follow behind. Once they reach the packing facility, they are lined up in rows (Figure 10.35). The carts are then pushed by hand to a machine that pushes all of the boxes from the cart and places them so that another machine can pick up one tier of the boxes (five boxes) and place them on a belt taking the boxes to the grading and packing area (Figures 10.36 through 10.38).

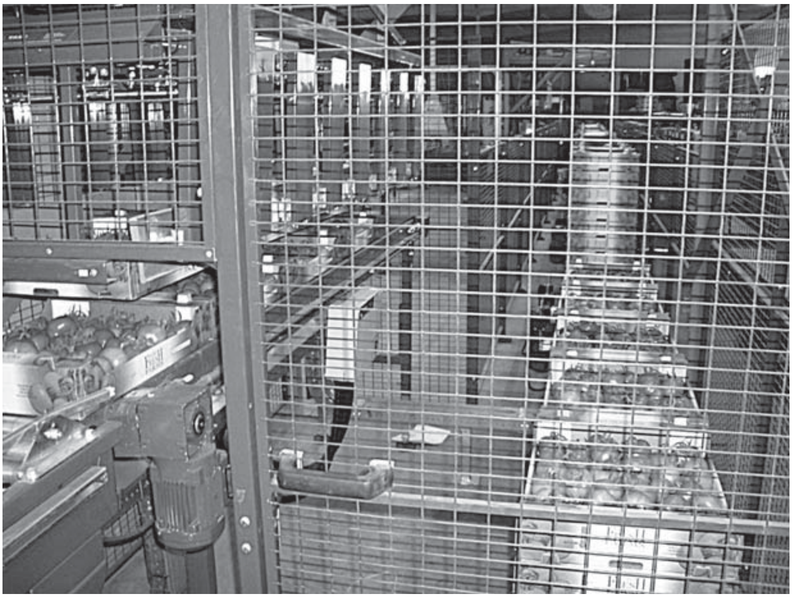

FIGURE 10.36 Machine lifts boxes from picking carts and places them on the grading–packing belt. (From Eurofresh Farms, Wilcox, AZ. With permission.)

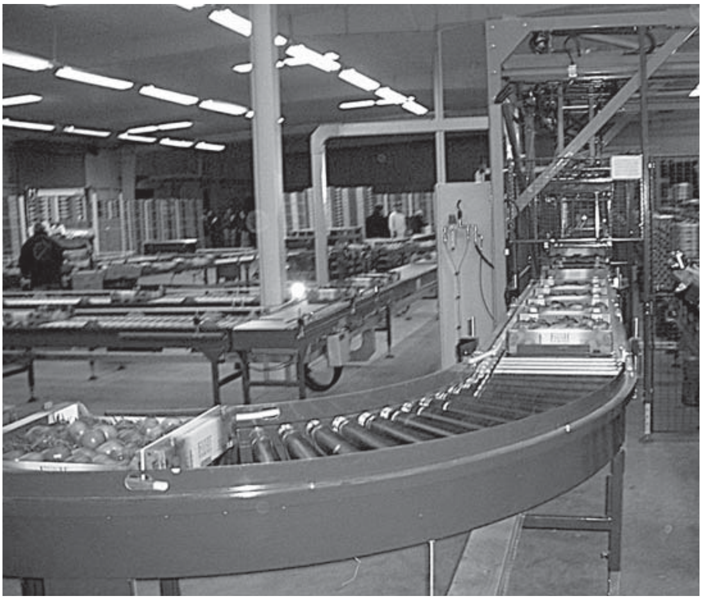

FIGURE 10.37 The machine lifts the cases of tomatoes from the picking carts. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.38 Boxes of tomato-on-vine (TOV) in route to grading–packing area. (From Eurofresh Farms, Wilcox, AZ. With permission.)

At Eurofresh Farms, they pick, pack, and ship every day. There are no on-site refrigeration walk-in coolers. The tomatoes are placed in refrigerated trailer trucks where the temperature is maintained at 55°F (13°C). In 2007, they shipped 220,000 kg/d (484,000 lb/d). They produce 75 kg/m^2/yr (15.3 lb/ft^2/yr) (50 lb per plant per year using the conversion of 3.3 plants per square meter).

Harvesting and packing facilities differ with most greenhouse operations, but the objective is to make it as efficient and least labor intensive as possible. As described above, TOV tomatoes are handled in a specialized manner that is somewhat different from beefsteak and other types of tomatoes. For example, Houweling Nurseries Oxnard, Inc. uses the same type of picking carts as Eurofresh Farms, but, beefsteak and loose tomatoes are harvested in tote bins and transported by carts towed by electric or natural gas airport tractors to a central packing facility, where they are washed, graded, and packed. The tomatoes are floated into the packing facility and then dried before being graded and finally packaged (Figures 10.39 through 10.41). The floating trough has a U-shaped corner to help push the tomatoes together so that they will all enter the packing system consistently without gaps so that workers have a steady supply to package.

Beefsteak tomatoes are packed according to size, so they look uniform (Figure 10.42). TOV may be packaged in open boxes or in sacks that are then packed in boxes (Figures 10.43 and 10.44).

FormFlex Horticultural Systems and FormFlex Automation USA market MTZ products (Metazet) such as the lift carts that travel on the heating pipes. A rechargeable battery operated “M-Truck” is a tractor unit that tows the picking carts. Various models are sold by FormFlex. They can customize carts to be used in conjunction with the M-Truck. For large greenhouse operations, an MTZ chain track system has been developed as an unmanned chain track system for harvesting. It is an in-floor chain track system. Harvesting carts from the crop aisles are connected to the chain in the central passageway. The chain track is installed as a slotted track with a chain in the main passageways and packing facility of the greenhouse operation (Figure 10.45). Peppers, eggplants, and cucumbers are harvested into bins that move on the track system (Figure 10.46) that travel unmanned to the packing facility where they are transferred to the grading belt (Figures 10.47 through 10.49).

Since 2004, the chain track system has been installed in over 134 greenhouses worldwide for ornamentals, flowers, and vegetables. Advantages of this system include a continuous supply of carts to the packing facility, a reduction in labor costs, and return of empty

FIGURE 10.39 Tote bins with loose tomatoes are dumped into a water trough to float to the packing facility. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

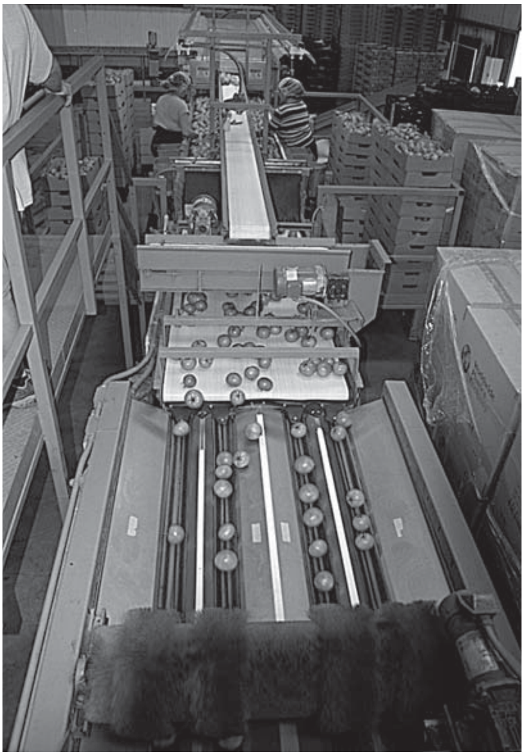

FIGURE 10.40 Tomatoes being dried. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 10.41 Grading and packaging of beefsteak tomatoes. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 10.42 Large grade beefsteak tomatoes in panta packs in cases. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

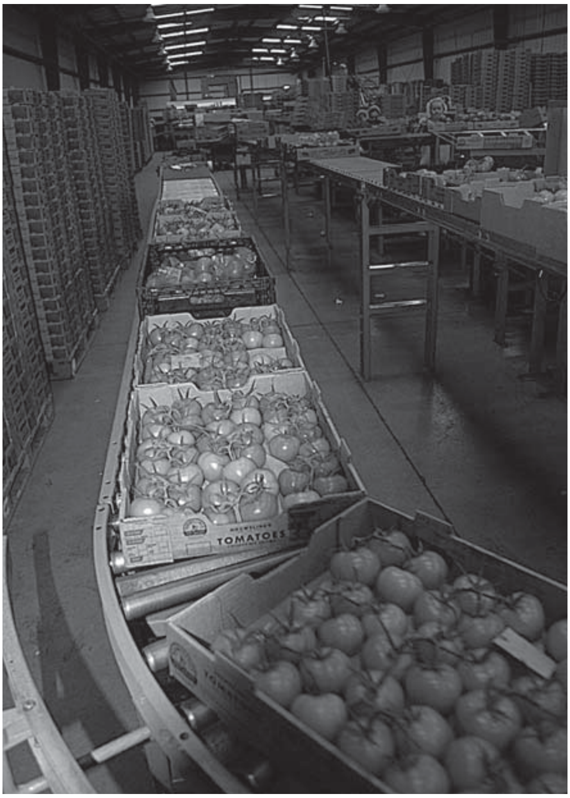

FIGURE 10.43 Tomato-on-vine tomatoes packed in boxes. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 10.44 Tomato-on-vine packed in net sacks. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 10.45 Carts moving in the central passageway on the chain track system. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

carts automatically to the production area. Many automation systems such as this are being developed to reduce labor costs and increase efficiency of greenhouse operations. We will continue to see this in the future, with trends toward robotics in planting, harvesting, transporting, and packing, as was described in the Hortiplan lettuce system in Chapter 6.

At Eurofresh Farms, the first cropping period is from July through March. They purchase 3-wk-old transplants. Production is from October through March. The second crop is interplanted by the middle of December and continues until July. It is intercropped on the

FIGURE 10.46 Bins for harvesting peppers and cucumbers travel on the chain track system. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

FIGURE 10.47 Peppers in large bins are unloaded automatically. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

same slabs as the first crop (Figure 10.50). The older plants are placed on one side of the slabs and the younger ones on the other side. There are four support wires (Figure 10.51). The older plants are strung on one set of two support wires and the younger plants on the second set of two support wires. Plants are V-cordon trained. When the first flowers form on the intercrop the older crop is headed (growing tip is removed). After heading the older crop, leaves at the base of the plant are removed above the ripening fruit to allow light on the younger plants.

While initially this intercropping was practiced only in very high light areas such as Arizona and Mexico, it is now done in California by Houweling Nurseries Oxnard, Inc.,

FIGURE 10.48 Eggplants in tote bins are automatically unloaded. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

FIGURE 10.49 Tomatoes in cases are transferred to a belt to the packing area. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

FIGURE 10.50 Intercropping tomatoes.

and most growers in northern latitudes do it in the spring through summer months during the long-day-length season as outlined earlier. In these northern latitudes of the United States and Canada, however, all of the crops are removed in mid- to late-November, and the crop cycle is repeated.

As the relative humidity (RH) is very low in desert regions such as Arizona, the greenhouses must not be ventilated too quickly resulting in a sudden drop in the RH, which would stress the plants. For this reason, they shade the glasshouses with whitewash rather than a shade curtain during the summer months from March through September. They shade by airplane. They apply “ReduHeat” again in March and April to get 25% cooling. “ReduSol” is applied by airplane to remove the shade compound during the monsoon period. When the shade compound is removed by the end of September, the shade curtains are operated. They also clean the glass with a specialized cleaning machine to remove the desert dust (Figure 10.52). This is done by a night crew working every day to continually wash the glass year round.

Suckering of the plants is done specifically to retain RH in the greenhouse. Wilcox Greenhouses, an operation of 7.5 acres (3 ha), leaves two leaves on the suckers before pinching the growing tips. In some plants they prune all suckers in this way, while in others they leave two to three suckers per plant trained to two leaves. The number of suckers left depends on the plant growth characteristics, season, and RH. The suckers retain the RH

FIGURE 10.51 Support of tomato plants. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

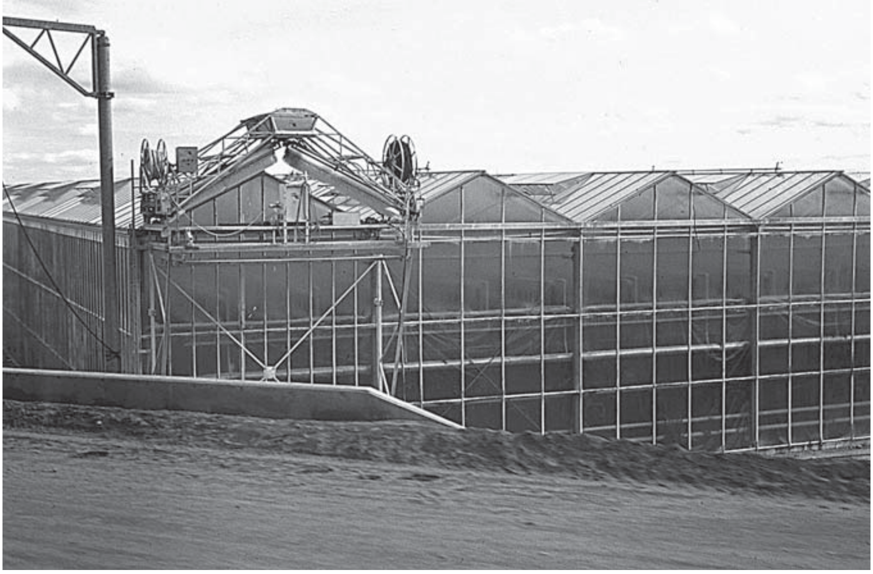

FIGURE 10.52 Machine to whitewash and wash the greenhouse roofs. (From Eurofresh Farms, Wilcox, AZ. With permission.)

in the crop canopy. The RH may be 75%–80% inside the green house, while it is only 8% outside. They stress that a lot of care must be taken with ventilation to prevent drying of the plants. They remove three leaves per plant per week as the plant grows three leaves per week. More leaves are kept on the plant during summer and more are removed during winter. Hot air is kept above the crop and air circulation is improved with 6-m (19.7-ft) gutters.

10.13 PEPPERS IN ROCKWOOL

Peppers are propagated similar to tomatoes. Seed is sown into rockwool cubes and seedlings are transplanted to rockwool blocks. During germination, maintain temperatures at 25°C–26°C (77°F–79°F) and RH from 75% to 80%. Maintain the same temperature during the day and night. Emergence occurs in 7–10 d. Use a dilute pepper nutrient formulation of 0.5 mS. After a week, as the seedlings emerge, reduce the temperature to 23°C–24°C (73°F–75°F). At the first-true-leaf stage, separate and space the seedlings to double the spacing and place them on their sides, similar to the tomatoes. This procedure is fine for small growers, but not feasible for larger growers. Also, if the peppers are grafted they must not be placed on their sides. Most large commercial operations also purchase their seedlings from a specialized propagator as is done for the tomatoes. They are usually purchased at the 4- to 5-wk stage.

About 2 wk later (3 wk from sowing), transplant them to rockwool blocks of 7.5 cm × 10 cm (3 in. × 4 in.) dimensions. Similar to tomatoes, presoak the blocks with nutrient solution of EC 2.5 mS at 23°C (73°F). The peppers may also be laid on their sides when placing them in the blocks (Figure 10.53). This stimulates root growth to give better stem support. Maintain air temperatures at 24°C (75°F) during the day and 22°C (72°F) at night, with a 24-h average of 22°C (72°F). As for tomatoes, space the blocks apart as soon as the leaves start to overlap. Keep the RH at 70%–75%. At 30 d, space the plants at 20 per square meter. Enrich with carbon dioxide at 800 ppm. Seedlings are transplanted to the

FIGURE 10.53 Peppers transplanted to rockwool blocks.

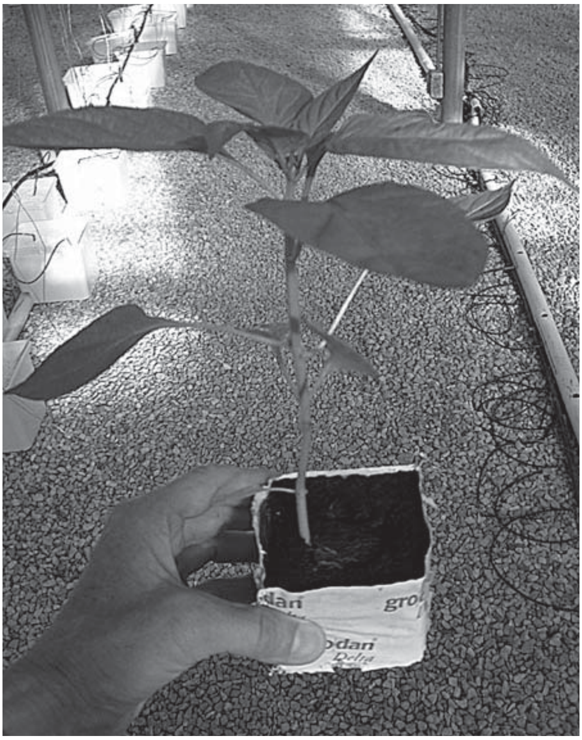

FIGURE 10.54 Pepper at 39 d ready to be transplanted.

greenhouse production area when they are from 5 to 6 wk old from sowing (Figure 10.54). The EC of the blocks should at that stage be from 3.0 to 3.5 mS. Four blocks per slab, each with one plant, will give similar spacing as for tomatoes.

As root temperatures are very important, it is best to propagate plants on slatted benches to provide good air movement, especially in more northerly climates where ambient temperatures are low during the propagation season. Piped hot water heating under the benches allowing heat to rise up through the plants is ideal.

Plant density for greenhouse production is between 8,000 and 10,000 plants per acre (20,000 and 25,000 plants per hectare). That is equivalent to 3.3–3.5 plants per square meter of greenhouse area. This is similar to that of tomatoes. As the peppers are trained to two stems each, this density increases to 6.5–7 stems per square meter.

If the rockwool slabs are placed as two rows (double), locate three plants per slab, whereas, in a single row use five plants per slab. Most growers use the single-row method with more plants and V-cordon them overhead. Spacing between two single rows is 40 cm (16 in.) and 1.46 m (57 in.) between the drainage/irrigation lines. Slabs are spaced 23 cm (9 in.) apart within each row if the slabs are 100 cm (39 in.) in length. For a single-row configuration, rows are 1.8 m (71 in.) apart, and the slabs placed together end to end within the row. With V-cordon training to the upper support cables the final plant density regardless of the row configuration is from 3.3 to 3.5 plants per square meter of greenhouse floor area.

Once good rooting into the slabs has become established and shoot growth has reached 40 cm (16 in.), the temperature regime should be reduced to 18°C–19°C (65°F) at night and 22°C–23°C (72°F) by day. A vigorous crop will tolerate day temperatures as high as 30°C (86°F) in full sunlight, but temperatures of 35°C (95°F) or above will be harmful.

Pepper seedlings should be approximately 25 cm (10 in.) tall with at least six leaves on the main stem when transplanting to the slabs. Presoak the slab with nutrient solution of EC 2.5–3.0 mS for 24 h before transplanting. Soak the slabs well by placing three to five drip lines in each before cutting drainage holes in them as was described earlier for European cucumbers. After the slabs are thoroughly soaked, cut the drainage holes in them. Cut about 2-in.-long slits between the plants at an angle to the bottom of the slab to allow complete drainage. Today, most growers use the Formflex or equivalent raised collection trays to support the slabs to enable the nutrient solution to be recycled. If the solution is not recycled, it can be drained to a large outdoor reservoir for use on field crops or pastures during the summer months in the northern climates.

For the first week after transplanting, maintain the greenhouse at day/night temperatures of 20°C–21°C (68°F–70°F) and CO_2 concentration at 800–1000 ppm. Establish the plants with a strong root system. The EC of the feed solution should be 2.5–3.5 mS, with the slabs at EC of 3.5–4.0 mS. The optimum temperature for vegetative growth is 21°C–23°C (70°F–73°F) and for production, about 21°C (70°F) (Bakker, 1989).

In British Columbia, the growers seed peppers on October 1 and transplant to the rockwool slabs by early December, with the first harvest by early March. Harvesting continues until mid-November.

Greenhouse peppers are trained vertically with two stems in a V-cordon form. They must be pruned correctly to keep them in balance between vegetative and generative growths. Train peppers at least every 2 wk.

About 1–2 wk after transplanting, the peppers will form two to three stems. If three stems form, prune out the third stem, leaving only the strongest two stems. Each stem will grow to about 4–5 m (13–16 ft), supported by overhead cables and string. One string is needed per stem. Attach one string just below the bifurcation of the main stem early after transplanting and then later attach a second string to the second stem on initial pruning (Figure 10.55). Secure the support string with plastic stem clamps just under the side shoots as they develop.

Where the stem first bifurcates a “crown” flower will form. This flower bud can be removed to keep the plant more vegetative initially. However, if the climate favors rapid vegetative growth and the plants are strongly in that phase, leave the crown flower on to help shift the plant toward being generative. In general, it is recommended to remove the flowers at the first and third nodes, but this again is determined by the amount of sunlight. Under high sunlight conditions, allow these fruits to develop. Allow two leaves on the side shoots (laterals) before cutting the tip (Figure 10.56). Be careful to maintain the strong main stem. If by mistake or other damage it should be terminated, allow a strong side shoot to take over as the main leader. Usually, one fruit will develop at each side shoot, but often a second will set along the side shoot. Do not permit any more, or the side shoots will break. Training of peppers and other crops is discussed in more detail in Chapter 14.

10.14 RECIRCULATING ROCKWOOL SYSTEMS

With increasing pressure due to public awareness of the environment and water as a natural resource, it has become important to conserve water and minimize any runoff of fertilizer-enriched solution. In countries such as Holland with a high population and a large greenhouse industry using large volumes of water, the recirculation of nutrient solutions in hydroponic systems is imperative. One of the earliest forms of recirculation rockwool

FIGURE 10.55 Clamp the main stem of the peppers below the bifurcation.

FIGURE 10.56 Cutting of side shoots at second leaf and clamping pepper.

cultures is the use of plastic semirigid channels in which the rockwool slabs are contained. There are a number of manufacturers of these channels. Some may be used as NFT systems as well as with rockwool.

These channels come in rolls, which, when unwound, form a channel by staking the sides upright with special clamps. The ends are folded up and stapled. A special drain-pipe adapter is fitted onto the return end of the channel. PVC piping conducts the solution back to a nutrient cistern. Each plant is irrigated with a drip system as discussed above. It is important that the channel is about 0.5 in. (~1–2 cm) wider than the slabs to allow flow of the drain water past the slabs.

The most common channel used now is that by FormFlex, as discussed earlier. These gutters are available in the lower ones raised slightly above ground level and the plateau trays that keep the return channels raised at about waist level to facilitate working with the plants. The trend now is to use the plateau trays to get better air circulation and more efficiency in workers' time for carrying out their tasks with the plants. The earlier lower level trays are shown in Figures 10.57 and 10.58. The FormFlex gutters all have collection channels on the sides to return the water to storage tanks for treatment in the injection area of the greenhouse. The "AG" gutter by FormFlex is the international standard for vegetable crops. It is available in numerous widths and styles for specific crops. The "LG" gutter is specifically for growing sweet bell peppers. It has high stability and draining capacity. They manufacture 13 types of gutters with various configurations for use with specific vegetable and flower crops. Most of these gutters are now used in combination with the plateau trays, especially with vegetable crops (Figure 10.59).

Unlike the earlier lower gullies that had Styrofoam insulation underneath to maintain optimum root temperatures, the plateau trays do not need the Styrofoam as root temperature in the slabs can be controlled by the temperature of the air from the convection tube below the FormFlex or other recirculation trays. Regardless of whether the trays are the plateau or lower ones, the slope of the slabs can be evenly graded by the adjustment of the

FIGURE 10.57 FormFlex "AG" gutter. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.58 Very productive crop of "Brilliant" TOV tomatoes. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.59 FormFlex gutters as raised trays above the convection tube. (From Eurofresh Farms, Wilcox, AZ. With permission.)

raised frame supporting the trays. A slope of 1–2 in. (~2.2–5 cm) is adequate for drainage as the side collection channels are free of any roots or debris. Several holes between the plants in the slab wrapping will provide good drainage. Runoff from the slabs is vertically away from the base of the slabs into the side drainage troughs of the tray. This gives good aeration of the slabs. The solution is recirculated from the drain channels of the tray at the end through a 1.5-in.-diameter PVC drainpipe connected to an underground 4-in.-diameter collection pipe to the nutrient tank. Solution is applied to each plant individually through a drip irrigation system (Figure 10.57).

The return solution is collected in a cistern and then pumped up into an above-ground nutrient return tank. Large particles are removed from the solution by a separator, followed by a filtration system (usually sand filters in large operations) before the solution enters the return tank (Figures 10.60 and 10.61). The solution is also sterilized before it enters the return tank. Sterilization may be by one of several methods: heat treatment, ozonation, UV (Figure 10.30), or hydrogen peroxide. Hydrogen peroxide is now becoming the most popular method. The return tank solution is then pumped to a batch tank where the EC and pH are monitored and adjusted by an injection system. This is controlled by a computer system, such as Priva or Argus, which monitors these data and on a feedback basis with preset levels for the EC and pH allocates the volumes of the injector stock solutions that are added to the batch tank. From there, the solution is pumped back to the plants in the greenhouse through the drip irrigation system.

The nutrient return and batch tanks must be of sufficient volume for at least 1 day's supply for the plants (approximately 1 L/ft^2/d). The irrigation system, therefore, consists of an injector system operated by a computer monitoring the EC and pH, pumps, sand filters, sterilization system, and emitters at the plants. Locating the emitters on the poly lateral line instead of at the ends of the drip lines will help.

Nutrient analyses of both feed and drain solutions provide data on which to base adjustments of the solution. This must be done weekly. The returning solution has to be diluted with raw water to make up the loss in volume by the uptake of the plants. This decreases the EC level and changes the pH. If the raw water is coming from wells, it should be treated

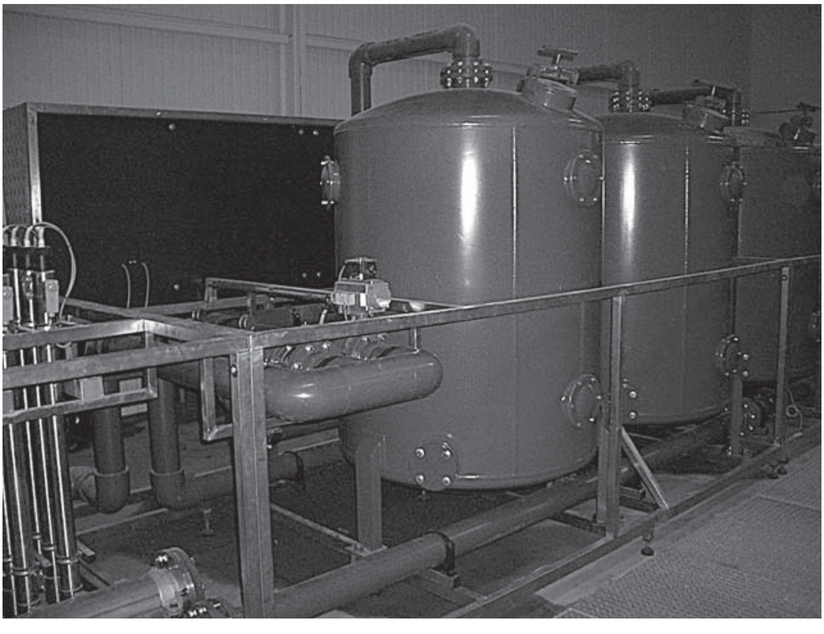

FIGURE 10.60 UV sterilizer and sand filters. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.61 Sand filters with return tank. (From Eurofresh Farms, Wilcox, AZ. With permission.)

with hydrogen peroxide to eliminate potential fungal and bacterial infections. Water can be pumped to a pretreated tank and then be sterilized before entering a supply tank from which it is drawn as makeup water. The computer monitoring the EC and pH adds stock solutions and acid to bring these factors back to a preset level. However, as discussed in Chapter 3, EC measures total dissolved salts (TDS), not the levels of individual ions.

Nutrient-solution analysis is imperative to enable the grower to make changes in the composition of the nutrient solution to keep it within optimum levels.

10.15 ADVANTAGES AND DISADVANTAGES OF ROCKWOOL CULTURE

The advantages of rockwool culture are as follows:

1. As an open system, there is less chance for disease to spread throughout the crop.
2. There is uniform application of nutrients to the plants; each plant is fed individually.
3. Since rockwool is light, it can easily be handled.
4. It is simple to provide bottom heat.
5. It is easily steam sterilized if the grower wishes to use it several times. Structurally, it will not break down for up to 3–4 yr.
6. Rapid crop turnaround is possible at minimal labor cost.
7. It provides good root aeration.
8. There is less risk of crop failure due to mechanical breakdown in the system than with NFT.
9. Little growth setback occurs during transplanting.
10. It requires less capital cost for equipment and installation than many NFT systems.

The disadvantages of rockwool culture are as follows:

1. Rockwool is relatively expensive in countries not manufacturing it locally.
2. Accumulation of carbonates and sodium may occur in the rockwool slabs in regions having high salts in the raw water. In such areas, a reverse osmosis water purifier would be required.

Overall, rockwool culture offers many positive factors in the growing of not only vine crops, but also cut flowers such as roses and potted flowering plants. It is also widely used as a propagation medium for vegetables such as lettuce, spinach, and other low-profile crops.

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11 Coco Coir Culture

11.1 INTRODUCTION

With increased environmental pressures on greenhouse operations to use sustainable or renewable resources, coco coir is quickly expanding as the newest environmentally safe substrate. Many large hydroponic greenhouse operations in Canada, the United States, and Mexico have converted to coco coir as their preferred substrate. Houweling Nurseries, Oxnard, Inc., Camarillo, California, expanded by 40 acres (16 ha) in 2009 and initiated the use of coco coir in the new greenhouse. Gipaanda Greenhouses, Delta, British Columbia, have converted their 18 acres (7 ha) into coco coir a few years ago. Many growers in British Columbia and Ontario have done the same. Many of the growers produce tomatoes, but others are now also converting to coco coir for peppers and eggplants. According to a 2009 publication, *Grow-How* by Van der Knapp-Braam, B.V., who make coco coir products coming from Sri Lanka under the name Forteco, in 2008 approximately 70 ha (175 acres) of tomatoes and sweet peppers were grown on Forteco coco peat slabs in Mexico. This is the same product as that used by Gipaanda Greenhouses. One grower in Poland, Mularski Nursery, has 56 ha (140 acres) of tomatoes with coco coir substrate (Lindhout, 2010). In 2006, they converted the entire operation from rockwool to Forteco coco coir.

11.2 SOURCE OF COCO COIR

Coco coir comes from ground-up coconut palm (*Cocos nucifera*) husks after they have dried (Anonymous, 2011). Coco coir is not screened to remove the fibers, so this adds to its porosity and gives better aeration than peat moss. The components of the coconut fruit are in layers from the outside to the inside and include the exocarp, mesocarp, endocarp, endosperm, and embryo (Gunn, 2004). The endosperm is the white edible part of the coconut and the liquid. The husk consists of an outer skin (exocarp), middle hard layer (mesocarp), and the shell (endocarp). The testa is the seed coat located between the shell and the meat (endosperm).

Coir is the fiber from the husk. The fibrous strands are used to make brushes, doormats, nets, and twine. The husk can be separated into coir fibers and coir pith or pulp, a coir dust that has been a waste product. This coir pith is biodegradable, but can take up to 20 yr to decompose. Research in the 1980s developed a process to transform coir pith into a medium used in mulching, soil treatment, and hydroponics, where it can be used as a substitute for peat moss and vermiculite.

The largest coconut producers include the Philippines, Indonesia, India, Brazil, Sri Lanka, and Thailand. The coconut shell consists of (dry basis) 34% cellulose, 36.5% lignin, 29% pentosans (five-carbon sugars), and 0.6% ash (Woodroof, 1979).

11.3 COCO COIR GRADES AND CHARACTERISTICS

Forteco B.V., a subsidiary of the Van der Knapp group companies, has headquarters in Holland but production facilities in Sri Lanka and India, where they source their coconut husks. They also have a research center in Holland where they test new coco coir products, such as plugs, blocks, discs, and slabs in various crop trials.

Forteco has developed four different coco slabs, each having characteristics to steer toward generative or vegetative growth of specific crops. The "Forteco Basic" slab steers toward the vegetative phase, with an air-holding capacity of 20% at full water saturation. It is composed of coco pith. The "Forteco Power" slab is suited for generative and vegetative steering and has 25% air-holding capacity at full saturation. It is composed of crushed husk and coir pith. The "Forteco Profit" slab is for generative growth, with 30% air capacity at saturation. It is made from crushed husk and is buffered. Lastly, the "Forteco Maximum" is for maximum generative growth, having 40% air capacity at saturation. It is composed of buffered crushed husk.

Forteco slabs are "ready to use," with drain slits and precut plant holes. The company claims that because of the unique air/water ratio, plant roots grow evenly throughout the substrate. They claim that the homogenous nature of the substrate gives excellent growing, resulting in maximized yields.

Forteco has designed weighing scales that monitor the weight of the slabs at 1-min intervals and send the data to a computer controller that analyzes and regulates irrigation cycles. With this data, irrigation cycles are refined to also decrease the moisture content of the slabs during night. This type of feedback system for irrigation control was discussed in Chapter 10. Coco coir slabs are very stable and are therefore suitable for several years of crop cultivation. Since they are 100% organic, they may be completely recycled as a soil conditioner.

In the tropics, coco coir can be purchased very cheap by the truckload in bulk form. However, a number of companies in North America compress it into an expandable hard brick. By adding 5 qt (5 L) of water to each brick of 20 oz (567 g), it expands to approximately 9 qt (9 L) within 15 min. It has a fluffy texture, with a pH 5.7–6.3. One precaution to observe is to check its sodium chloride content, especially if purchasing bulk coco coir from coastal areas close to the ocean.

Coco coir may be mixed with perlite or vermiculite in similar ratios, as is discussed later for peat in peat-lite mixes. It can also be used as a mixture with rice hulls, as discussed later in Chapter 13.

The high cation exchange capacity (CEC) of the cellulose in coir traps cations from the solution and releases them at root absorption. Cations are positively charged atoms and minerals dissolved in solution, such as K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}, Zn^{2+}, and B^{3+}. These were discussed in detail in Chapter 3. Coir has a higher pH than peat moss. The cellulose and lignins in coir are highly electronegative molecules that absorb or "trap" cations. So, the absorptive capacity of coir is high, with a very large surface area in the granular structure of the coir. These absorbed cations will be exchanged for other cations in solution. The CEC changes with pH since H^+ is a very small cation and is also attracted by the cellulose in coir.

Jiffy Products make coco coir blocks wrapped with a fine capillary fleece that are similar in shape and size to rockwool blocks (Figures 11.1, 11.4, and 11.5). They claim that their coco "Growblocks" are 100% pathogen free and that with the presence of antagonistic

FIGURE 11.1 Jiffy Growblocks on Jiffy Growbag with peppers. (From Jiffy Products. With permission.)

bacteria in the substrate they suppress *Pythium* fungal infection of plant roots. Jiffy is now making coco coir slabs (Jiffy Growbags). They have four sizes to suit the gutter or raised tray channels.

All growbags are 100 cm (39.4 in.) in length, but their width and height vary according to the gutters in which they are to be located. For small gutters or low-volume systems, Jiffy Products recommend a width of 15 cm (6 in.) and two possible heights (8 cm or 3 in. for low volume and 10 cm or 4 in. for moderate volume). For wider gutters or high-volume systems, they created a 20-cm (8-in.) width, and heights of 8 cm (3 in.) and 10 cm (4 in.) for moderate and large volume systems, respectively.

They also have three substrate characteristics to best suit specific crops. Their "Jiffy Premium Growbag" is a double-layered substrate with 50% husk chips and 50% coco pith, used for tomatoes and peppers in all climates (Figure 11.2). The "Jiffy HC Growbag," which is 100% husk chips, is used for cucumbers in moderate climates. The "Jiffy 5050 Growbag," which has a uniform mixture of 50% husk chips and 50% coco pith, is for rose and strawberry growing in Mediterranean climates (Figure 11.3).

11.4 COCO PLUGS AND BLOCKS

At present, most growers using coco slabs seed into rockwool cubes or Kiem plug trays using small plugs, Growcubes, or granulate rockwool. Each Kiem plug tray has 240 rockwool plugs that are suitable for sowing seed and later transplanting to rockwool blocks or coco blocks. The Growcubes are 0.25-in. (0.7-cm) cubes of rockwool.

Jiffy Products make coco coir plugs, blocks, and slabs. Jiffy coco coir plugs are 3 cm × 3.5 cm deep (1.2 in. × 1.4 in. deep) on soaking with water. They also make grow blocks with a single hole to fit either their plug or rockwool plugs. These blocks are composed of pithy tissues of coconut husks manufactured in Sri Lanka. They claim that they

FIGURE 11.2 Jiffy Growbag showing root growth. (From Jiffy Products. With permission.)

FIGURE 11.3 Strawberries growing in coco coir in raised gutter. (From Jiffy Products. With permission.)

FIGURE 11.4 Double Jiffy Blocks with tomatoes. (From Jiffy Products. With permission.)

hold slightly less water than rockwool blocks in order to promote early root growth. The coco substrate is stable and will not degrade during the growing cycle. The coco coir is wrapped in a biodegradable fine capillary "fleece" to contain the coco coir so that the coco substrate will not enter the hydroponic system during the cropping period. They come in two sizes, 7.5-cm (3-in.) and 10-cm (4-in.) blocks with holes that will contain their Jiffy-7C coco coir plugs or rockwool plugs. They are now also making double blocks to contain two plants (Figures 11.4 and 11.5). When water and nutrient solution are added to the blocks, they expand to their full size and are then ready for transplanting seedling plugs.

11.5 SUSTAINABLE AGRICULTURE GREENHOUSE TECHNOLOGY

In 2009, Houweling Nurseries Oxnard, Inc. constructed a new 16-ha (40-acre) greenhouse range for growing tomatoes in coco coir (www.houwelings.com).

The greenhouses use the most recent advances in technology, making this operation one of the most high-tech greenhouses in the world. It includes 4 acres (1.6 ha) of solar panels to generate electricity for the new range. Houweling terms their new greenhouse range, "Future of Sustainable Agriculture" greenhouses (Schineller, 2009). The greenhouses are a Dutch Venlo type of glass structure manufactured by KUBO Greenhouse Projects (www.kubo.eu) of the Netherlands. The greenhouse sidewall height is 7 m (23 ft) to permit the hot air in the greenhouse to rise above the plant crop (Figure 11.6). This height also gives better air circulation than lower structures of the same nature. Above are small vents with bug screens to prevent insects from entering. Air circulation, heating, cooling, and carbon dioxide enrichment are all based on positive pressure.

American Capital Energy (www.AmericanCapitalEnergy.com) worked with Houweling to provide electric power and stored heat to power and warm the greenhouse operation.

FIGURE 11.5 Base of Jiffy Block showing extensive, healthy root growth. Note: The "fleece" net wrapping. (From Jiffy Products. With permission.)

FIGURE 11.6 High sidewalls of Houweling Nurseries greenhouse. Note: The insect screen covering the entire end. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

The solar unit is a 1.1-MW solar photovoltaic system mounted on a tilting rack located over a 4-acre water-retention pond (Figures 11.7 and 11.8). The tilting design positions the panels to maximize sunlight interception. The solar thermal heat system heats the water in the retention pond below to reduce the overall heating costs of the greenhouse during the night. The system is projected to provide over 50% of the facility's energy needs.

FIGURE 11.7 Four acres of solar photovoltaic system with water-retention pond below. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.8 Tilting solar panels above electrical panels. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

Argus Control Systems Ltd., White Rock, British Columbia (www.arguscontrols.com), provided climate control systems to closely monitor and adjust all environmental and irrigation systems to optimize conditions for plant growth and efficient use of greenhouse systems to reduce production costs.

This greenhouse operation is a semiclosed, positive-pressure greenhouse that improves insect exclusion, reduces disease, reduces water and fertilizer use, and enhances efficiency in carbon dioxide enrichment. According to Casey Houweling, the owner, the closed greenhouse environment reduces evaporation of irrigation water. The excess irrigation leachate is collected by FormFlex raised growing gutters and is transported to a water treatment system. Treatment and recycling of condensation, rain, and runoff water, and fertilizing nutrients are accomplished through a system designed by Pure-O-Tech of Escondido, California (www.pureotech.com), that involves filtration and ozonation.

Water is heated by the solar thermal array and warehouse refrigeration exhaust heat, stored in million-gallon hot water storage tanks, and circulated through the system, especially at night. The older greenhouse ranges burn natural gas to create carbon dioxide to enrich the atmosphere during the day. The heated water from the boilers generating the CO_2 is stored in these large storage tanks. This heated water is pumped back through the boilers to heat the greenhouse at night. Automated insulation screens close over the plants at night to hold in accumulated heat.

The greenhouse metal structural membranes are powder coated to maximize light reflection to the crop (Figure 11.9). Below, a white weed mat on top of the floor also helps to reflect light up into the crop. With positive pressure and the high gutters, only a small number of roof vents are required. Each is covered with an accordion-shaped insect screen to maximize the surface area (Figure 11.10). The vents are needed only to release pressure in the greenhouse so that excess pressure does not break the glass. All this is controlled by the Argus computer system. The atmosphere in the greenhouse is constantly recirculated by the use of horizontal airflow fans and the large polyethylene convection tube located under the raised growing trays (Figure 11.11). This system was described in Chapter 10. At the greenhouse wall on the outside is an insect screen to prevent insects from entering as the exhaust fans take in the outside air (Figure 11.6). An evaporative cooling pad located on the same outside wall permits air from outside to be drawn through it to reduce temperature by evaporation of

FIGURE 11.9 Powder coated structural membranes to improve light. Note: The height of the structure at the gutters is well above the crop. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

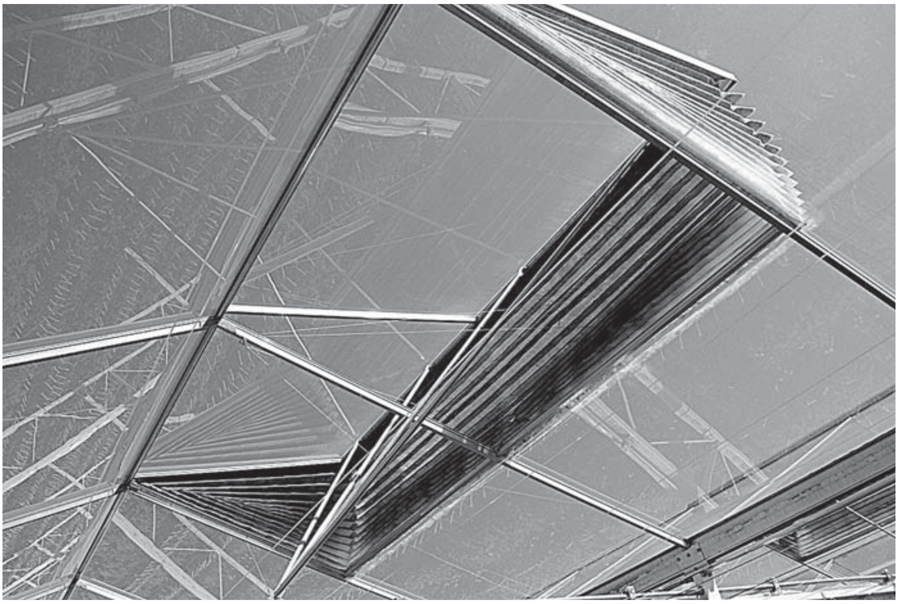

FIGURE 11.10 Roof vent with insect screen. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.11 Raised growing trays with polyethylene heating/cooling convection tube below. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.12 Evaporative cooling pad above on the right, glass shutter directly above. Note: The shutter is fully open for cooling cycle. Hot water mains on the left. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

the water running down the cooling pad (Figure 11.12). From there, the cooled air is pushed down the convection tubes under the plants by two exhaust fans per plant row.

Temperature control is by glass shutters that adjust to any degree to permit air from outside to mix with the inside greenhouse air. During heating cycles, the cooling pads are covered with this shutter in its closed position and the air from the fans is pushed through heat exchangers (Figure 11.13). There are two heat exchangers per set of two fans per plant row. The heat exchangers use hot water from the storage tanks and boilers of the other greenhouse ranges. When no or little cooling is required, the louver system partially closes to the degree needed to just mix the correct amount of cool air with the recirculated air. This is all controlled with the Argus computer system. There are heating pipes in the aisles between the plant rows, but they are not connected to the hot water heat. Their only purpose is to act as tracks for the picking/working carts to travel on. After the hot water passes through this new positive-pressure greenhouse, it goes back to the main boilers of the other greenhouse ranges and is stored in the large water tanks (Figure 11.14). The new range has no boilers; it only uses the residual hot water from the other ranges' boilers.

11.6 TOMATOES IN COCO COIR

Houweling Nurseries start their seedlings in their British Columbia nursery. They green graft the tomatoes to vigorous, disease-resistant rootstocks and ship them to their California operation at 5 wk. The Camarillo operation uses coco coir slabs in the new 40-acre range. The tomato seedlings are transplanted to mini coco coir slabs. Each slab normally has two blocks of double-stem seedlings or two blocks with two tomato plants each, so the total stems per slab is four. When intercropping, the slab will contain four blocks, two blocks with the older bifurcated plants and two blocks containing two plants each for the intercrop.

FIGURE 11.13 Cooling pad on the upper left; on the right are the heat exchangers in the fan housing. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.14 Hot water storage tanks. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

The slabs are set on top of a FormFlex raised gutter that recirculates the solution. The large convection tube underneath the raised gutter circulates the air, adds carbon dioxide, and maintains optimum temperatures as described in Chapter 10.

Tomatoes are intercropped, so there are two irrigation systems (Figures 11.15 and 11.16). One system is for the mature plants, and the other is for the young plants. In this way, it is possible to set different irrigation cycles for each crop. However, this is only for the inlet drip lines, so the same formulation is used on all the plants, but the young plants get less cycles than the older ones.

This method of intercropping is particularly applied to high-sunlight regions such as southern California and Arizona. Both Houweling Nurseries Oxnard, Inc. and Eurofresh Farms, Bonita, Arizona, follow these practices. Intercropping saves on the use of the slabs (whether rockwool or coco coir), as two crops can be placed on the same slabs consecutively.

In the case of Houweling, they start their plants in their British Columbia nursery operation. They graft the tomato-on-vine (TOV) variety "Success" to Maxifort rootstock. The grafted seedlings are shipped by truck to Camarillo when the plants are about 5 wk old (Figure 11.17). The new plants are planted between the existing ones on the same slabs or on new slabs placed between the slabs of the mature plants (Figures 11.18 through 11.20). The older plants have the lower part of their stems de-leafed as the fruit is harvested. This permits light to reach the younger intercrop. When the intercrop plants are within a week or so of starting to produce fruit the older plants are removed (usually about 9–10 wk after transplanting the intercrop). The intercrop is trained by string on tomahooks to the inside two of the four support wires. When the old crop is removed, the intercrop hooks are placed onto the outside two wires so that the plants are trained in a V-cordon fashion.

Gipaanda Greenhouses has 18 acres (7.2 ha) of greenhouses growing numerous varieties of tomatoes. One TOV variety they grow is Tricia grafted on Maxifort rootstock. They purchase their seedlings from Houweling Nurseries Ltd., Delta, British Columbia.

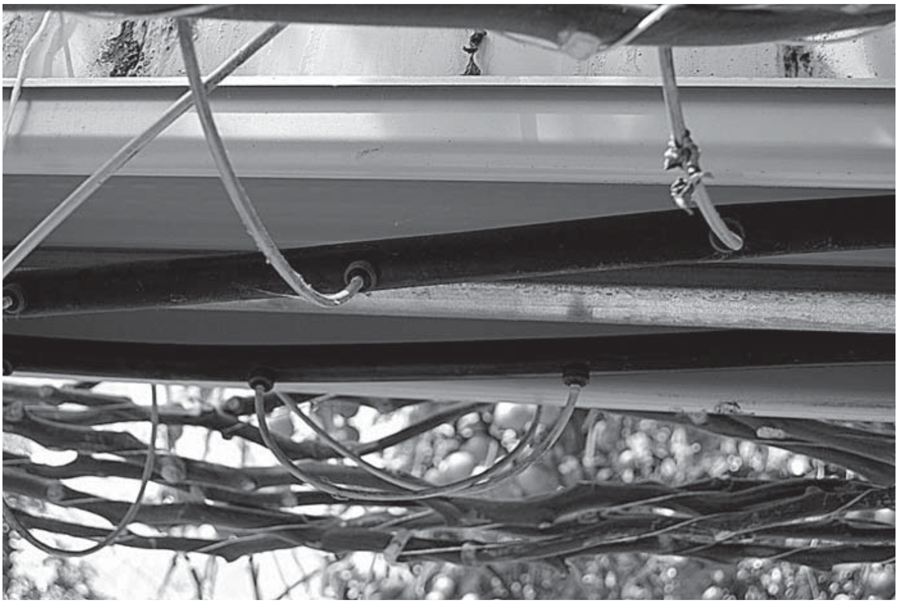

FIGURE 11.15 Two inlet irrigation systems to the crops for intercropping. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.16 Drip line inlet laterals, two per growing tray for intercropping. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.17 New seedlings for intercropping are brought from British Columbia. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.18 Mini coco coir slabs. Slab on the left has two mature plants with two stems per plant, while the one on the right has two mature plants and two seedlings recently transplanted. The older plants will be removed as the young ones approach maturity. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.19 A mini slab with two recently transplanted blocks, each with two seedling plants. Note: The older plants were removed to permit more light to the young transplants. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 11.20 Intercrop of tomatoes. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

Gipaanda Greenhouses is now growing on coco coir by Forteco. The slabs are 1.2 m × 20 cm × 6 cm deep, but they will use ones that are 8 cm deep in the future. The recirculated nutrient solution is treated between cycles. Crop density is increased by allowing the plants to form two shoots as sunlight increases with the spring season, as described in Chapter 10. However, with low light levels in winter, intercropping is not done, and the crops are replaced in late November.

The training of plants in coco coir is the same as in rockwool, as discussed in Chapter 10. The main difference between coco coir and rockwool cultures is nutrient management. Less frequent irrigation cycles are needed because of the greater water retention of the coco coir.

11.7 ADVANTAGES AND DISADVANTAGES OF COCO COIR CULTURE

Advantages of coco coir culture are as follows:

1. This is a closed system to conserve water and fertilizers.
2. Coco slabs have high air-holding capacity, which is important in steering the crops.
3. With good capillarity, the slabs can be dried more than rockwool to permit easy steering of the crops.
4. When the slabs are dried, they easily reabsorb adequate water without any remaining dry spots, as can occur with rockwool.
5. Coco slabs come in different proportions of fine pith material to fibrous material or husk chips to best suit specific crops. Most slab producers have at least four grade types.
6. Owing to the unique air/water ratio, roots easily penetrate and grow throughout the substrate.

7. Coco slabs are very stable and can be used for more than one season.
8. Coco is 100% organic and can easily be recycled as a soil conditioner. It does not create a disposal issue with landfills as does rockwool.
9. Coco substrates maintain antagonistic bacteria and can be inoculated with other beneficial microorganisms to reduce risk of fungal diseases caused by organisms such as *Pythium*.

The disadvantages of coco coir culture are as follows:

1. As coco coir is used with closed systems, if the return leachate is not treated adequately against disease organisms, pathogens could build up in the substrate.
2. Some coco coir, if not leached adequately by the manufacturer, could contain high levels of sodium chloride that must be leached by the grower. Most coco coir producers state that their product is free of such salt.
3. Coco coir may contain potassium. If so, the grower needs to adjust the nutrient solution accordingly and flush the slabs with a low potassium nutrient solution.

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12 Other Soilless Cultures

12.1 INTRODUCTION

Many other methods of soilless culture are being used successfully. Some of the media used are peat, vermiculite, perlite, pumice, rice hulls, and plastic Styrofoam. Often mixtures of these media are used in various proportions. Growing trials with various mixtures determine which proportions are most suitable to the plants in question. For example, flowering potted plants such as chrysanthemums, poinsettias, and Easter lilies and tropical foliage plants can be grown well in mixtures of peat–sand–pumice in a 2:1:2 ratio.

12.2 MEDIA

12.2.1 Peat

Peat consists of partially decomposed aquatic, marsh, bog, or swamp vegetation. The composition of different peat deposits varies widely, depending on the vegetation from which it originated, the state of decomposition, mineral content, and degree of acidity (Lucas et al., 1971).

Of the three types of peat—moss peat (peat moss), reed sedge, and peat humus—peat moss is the least decomposed and is derived from sphagnum, hypnum, or other mosses. It has a high moisture-holding capacity (10 times its dry weight), is high in acidity (pH 3.8–4.5), and contains a small amount of nitrogen (about 1.0%) but little or no phosphorus or potassium. Peat from hypnum and other kinds of mosses breaks down rapidly, as compared with sphagnum, and is not as desirable. Peat from sedges, reeds, and other swamp plants also decomposes rapidly.

Sphagnum moss is the dehydrated young residue or living portions of acid-bog plants in the genus *Sphagnum*, such as *S. papillosum*, *S. capillacium*, and *S. palustre*. It is relatively sterile, light in weight, and has a very high water-holding capacity. It is generally shredded before being used as a growing medium.

12.2.2 Vermiculite

Vermiculite is a micaceous mineral, which is expanded when heated in furnaces at temperatures near 2,000°F (1,093°C). The water turns to steam, popping the layers apart, forming small, porous, spongelike kernels. Heating to this temperature gives complete sterilization. Chemically, it is a hydrated magnesium–aluminum–iron silicate. When expanded, it is very light in weight (6–10 lb/ft^3) (96–160 kg/m^3), neutral in reaction with good buffering properties, and insoluble in water. It is able to absorb large quantities of water, 3–4 gal/ft^3 (0.4–0.5 mL/cm^3). It has a relatively high cation exchange capacity and thus can hold nutrients in reserve and later release them. It contains some magnesium and potassium, which is available to plants.

Horticultural vermiculite is graded in four sizes: No. 1 has particles from 5 to 8 mm in diameter; No. 2, the regular horticultural grade, from 2 to 3 mm; No. 3, from 1 to 2 mm; and No. 4, which is most useful as a seed-germinating medium, from 0.75 to 1 mm. Expanded vermiculite should not be pressed or compacted when wet, as this will destroy its desirable porous structure.

12.2.3 PERLITE

Perlite is a siliceous material of volcanic origin, mined from lava flows. The crude ore is crushed and screened, then heated in furnaces to about 1,400°F (760°C), at which temperature the small amount of moisture in the particles changes to steam, expanding the particles to small, spongelike kernels, which are very light, weighing only 5–8 lb/ft^3 (80–128 kg/m^3). The high processing temperature gives a sterile product. A particle size of 0.063–0.13 in. (1.6–3.1 mm) in diameter is usually used in horticultural applications. Perlite will hold three to four times its weight of water. It is essentially neutral, with a pH of 6.0–8.0, but with no buffering capacity; unlike vermiculite, it has no cation exchange capacity and contains no minor nutrients. It is most useful in increasing aeration in a mixture since it has a very rigid structure. While it does not decay, the particle size can become smaller by fracturing as it is handled. A fine grade is useful primarily for seed germination, while a coarser type of horticultural grade is best suited for mixing with peat, in equal parts, for propagation or with mixtures of peat and sand for growing plants.

12.2.4 PUMICE

Pumice, like perlite, is a siliceous material of volcanic origin. However, it is the crude ore after crushing and screening without any heating process. It has essentially the same properties as perlite, but is heavier and does not absorb water as readily since it has not been hydrated. It is used in mixtures of peat and sand for the growing of potted plants.

12.2.5 RICE HULLS

Rice hulls are the outer husk or shell of the rice grain. After the rice grains are dried, the outer hulls are removed in the milling as a by-product. The rice hulls are thin, feather-light, and pointed in shape similar to rice grains. They do not decompose readily, lasting from 3 to 5 yr. They are neutral in pH and have no nutrients. Their smooth surface does not allow them to retain moisture. They are used in the raw state to free up heavy soils to help oxygenate the soils. They can also be used as a hydroponic substrate (Laiche and Nash, 1990). They are mixed with peat or coco coir, usually at 20% of rice hulls. In the past, as described later in this chapter, they can, under some soilless systems, be used by themselves. However, most soilless mixes using rice hulls prefer to use charcoaled rice hulls. This is done extensively in the greenhouse flower industry in Colombia. Rice charcoal is created by burning (smoldering) the rice hulls very slowly. After burning, their structure becomes full of tiny pores, thus increasing their water-holding capacity and capillary action. Also, in this state with their large surface area, they provide sites for beneficial bacteria and other microorganisms and therefore are an excellent soil amendment.

12.2.6 Soilless Mixtures

Most mixtures contain some combination of sand, peat, perlite, pumice, and vermiculite. The specific proportions of each component used depends on the plants grown. The following are some useful mixtures.

1. Peat:perlite:sand	2:2:1 for potted plants
2. Peat:perlite	1:1 for propagation of cuttings
3. Peat:sand	1:1 for propagation of cuttings and for potted plants
4. Peat:sand	1:3 for bedding plants and nursery container-grown stocks
5. Peat:vermiculite	1:1 for propagation of cuttings
6. Peat:sand	3:1 light weight, excellent aeration, for pots and beds, good for azaleas, gardenias, and camellias, which grow well in acid conditions
7. Vermiculite:perlite	1:1 light weight, good for propagation of cuttings
8. Peat:pumice:sand	2:2:1 for potted plants

In general, pumice, which costs less, may be substituted for perlite in most mixes.

The most common mixtures are the University of California (U.C.) mixes of peat and fine sand, and the Cornell “peat-lite” mixes. The U.C. mixes were derived from the California Agricultural Experiment Station in Berkeley. The U.C. mixes vary from fine sand only to peat moss only, but the mixes that are used more commonly contain from 25% to 75% fine sand and from 75% to 25% peat moss. These mixes are used for growing potted plants and container-grown nursery stock. The peat-lite mixes were devised by Cornell University, New York, from equal proportions of peat and vermiculite. They have been used primarily for seed germination, growing of transplants, and for container growing of spring bedding plants and annuals. Some growers have used them to grow tomatoes commercially in beds, similar to sawdust culture.

All of the required minerals must be added to these mixes, and some or all of them are added at the time of mixing. The Cornell peat-lite mixes are considerably lighter in weight than the U.C. mixes, as either perlite or vermiculite weighs about one-tenth as much as fine sand. The peat-lite mixes are made from equal parts of sphagnum peat moss and either horticultural perlite or No. 2 vermiculite.

12.2.6.1 The U.C. Mix

The basic fertilizer additions recommended for a U.C. mix of 50% fine sand and 50% peat moss are given here (Matkin and Chandler, 1957).

To each cubic yard (0.7645 m^3) of mix, add

2.5 lb (1.136 kg) hoof-and-horn or blood meal (13% nitrogen)
4 oz (113.4 g) potassium nitrate
4 oz (113.4 g) potassium sulfate
2.5 lb (1.136 kg) single superphosphate
7.5 lb (3.41 kg) dolomite lime
2.5 lb (1.136 kg) calcium carbonate lime

The fine sand, peat moss, and fertilizer must be mixed together thoroughly. The peat moss should be moistened before mixing. As the crop grows, additional nitrogen and potassium fertilizer must be provided.

12.2.6.2 The Cornell "Peat-Lite" Mixes

Instructions for three peat-lite mixes are as follows (Broodley and Sheldrake, 1964, 1972; Sheldrake and Broodley, 1965):

1. Peat-lite mix A (to make 1 yd^3 or 0.7645 m^3).
   11 bu (88 U.S. gal) (333 L) sphagnum peat moss
   11 bu (88 U.S. gal) (333 L) horticultural vermiculite No. 2 grade
   5 lb (2.27 kg) ground limestone
   1 lb (0.4545 kg) superphosphate (20%)
   2–12 lb (0.909–5.4545 kg) 5–10–5 fertilizer
2. Peat-lite mix B.
   Same as A, except that horticultural perlite is substituted for the vermiculite.
3. Peat-lite mix C (for germinating seeds).
   1 bu (8 U.S. gal) (30.3 L) sphagnum peat moss
   1 bu (8 U.S. gal) (30.3 L) horticultural vermiculite No. 2
   1.5 oz (42.5 g) ammonium nitrate
   1.5 oz (42.5 g) superphosphate (20%)
   7.5 oz (212.6 g) ground limestone, dolomitic

The materials should be mixed thoroughly, with special attention given to wetting the peat moss during mixing. Adding a nonionic wetting agent such as Aqua-Gro (1 oz/6 U.S. gal water (28.35 g/22.7 L water) initially will aid in wetting the peat moss.

12.2.6.3 Fertilizer, Sphagnum Peat Moss, and Vermiculite Mixture

The Vineland Research Station in Ontario, Canada (Sangster, 1973), uses a slight modification in fertilizer ingredients for addition to a mixture of equal volumes of sphagnum peat moss and vermiculite (50:50 peat–vermiculite) per cubic yard (0.7645 m^3) as shown below.

1.75 bales of 6 ft^3	peat moss
2 bags of 6 ft^3	bags vermiculite (No. 2)
12 lb (5.45 kg)	ground limestone (dolomitic)
5 lb (2.273 kg)	calcium sulfate (gypsum)
1.5 lb (0.682 kg)	calcium nitrate
2.5 lb (1.136 kg)	20% superphosphate
8–10 lb (3.64–4.54 kg)	Osmocote 18-6-12 (9 mo)
6 oz (170 g)	fritted trace elements (FTE 503)
1 oz (28.35 g)	Iron (chelated, such as Sequestrene 330)
0.5 lb (227 g)	magnesium sulfate

Osmocote 18-6-12 provides a continuous supply of nitrogen, phosphorus, and potassium throughout the growing season. FTE 503 slowly releases iron, manganese, copper, zinc, boron, and molybdenum.

Mixing the fertilizer ingredients with the peat–moss mixture can be done in several ways. Small volumes can be mixed with a shovel on a concrete floor. When mixing on a floor, first disinfect the floor area with a solution of five parts water to one part Clorox

(5.25% sodium hypochlorite). Spread the fertilizer evenly over the medium and turn the mix back and forth from one pile to another several times with a shovel. A large garbage can is useful for mixing a 2-bu batch. Scoop the mix into the garbage can, pour the mix back onto the floor, and repeat this procedure several times.

A large concrete mixer works well for mixing large amounts. Often commercial growers acquire a "ready-mix" unit from an old concrete truck. This unit can be mounted on a concrete slab and a motor attached to operate it. A series of conveyors can feed in ingredients and also pile the finished product in the potting area of the greenhouse.

If plastic-lined beds are used for the plants, the medium can be mixed directly in the beds. It can be mixed with a padded hoe, taking care not to rupture the plastic liner. For large greenhouses a read-mix unit should be used, with conveyors conducting the finished product directly to the beds.

Dry peat is usually hard to wet. Adding two ounces (56.7 g) of a nonionic wetting agent such as Aqua-Gro in 10 gal (37.85 L) of water will help wet the peat in 1 yd^3 (0.7645 m^3) of mix. Micronutrients should be dissolved in water, which is then sprinkled over the medium or added directly to the mixer while mixing. For a 2-bu (16-U.S.-gal) (60.6-L) batch, the nutrients can be dissolved in 1 gal (3.785 L) of warm water and then sprinkled over the medium before mixing.

12.2.7 Coco Coir

As discussed in Chapter 11, coco coir is becoming increasingly popular as a soilless substrate. Coco coir is not screened to remove the fibers, so this adds to its porosity and gives better aeration than peat.

In the tropics it can be purchased very cheap by the truckload in bulk form. However, a number of companies in North America compress it into an expandable hard brick. By adding 5 qt (5 L) of water to each brick of 20 oz (567 g), it will expand to approximately 9 qt (9 L) within 15 min. It has a fluffy texture with a pH of 5.7–6.3. Most coco coir comes from Indonesia, but future sources could come from South America and Mexico. One precaution to be taken is to check its salt (sodium chloride) content, especially if purchasing bulk coco coir from coastal areas close to the ocean. Also, it may contain residual potassium, so initial nutrient solutions should be adjusted accordingly. It may be mixed with perlite or vermiculite in similar ratios as discussed earlier for peat in peat-lite mixes.

12.3 HYDROPONIC HERBS

The demand for fresh herbs is increasing in the marketplace. Many are now packaged in zip-lock type plastic bags to keep them fresh. "Live" herbs are even more popular. These are clumps of herbs grown in a water culture or an NFT system. Rockwool or oasis cubes can be used to start the plants. They are transplanted to an NFT hydroponic system and grown there for a number of weeks depending on the growth rate of the specific herb. They are harvested as a complete bunch with roots in the growing block. The bunch is placed in a sleeve or rigid plastic clamshell container to maintain freshness at the supermarket.

Some of the more common culinary herbs include anise, basil, chervil, chives, coriander (cilantro), dill, fennel, mint, oregano, parsley, rosemary, sage, savory, sweet marjoram, tarragon, and thyme. Many are grown in the field on a large scale; however, some are particularly suitable for hydroponic greenhouse culture. These include basils (sweet Italian, Thai basil, cinnamon basil, lemon basil, and purple/opal basil), chervil, chives, baby dill, fennel, oregano, sweet marjoram, sage, savory tarragon, thyme, upland cress, and watercress.

Herbs may be grown in a number of soilless substrates such as sand, peat-lite mixes, rice hulls, coco coir, perlite, foam, rockwool, and NFT. However, many are sensitive to moisture levels in their root zone. Basil, for example, does not like a lot of moisture in its crown (but does well in NFT), tarragon requires relatively dry conditions, and mint prefers a lot of water, similar to watercress.

12.3.1 GROWING HERBS IN A PEAT-LITE MIX

California Watercress, Inc., Fillmore, California, grew a number of herbs in a peat medium containing 60% peat, 15% sand, 15% fir bark, and 10% perlite. Dolomite lime was added to stabilize the pH between 6.0 and 6.5. A wetting agent and a 9-mo formulation of slow-release fertilizer were incorporated into the medium. Mint, chives, thyme, basil, and oregano were grown successfully in the medium.

About 1 acre (0.4 ha) of greenhouses was constructed to grow these herbs hydroponically year-round, but emphasis was on winter production in the greenhouses. Beds 8 ft × 155 ft (2.4 m × 47 m) were constructed of 8 in. × 8 in. × 16 in. (20 cm × 20 cm × 40.5 cm) cement blocks and 4 ft × 4 ft (1.2 m × 1.2 m) pallets (Figure 12.1). Sides were formed using 1 in. × 8 in. (2.5 cm × 20 cm) lumber nailed to the edges of the pallets. This gave a bed depth of 5 in. (13 cm). The beds were lined with chicken wire and 6-mil black polyethylene (Figures 12.2 and 12.3). The chicken wire prevented the black poly from sagging between the spaces of the pallet tops. Small slits were made in the bottom of the poly liner at centers of 16–18 in. (40–46 cm) to allow adequate drainage. The polyethylene liner was stapled along the top edges, sides, and bottom of the beds. Support braces to secure the sides of the beds were nailed every 20 ft (6 m) along the bed length before

FIGURE 12.1 Beds constructed of cement blocks and pallets. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.2 Beds are lined with chicken wire to support a polyethylene liner. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.3 Black polyethylene liner is stapled to the bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

putting the medium in the beds (Figure 12.4). The medium must be moistened before placing it in the beds.

The irrigation system consisted of a central injector and 2-in.-diameter PVC mains and 1-in.-diameter PVC headers supplying nutrients via "T-tape" drip hoses at 12-in. (30.5-cm) centers (Figure 12.5).

FIGURE 12.4 Placing of a peat-lite medium in the completed bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.5 Irrigation ooze hoses, T-tape at 12-in. centers. Chives were transplanted. (From California Watercress, Inc., Fillmore, CA. With permission.)

Two headers, one at the front of the beds and the second in the middle are connected to the drip lines so that each set ran only half the length of the beds (about 75 ft) (23 m). The drip tape was prepunched at 12-in. (30.5-cm) centers along its length. The irrigation system was operated by two timer controllers. Irrigation cycles were generally every 2–3 d for 1–1.5 h depending on the stage of plant growth and weather conditions. The duration of each cycle was long enough to produce sufficient leaching to flush any salt buildup.

Seedlings or rooted vegetative cuttings grown in small pots or trays were transplanted to the beds (Figure 12.6). In some cases, as for chives and mint, field plants were divided and roots washed before transplanting to the beds.

It was expected that since these herbs are perennials, the plants could remain in the beds for several years under continual cropping (Figures 12.7 and 12.8). When the crop needs to be replaced, the medium should be changed as no steam sterilization equipment is available.

The greatest problem with this medium is the root buildup. After more than 2 yr of cropping the same plants, a highly compacted root system formed throughout the medium. This reduced oxygenation, with resultant root dieback. The crop should be changed each year, and the medium sterilized or changed to prevent root rots.

Owing to the hard water, containing over 150 ppm of Ca as calcium carbonate and over 50 ppm of Mg as magnesium carbonate, crusting of the medium developed, especially when using overhead sprinkler irrigation. With a drip irrigation system less crusting

FIGURE 12.6 Transplanting oregano seedlings. Note: The drip lines were placed immediately after transplanting. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.7 First harvest of mint 58 d after transplanting. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.8 Oregano, thyme, and mint in beds of peat-lite medium. (From California Watercress, Inc., Fillmore, CA. With permission.)

developed. However, it became necessary to rake the surface of the substrate periodically to loosen it.

While the substrate grew the herbs well for almost a year, eventually salt buildup due to the hard water reduced production. After 2 yr, the peat-lite medium was removed and substituted with rice hulls containing about 15%–20% sand. This medium was placed on top of a capillary matting, which assisted in distributing the solution laterally as the rice hulls have little capillary action.

12.3.2 HERBS IN RICE HULLS

As mentioned above, the peat-lite medium accumulated high levels of salt over a period of 2 yr and therefore had to be replaced. In 1999, peat-lite medium was relatively expensive in comparison to rice hulls ($30–$35 per cubic yard vs. $6 per cubic yard).

The beds were constructed somewhat differently from the peat-lite beds. They were built of steel supports with 2 in. × 4 in. treated wood frames and plywood surfaces. Two beds, 4-ft wide by 156 ft (47.5 m), were sloped 2 in. (5 cm) across toward the center and lined with 10-mil black polyethylene (Figure 12.9). Sides were constructed of treated 1 in. × 8 in. boards (2.5 cm × 20 cm).

The system was modified to be recirculating. Plastic gutters or 3-in. PVC pipes were installed in the center where the beds sloped to collect the leachate (Figure 12.10). A capillary matting, as described in Chapter 6, was placed on top of the polyethylene liner to move the irrigation water laterally as the rice hulls have little capillary action. To prevent the rice hulls from floating into the catchment gutter, a painted, galvanized gyproc corner bead was secured to the bottom edge of the bed next to the gutter (Figure 12.11). The beds were filled with 2 in. (5 cm) of rice hull and sand mixture (20% sand) (Figure 12.10).

The irrigation system was modified from the existing drip system used with the peat-lite medium. A 0.75-in. black polyethylene hose with 0.5-in. tees placed every 2 ft (61 cm) along its length was located at the high side of the beds (Figure 12.12). It ran both ways for 25 ft (7.5 m) from 1-in. headers located with vertical lines from a tee every 50 ft (15 m) (Figure 12.12). A controller with a solenoid valve on each bed programmed the irrigation

FIGURE 12.9 Lining double beds with black polyethylene. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.10 Double beds slope to the center catchment trench. (From California Watercress, Inc., Fillmore, CA. With permission.)

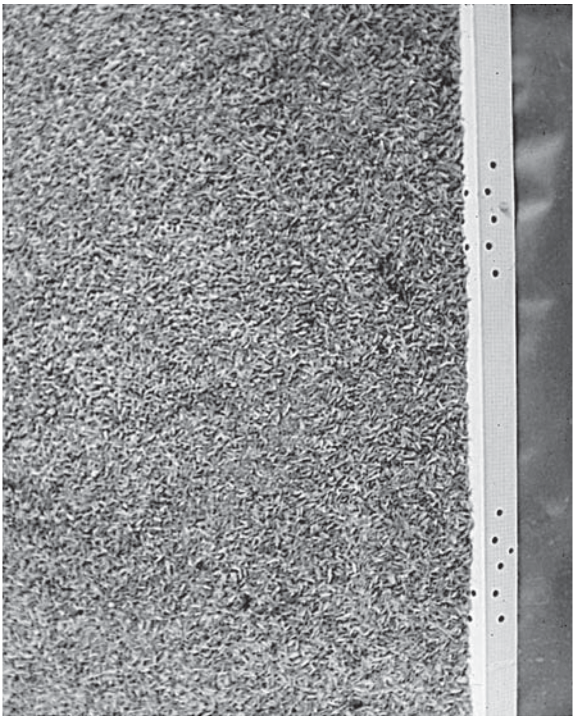

FIGURE 12.11 Gyproc corner bead next to gutter. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.12 Transplanting 4- to 5-wk-old mint cuttings. (From California Watercress, Inc., Fillmore, CA. With permission.)

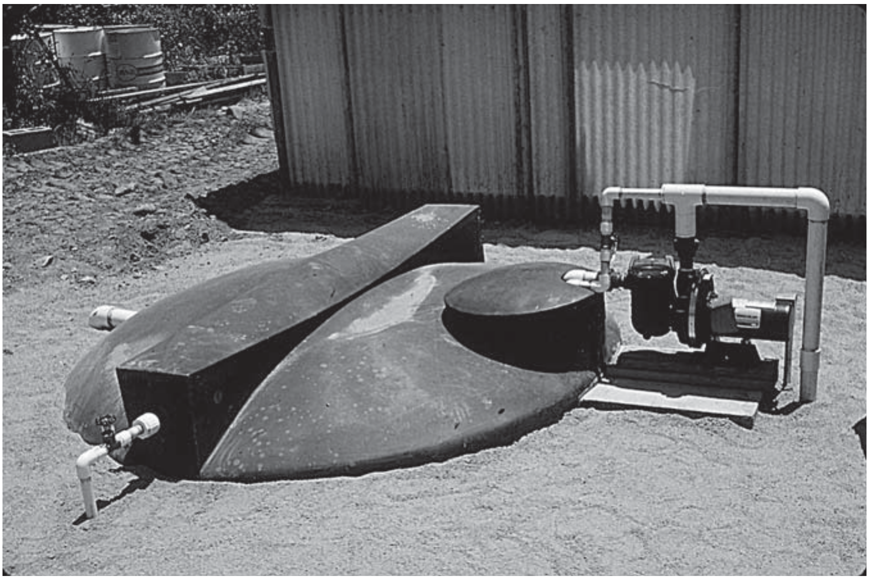

FIGURE 12.13 A 2,500-gal cistern with pump at right. (From California Watercress, Inc., Fillmore, CA. With permission.)

cycles. The leachate collected in the gutter returned to a 2,500-gal (9,462-L) cistern outside the greenhouse via a 3-in. return line (Figure 12.13).

The rice hull mixture must be moistened well before adding it to the beds. A portable cement mixer is useful, but it can be mixed by hand on a concrete slab or on pieces of plywood. If rice hulls are not thoroughly wetted before placing them in the beds, they will not retain water uniformly, especially if the rice hulls are new. The rice hulls generally contain many embryos that will germinate in the beds as water is applied to the substrate.

This grasslike growth must then be weeded by hand. This problem may be reduced greatly by aging the rice hulls several months before use. Moisten the rice hulls with overhead sprinklers for several weeks to germinate the seed. Then, allow it to dry or apply a herbicide (nonpersistent one) to kill the growth. Alternatively, fill the beds with the rice hull substrate, irrigate it to germinate the seeds and then apply a nonpersistent herbicide such as “Roundup.” Transplant after 7–10 d.

Mint was the principal crop. It is vegetatively propagated from shoot cuttings. Stick the cuttings in 200-cell trays using a rooting hormone and placing them in a coarse peat-lite medium. Place the trays in a propagation house having overhead misting. Within 4–5 wk the cuttings root and are ready to transplant to the growing beds (Figure 12.12). They are transplanted at 3 in. × 3 in. (7.5 cm × 7.5 cm) spacing so that a full crop will establish within 3 mo. The first and second harvests (first and second month, respectively) will produce 50%–70% of the fully mature harvests (Figures 12.14 and 12.15).

The mint crop, together with the rice hull substrate, needs to be changed every year to maintain high yields. This is done during the summer months when prices are depressed. The key function of the rice hulls is to keep the surface of the underlying capillary mat dry to prevent fungus gnats, algae, and snails from infesting the substrate. With experience it was found that rice hulls alone without the sand additive was better because the sand settled to the bottom of the rice hulls and impeded the flow of irrigation across the bed. Slightly more depth, up to 3–4 in. (8–10 cm) of rice hulls alone on top of the capillary matting, improved aeration and eliminated pest problems with fungus gnats and snails.

With the rice hulls, initial mint production ranged from 250 to 300 dozen bundles per bed of 1,200 ft^2 (111 m^2). This rose to 450–500 dozen bundles per bed during its optimum growth.

Herbs are sold normally as dozens of bundles, which is a variable measure. The size of bundles is a function of the person harvesting and market demand. When the market is short of supply and good quality, growers may harvest smaller sized bundles, resulting in

FIGURE 12.14 Mint ready for first cut 31 d after transplanting in rice hulls. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 12.15 Fully established mint 36 d after previous harvest. (From California Watercress, Inc., Fillmore, CA. With permission.)

higher numbers of bundles harvested per lineal foot of bed length. In general, with thyme, oregano, basil, and mint, one dozen bundles are equivalent to 1 lb during summer, while during winter two dozens make up 1 lb.

Owing to bundle size variability and corresponding weight differences, the market now wishes to use weight measurement. The trend is now to market high-quality herbs in attractive packaging for supermarket sales. Bulk sales to restaurants should be in boxes with a plastic bag liner containing 1–2 lb (454–908 g) of product.

12.4 FOAM CULTURE

Houweling Nurseries Oxnard, Inc., Camarillo, California, grew 20 acres (8 ha) of tomatoes in foam slabs in 1997. The foam slabs were of the same dimensions as rockwool slabs (Figure 12.16). They felt that the foam might have better aeration than rockwool. Similar to rockwool, five to six plants were grown on each slab, and the plants trained in a V-cordon configuration. Plants were started in rockwool cubes and blocks as for rockwool culture. The foam could be steam sterilized between crops and then wrapped with white polyethylene in the rows.

The layout of plants and the irrigation system was the same as for rockwool culture (Figure 10.8). Irrigation was by an injector system with stock tanks. The 20-acre (8-ha) complex was separated into six sections. Each plant was irrigated with an individual drip emitter and line. Leachate ran to drainage pipes situated in the ground underneath the plant row. This was an open system.

Production was less than expected from a comparable rockwool or sawdust culture system. They encountered a lot of localized dry spots in the slabs, which reduced plant yields. For this reason, in subsequent crops they changed back to rockwool and sawdust cultures, with which they had more experience and better results.

FIGURE 12.16 Foam slabs for growing tomatoes. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

There is potential in using foam culture for vine crops, but it will require trials on a smaller scale to determine the frequency and period of irrigation cycles to obtain optimum yields. A large greenhouse complex should not attempt to use the foam substrate until they have grown several crops with it in a small section of their greenhouse. Further information on the use of foam in hydroponics is presented by Cook (1971) and Broodley and Sheldrake (1986).

12.5 PERLITE CULTURE

12.5.1 Perlite Blocks and Slabs

Perlite blocks are becoming a competitive alternative to rockwool blocks. They are gaining popularity in the propagation of young tomatoes, peppers, cucumbers, and eggplants. A Belgium company, Willems Perlite NV, claims that millions of these seedlings are grown in perlite. The seedlings in perlite blocks are grown in large nurseries using the ebb and flood system as was described in Chapter 6 (Figure 12.17). They claim that these blocks with their transplants grow more generative plants on slabs of perlite, coco coir, and peat. They attribute this growth to the optimum combination of water and air regulation that develops many fine and active roots (Figure 12.18). They state that the blocks do not dry out on other substrates because of their strong capillarity.

Perlite culture is an alternative to rockwool culture (Gerhart and Gerhart, 1992; Munsuz et al., 1989). In Great Britain, it is considered the third most important hydroponic system behind rockwool and NFT. Day (1991) states that it is mainly used in Scotland and the north of England for growing 16 ha (40 acres) of greenhouse tomatoes. At present, rockwool culture is still the most important hydroponic system. In 2008, the largest greenhouse complex in the United Kingdom, Thanet Earth, was begun in East Kent on the Isle of Thanet, near Birchington. Three of the planned seven greenhouses were constructed by 2010. When the seven greenhouses are completed, they will occupy 91 ha or about 220 acres under glass

FIGURE 12.17 Pepper transplants growing in perlite blocks. (From Willems Perlite NV., Belgium. With permission.)

FIGURE 12.18 Large root system with many fine and active roots in perlite block. (From Willems Perlite NV., Belgium. With permission.)

and house 1.3 million tomato, pepper, and cucumber plants. The greenhouses are high-tech Dutch glasshouses using rockwool culture. As a result, with this new operation rockwool remains the most important hydroponic cultural system in Great Britain.

The perlite-slab system is set up in the same way as rockwool culture, with similar drip irrigation design using an injection system. Seedlings are started in rockwool cubes and transplanted to rockwool blocks several weeks before transplanting to the perlite slabs. The pH and EC of the nutrient solution entering and leaving the perlite slabs must be monitored and recorded, and adjustments made to the formulation and watering cycles as required, maintaining an optimum feeding program. The number of cycles, duration of each cycle, formulation, and leachate rate must all be monitored. The leachate may vary up to 25%–30% depending on the status of the growing slab and crop performance. About 1–1.5 in. (2.5–4 cm) of solution is maintained in the slab as a reservoir by cutting a slit in the side of the slab facing the irrigation line at a height of 1–1.5 in. (2.5–4 cm) up from the bottom. Coarse perlite is used as the substrate. After cutting holes in the top of the bag for the plant sites, the rockwool blocks are placed in these positions and a drip line placed at each block.

In 2005, one greenhouse in Naica, Mexico, near Chihuahua, was growing cherry tomatoes in slabs of perlite (Figure 12.19). Their production was very good, as can be seen from Figure 12.19.

12.5.2 PERLITE BATO BUCKETS

The use of "bato buckets" for perlite culture originated in Holland. This system permits recirculation of the solution as the buckets sit on a drainpipe. While the bato bucket system may use substrates other than perlite, such as lava rock, sawdust, peat-lite, rice hulls, or coco coir, the most common is perlite. With sawdust, peat-lite, rice hulls, or coco coir, it would be difficult to recycle the nutrient solution because of salt buildup in the medium. Also, since the siphon mechanism of the bato buckets keeps about 0.5 in. (~1.2 cm) of

FIGURE 12.19 Cherry tomatoes in perlite slabs.

FIGURE 12.20 Bato bucket system using lava rock substrate. (From Agros, S.A., Querataro, Mexico. With permission.)

solution in the bottom of the pot, it would cause aeration problems with media such as sawdust, peat-lite, or coco coir. The bato bucket system is best adapted to perlite and lava rock.

One company in Queretaro, Mexico, Agros, S.A. de C.V., is growing 33 acres (13 ha) of tomatoes successfully in a bato bucket system with a lava rock medium (Figure 12.20).

CuisinArt Resort & Spa in Anguilla is growing about 10,000 ft^2 (approximately 1,000 m^2) of vine crops in a perlite bato bucket system. European cucumbers, beefsteak and cherry tomatoes, peppers, and eggplants are grown in the system (Figures 12.21 through 12.24).

The layout for the bato bucket system is somewhat similar to that of rockwool culture. The main difference is the installation of the drainpipe before setting out the buckets. A white-on-black polyethylene floor liner is laid out once the main drain headers (returns to cistern) have been installed. In the CuisinArt project a vinyl floor liner was placed on top of the underlying substrate before installing the return drains. Six inches (15 cm) of sand fill was placed on top, and finally after placing the pots and drain lines, 3 in. (7.5 cm) of coral gravel was put on top of the sand to give a clean surface (Figure 12.24).

The bato buckets were placed on top of the drainpipes, which were spaced at 6-ft (1.8-m) centers within the drainpipes. The buckets were spaced at 16-in. (40.6-cm) centers. Placing two tomatoes, peppers, or eggplants per bucket and one European cucumber per pot gives the standard spacing for these crops.

The bato buckets are made of rigid plastic, measuring 12 in. × 10 in. × 9 in. deep (30 cm × 25 cm × 23 cm), as shown in Figure 12.25. Their volume is approximately 4 gal (16 L) if filled within 1 in. (2.5 cm) of the top. They have a 2 in. × 1.5 in. (5 cm × 4 cm) indentation at the back of the base of the pot that lets the pot sit on top of a 1.5-in.-diameter drainpipe. Our experience with cucumbers and tomatoes indicated that the 1.5-in.-diameter drainpipe was too small, causing a lot of root buildup in the drainpipe. The drainpipes were later changed to 2 in. diameter. A 0.75-in.-diameter double elbow forms the siphon from the bottom of the pot into the drainpipe (Figure 12.25). This siphon keeps the moisture level in the pot at about 0.5 in. (~1.2 cm) depth. This reservoir of solution is important in perlite and any type

FIGURE 12.21 Beefsteak tomatoes in bato buckets of perlite. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.22 Three-month-old eggplants in bato buckets of perlite. (From CuisinArt Resort & Spa, Anguilla. With permission.)

of gravel medium. The siphon drains directly into the drainpipe on which the pot sits at one end. Be careful to use coarse perlite (Figure 12.26) and do not pack it into the bato bucket, as this may plug the drain siphon. Avoid using fine perlite. The pots are staggered one side to the other along the drainpipe at 16-in. (40.6 cm) centers (Figures 12.25 and 12.26).

The drip irrigation system supplies nutrients via a 0.5-in. black polyethylene hose having a 0.5-gal/h (2-L) compensating emitter connected to a drip line and stake at the end

FIGURE 12.23 Peppers 4 mo from seed, ready to harvest. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.24 European cucumbers 6 wk from sowing ready to harvest. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.25 Placing siphon elbows in bato buckets. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.26 Filling bato buckets with coarse perlite. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.27 Injection system. (From CuisinArt Resort & Spa, Anguilla. With permission.)

(Figure 9.15). A special grooved stake that conducts the solution down its length is very useful in directing the solution to each plant. We found that three drip lines per cucumber were needed, while two lines were suitable for tomatoes, peppers, and eggplants. The rest of the irrigation system is the same as for rockwool or sawdust culture employing stock tanks and injectors as illustrated in Figure 12.27, or a central cistern from which the solution could be recirculated after sterilization.

The bato bucket system grows healthy, highly productive vine crops. Occasionally a few bato buckets become plugged and fill up with solution. This occurs if any compaction of the perlite causes the siphon elbow to plug.

12.5.3 Eggplants in Perlite Culture

The author has grown eggplants successfully in bato buckets of perlite at the hydroponic farm at CuisinArt Resort & Spa, in Anguilla in the Caribbean. The eggplants were sown in 1.5-in. (3.75-cm) rockwool cubes and after 3 wk transplanted to 3-in. (7.5-cm) rockwool blocks. They are transplanted to the perlite system within 5–6 wk from sowing. This initial sowing and transplanting is very similar to tomatoes. Similar to tomatoes and peppers, two plants are placed in each bato bucket. Place a drip line at the edge of the rockwool block of each plant. The plants are trained vertically with plastic vine clips attached to the string from the overhead support cable. As with peppers, twice as many support strings will be needed than for tomatoes as two main stems per plant are permitted to grow.

Training of the plants is more similar to peppers than tomatoes, as they are permitted to bifurcate once to form two stems (Figure 12.28). Similar to peppers, the two most vigorous stems are permitted to grow while any additional ones are removed at an early stage in their growth, usually about 8 wk from sowing (or 2–3 wk after transplanting to the bato buckets).

Continue to maintain these two leader stems on the plant. If one should weaken and an adjacent plant forms a vigorous side branch, it could be used to train it onto the neighboring support string to replace the weak stem of the other plant. Side shoots should be allowed to form one fruit. Once one fruit has set on a side shoot, cut the tip to stop it from growing further. This is similar to training the pepper side shoots.

Eggplants have very big flowers that easily release pollen (Figure 12.29). They must be pollinated similar to tomatoes. This can be done with bumblebees, or for small operations one can use a tomato "tickler" (Figure 12.30). Daily pollination is critical to good fruit set and high yields.

Eggplants yield very heavily initially and then their growth slows, as the fruit production draws heavily on their nutrients (Figure 12.31). Once fruit is removed, the plant will set more fruit above.

FIGURE 12.28 Train eggplants to two stems. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.29 Receptive eggplant flower ready to pollinate. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.30 Pollination of eggplant using "Petal Tickler." (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.31 Initial heavy yields of eggplants. (From CuisinArt Resort & Spa, Anguilla. With permission.)

The eggplants will grow to about 12 ft (3.7 m) during a growing season. It is preferable, like peppers, not to lower them, as lowering shocks the plants. When lowering the plants, such as tomatoes, generally three leaves are removed weekly. This is not possible with eggplants, as they suffer too much by such a practice and will become stressed, resulting in small fruit. The best practice is not to lower the plants. The greenhouse at CuisinArt Resort & Spa has sidewalls of 10 ft (3 m) to withstand hurricane winds of up to 150 mph (240 kph). For this reason, the eggplants must be lowered. This results in a reduction in fruit size. In this situation, it is better to use two crops annually. The old stems could be cut back to several side shoots formed at the base of the plant, and these new shoots allowed to replace the tall old stems (Figure 12.32) but production is not as good as with new plants.

Mini bush eggplants have also been grown in plant towers with a perlite substrate. Their cropping schedule is 3–4 mo (Figure 12.33).

12.6 COLUMN CULTURE

The growing of plants in vertical columns was developed in Europe, particularly in Italy and Spain. This system originated from the use of barrels or metal drums stacked vertically and filled with gravel or a peat mixture. Holes were punched in the sides around the

FIGURE 12.32 Eggplant base shoots growing 8 d after cutting back. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.33 Mini eggplants in plant towers. (From CuisinArt Resort & Spa, Anguilla. With permission.)

containers in order to place the plants into the medium. Later, asbestos–cement pipes with spirally positioned holes were used.

Watering and feeding was supplied by a trickle irrigation system mounted at the top of each column. If gravel was used as a medium, the nutrient solution could be recycled by placing the column over a collecting trough, which conducts the solution back to a centrally located reservoir.

A more recent development in column culture is the use of Styrofoam pots stacked vertically. Verti-Gro, Inc. of Florida developed this culture. The system was originally designed for growing strawberries, but it soon became evident that it could be used for herbs, spinach, lettuce, and other low-profile crops.

Styrofoam pots of dimensions 9 in. × 9 in. × 8 in. deep (23 cm × 23 cm × 21 cm) with slightly tapered sides are stacked one on the other by offsetting their orientation by 45° (Figure 12.34). They have special grooves on the topsides to fit the base of the pot above. The volume of each pot is 0.1 ft^3 (2.8 L). In general, 7–10 pots are stacked to form the tower. The number of pots depends on the crop to be grown and the available sunlight conditions. For herbs, every corner of each pot is sown, whereas for bush peppers or tomatoes, with a seven-pot plant tower, every other pot is planted with the ones between left empty to act as a spacer. A collection pot can be placed at the bottom of the plant tower to collect the leachate and pipe it to a drainpipe for recirculation of the solution. If a pan or bucket filled with gravel to collect the drainage is used, a 0.75-in.-diameter tee with a 4-in. (10-cm)-long piece of 0.75-in. pipe inserted in each opening of the tee forms a base of the standpipe, keeping the pots from shifting their position. This base is placed at the bottom of the pot or

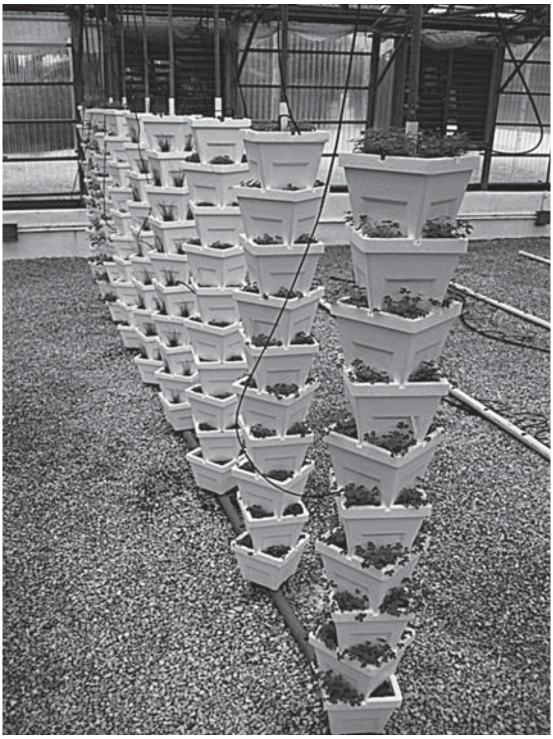

FIGURE 12.34 Herbs in plant towers 1 mo after sowing. (From CuisinArt Resort & Spa, Anguilla. With permission.)

bucket filled with gravel (Figure 12.35). The Styrofoam pots have holes in the bottom for drainage to the one below. In addition, each pot has a 1-in.-diameter hole in the center for the pipe guide to pass. The conduit support pipe is passed into the top of the 4-in. (10-cm) riser from the tee after the conduit passes through a 3 in. × 3 in. × 0.2 in. (8-cm × 8-cm × 0.6 cm) thick swivel plate. The swivel plate is a spacer between the two pieces of 0.75-in.-diameter sleeves supporting the plant tower pots. It allows the grower to rotate the towers easily for light orientation to the plants. This will produce more uniform growth by exposing the plants to an equal amount of sunlight. This is particularly important in the more northerly latitudes where sunlight casts shadows during the day.

When assembling the towers, the Styrofoam pots are slid over the conduit and 6.5-ft (2-m) plastic pipe sleeve. Fill the pots with a perlite–coco coir mix (85%–15%) sequentially from the lower pot up, placing the next pot into the topside grooves once the lower pot is filled with substrate (Figure 12.35). Other substrates can be used, from coco coir alone to coarse perlite by itself, depending on the crops to be grown and local climatic conditions.

Finally, attach the conduit to an overhead support cable or galvanized pipe with galvanized tie wire. Alternatively, the conduit can be supported in the substrate below by first pounding in a larger diameter section, about 3 ft (1 m) in length and then slipping the smaller diameter pipe into it (Figure 12.36). One-inch tees placed at the top of each support pipe act as a guide for passing the black poly irrigation lateral (Figure 12.37). Then, attach the drip irrigation lines coming from the black polyethylene irrigation hose above the pot towers into the top pot and one at about halfway down the tower (Figure 12.37). The nutrient solution enters the pot on top and trickles down to the others below.

FIGURE 12.35 Filling of pots with coarse perlite. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 12.36 Placing base conduit support in soil.

FIGURE 12.37 Plant towers in double rows outside with peppers. (From Verti-Gro, Inc., Summerfield, FL. With permission.)

The collection bucket sits on top of a 1.5-in.-diameter drainpipe, which can return the solution to a cistern or conduct it away from the greenhouse to waste. Towers are spaced about 3 ft (90 cm) apart within rows, and rows are 4 ft (1.2 m) apart. Allow from 10 to 14 ft^2 (1.0–1.3 m^2) per tower. This is equivalent to 36 in. (0.9 m) within rows and 47 in. (1.2 m) between rows. Closer spacing is possible in more southern locations and with smaller crops as some herbs.

Each plant tower will grow at least 40 strawberries, lettuce, or bok choy when using 10 pots per tower (Figure 12.38). Herbs that are sown in clumps will have many more plants

FIGURE 12.38 Plant towers of bok choy. (Courtesy of CuisinArt Resort & Spa, Anguilla.)

per tower, but the same number of clumps. Plants are transplanted or sown directly into the corners of each pot. Many herbs may be seeded directly into the pots, but it is better to use transplants for lettuce, bok choy, and of course strawberries to save time.

The pot column system is capable of producing six to eight times as much per unit area as equivalent field crops and three to four times as much as greenhouse bench crops. The plant density for lettuce, spinach, herbs, and strawberries is about three plants per square foot (32 plants per square meter) or 131,000 plants per acre (320,000 plants per hectare). One column of strawberry plants should produce between 10 and 13 pt of fruit per month. One acre (3,200 towers) (8,000 towers per hectare) should produce from 23,000 to 35,000 lb (10,500–15,700 kg) of strawberries monthly, which is equivalent to 31,500–41,000 pt. One acre of field crop having 17,500 plants produces from 4,000 to 6,000 pt/mo. Column culture grows about eight times as many plants in the same area as field cultivation.

In 1997, the author presented a paper on this type of column culture at the International Conference of Commercial Hydroponics at the Universidad Nacional Agraria La Molina, Lima, Peru (Resh, 1997). Interest in this column culture led to the development of a commercial installation at Cieneguilla, northeast of Lima, by Productos Hidroponicos ACSA. They worked with Mr. Alfredo Delfin of the Center of Hydroponic and Mineral Nutrition Investigation at the university to develop a Styrofoam pot tower similar to Verti-Gro (Figure 12.39) (Rodriguez Delfin, 1999). Their 4,000-m^2 (1-acre) facility had 3,000 pot columns with 10 pots per tower. With 40 strawberry plants per tower they grew a total of 120,000 plants. Four sectors were irrigated twice a day for 20 min per cycle. The substrate was composed of pumice and peat. Production varied from 125 to 600 kg (275–1,320 lb)

FIGURE 12.39 Strawberries in plant towers in Peru.

daily during winter and summer seasons, respectively. The objective was to produce 500 g of fruit per plant. The university also experimented with the traditional sack culture of strawberries for tropical conditions.

12.7 SACK CULTURE

Sack culture is a simplification of column culture (Linardakis and Manios, 1991). The system is basically the same except that polyethylene "sacks" are used instead of rigid drums, pipes, or pots. Black layflat 0.15-mm-thick polyethylene of about 6 in. (15 cm) diameter and 6 ft (2.0 m) length is filled with a peat–vermiculite mixture or any other substrate such as a coco coir mix. The bottom end is tied to prevent the medium from falling through, and the top end is tied to constrain the medium into a sausagelike form. The top end is tied by a wire or rope to the greenhouse, and the sack hangs down, giving a column effect.

Watering and feeding is automated by the use of a trickle drip line system to each sack from a central nutrient reservoir or fertilizer injector. Small holes 2.5–5 cm (1–2 in.) in diameter are cut around the sack's periphery, into which plants are placed (Figure 12.40). The nutrient solution is applied at the top end of the sack and percolated down through the entire sack.

The sacks, supported by the greenhouse superstructure or other supports, are spaced 80 cm (32 in.) apart within the rows, and the rows are spaced at 1.2 m (about 4 ft).

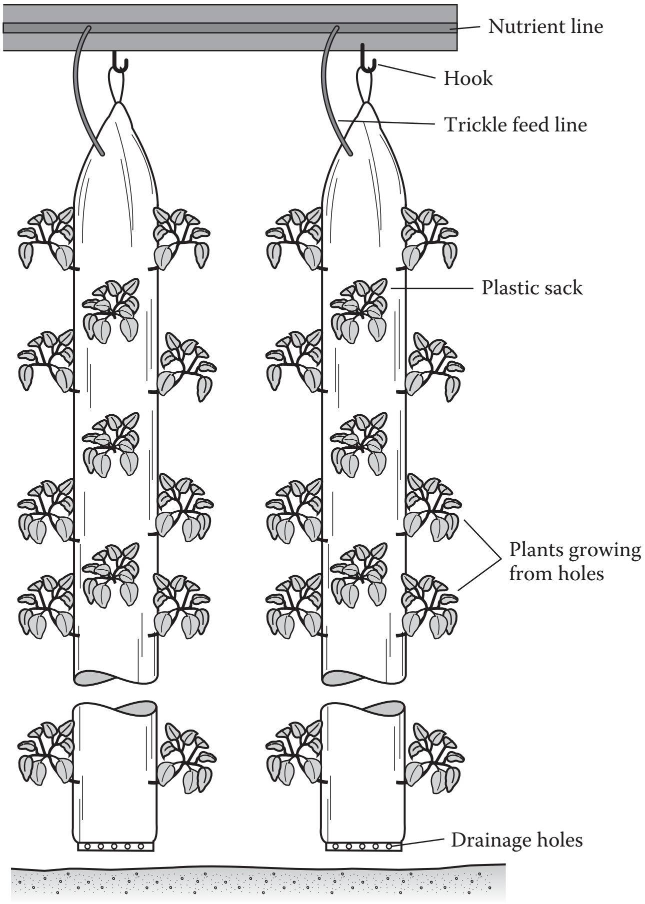

FIGURE 12.40 Schematic of hanging sack culture system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

Watering and feeding cycles are generally from 2 to 5 min, giving a volume of 1–2 L of nutrient solution per sack per irrigation cycle. The number of cycles per day depends on the plant stage of growth and weather conditions. Nutrients are not recycled but allowed to percolate from the top to the bottom of the sack and out the drainage holes. At the end of each growing period, the entire sack and substrate is disposed of and new ones are made up with sterile medium.

This system is particularly useful for lettuce, herbs, strawberries, and other low-profile plants, which normally require a lot of greenhouse floor area with little utilization of the vertical space. However, tests with bush varieties of tomatoes, peppers, eggplant, cucumbers, and other vegetables had been successful experimentally (Tropea, 1976).

A company in Bogota, Colombia, FRESEX, has been growing 8 ha (20 acres) of strawberries in sack culture from the late 1990s. The farm is located near Bogota at high elevation in an area of conventional field-grown strawberries. Field production of strawberries encounters many disease problems, resulting in reduced yields. For this reason, the company turned to an alternative method using a hydroponic system of sack culture. In 1997, the farm had 30,000 sacks with 28–30 plants each, giving a total of 800,000 plants.

FIGURE 12.41 Support of strawberries in sack culture in Colombia. (From Fresex, Bogota, Colombia. With permission.)

FIGURE 12.42 Sacks tied into seven sections. (From Fresex, Bogota, Colombia. With permission.)

With the tropical climate of the region, greenhouses are unnecessary. Simple systems of wooden posts and cross members support the sacks. The sacks are filled with a medium of 75% rice hulls and 25% coal ash (scoria). The 15 cm (6 in.) diameter by 2 m (79 in.) long sacks of 8-mil thickness are tied to the wooden cross members (Figure 12.41). Spacing is 0.8 m (31.5 in.) within rows and 2 m (6.5 ft) between rows. The sacks are tied into seven sections, each to prevent settling of the medium and resultant compaction (Figure 12.42). Four plants are set into each section to give at least 28 plants per sack. Drainage is through 10 holes punched in the lower heat-sealed end of the sacks. The leachate flows from the base of the sacks into a drainage ditch below, which takes the spent solution to waste (Figure 12.43). It is not recirculated.

A drip irrigation system distributes the nutrient solution to the sacks from a large central cistern. Two 0.5-in.-diameter black polyethylene laterals run along the wooden cross members from a PVC main. Drip lines enter the sacks at four sections (Figure 12.44) going down and around the sacks. About three to six irrigation cycles per day provide from 3 to 6 L (3–6 qt) per sack depending on weather conditions and crop maturity.

The most widely used varieties of strawberries are “Chandler” and “Sweet Charlie,” which are purchased from California as small plants. Yields range from 500 to 900 g (1–2 lb) per plant over a 7-mo cropping period (Figure 12.45). The objective is to produce from 800 to 900 g per plant. The company exports strawberries to North America, Europe, and the Caribbean, with the strongest sales from November through January. With the low capital cost of installing an outdoor sack culture system, the return on investment should be attractive.

FIGURE 12.43 Drainage at base of sack. (From Fresex, Bogota, Colombia. With permission.)

FIGURE 12.44 Drip irrigation system to sacks. (From Fresex, Bogota, Colombia. With permission.)

12.8 STERILIZATION OF MEDIUM

All the media mentioned in this chapter must be sterilized either chemically or by steam, as outlined in Chapter 8.

12.9 ADVANTAGES AND DISADVANTAGES OF PEAT AND COCO COIR MIXTURES

The advantages of peat and coco coir mixtures are as follows:

1. Similar to sand and sawdust cultures, they are open systems; therefore, there is less spread of diseases such as *Fusarium* and *Verticillium* wilts, especially in tomatoes.
2. The problem of plugging drainage pipes with roots does not occur.
3. There is good lateral movement of nutrient solution throughout the root zone.
4. There is good root aeration.
5. A new nutrient solution is added during each irrigation cycle.
6. The system is simple and easy to maintain and repair.
7. The high water-holding capacity of the medium reduces risk of water stress should a pump fail.

FIGURE 12.45 High strawberry yields in sack culture in Colombia. (From Fresex, Bogota, Colombia. With permission.)

8. It is adaptable to fertilizer injectors, and therefore less space is required for storage tanks.
9. Peat, perlite, and vermiculite are generally readily available in most regions of the world. This is also true for coco coir, and in addition, coco coir is a “sustainable” substrate.
10. Sack culture enables a greenhouse operator to efficiently utilize vertical space for crops such as lettuce and strawberries, which normally use a large amount of floor area. Therefore, a much greater number of plants can be grown in a given area of greenhouse.
11. Sack and column cultures keep plant parts and fruit off the underlying medium, thus reducing disease problems of fruit and vegetation.

The disadvantages of peat and coco coir mixtures are as follows:

1. The medium must be sterilized between crops by steam or chemicals, which requires more time than in gravel culture. However, sterilization is very thorough.
2. Over the cropping season, salt accumulation can build up in the medium to toxic levels. Proper and regular leaching (at least 25%) with each irrigation cycle will overcome this problem.

3. Plugging of drip feed lines may occur if proper filters are not used or if cleaning of these filters is neglected.
4. Since peat is organic in nature, it decomposes over time with continual cropping. Between crops it should be cultivated and additional peat must be added. Coco coir does not decompose as readily as peat.
5. Perlite, pumice, and vermiculite break down with continued use, resulting in compaction of the medium. For this reason, the peat mixtures are generally replaced between crops, resulting in replacement costs (of both medium and labor) each year.
6. If compaction occurs during the cropping period, root aeration will be greatly restricted, resulting in poor crop yields. Both the original mixture ratios and handling are important to prevent compaction.

In summary, peat mixtures are used extensively in container-grown plants. In beds, sand, rice hulls, coco coir, or sawdust would be more suitable. In sack culture, peat, rice hulls, coco coir, or sawdust are most suitable because of their light weight. Of these cultures, perlite bags and coco coir slabs offer the most potential for future commercial production of vine crops.

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13 Tropical Hydroponics and Special Applications

13.1 INTRODUCTION

Over the past 15 yr, there has been a great interest in hydroponics in tropical countries worldwide (Lim, 1985; Resh, 1998; Resh et al., 1998; Rodriguez Delfin, 1999a, 1999b; Mills, 1999; Furukawa, 2000; Wilson, 2000). A lot of commercial hydroponic operations have begun in Australia, China, Indonesia, Mexico, and Central and South America. Recently, in February 2011, news (www.freshplaza.com) was released on the opening of the largest greenhouse in Australia. It is located near Adelaide at Two Wells. The $65-million, 17-ha (42.5-acre) facility is projected to produce 11 million kilograms of truss tomatoes annually. The company is d'VineRipe (http://dvineripe.com.au). They are using raised trays with rockwool substrate slabs.

As economies in some of the less developed countries improve with control of inflation and political stability, the standard of living will rise. With improved economic conditions, new opportunities create a larger middle class of people who can afford to demand higher quality fresh vegetables. Brazil is an example of this progress, and a substantial hydroponic greenhouse industry is developing. At present they are focused on arugula, lettuce, and herbs.

Awareness of quality vegetables opens a market for controlled-environment agricultural crops such as tomatoes, sweet peppers, lettuce, watercress, and other herbs. These will be grown hydroponically to ensure that they are free of organisms that cause diseases such as dysentery and cholera. In tropical areas, most agriculture is located in valley bottoms where water is more plentiful; however, such areas, especially close to large cities, are often polluted because of runoff from residences. This was the reason for the success of Hidroponias Venezolanas in Caracas, Venezuela, in hydroponics (http://hidroponiasvenezolanas.com). This operation is used as an example of the potential use of hydroponics in tropical regions.

13.2 HIDROPONIAS VENEZOLANAS

In the region where the Hidroponias Venezolanas facility was established, local field growers of lettuce and watercress located in valley bottoms used runoff from the surrounding terrain that swept disease organisms into their crops. Much of this product went to restaurants where clients often became sick with dysentery after consuming the fresh salads. This provided an opportunity for Hidroponias Venezolanas to grow salad crops hydroponically with clean, mountain spring water available only on the steep inclinations of the mountain slopes, well above any agricultural field operations. In this situation, the hydroponic farm site was well above any farms or residences, and the area above was a park. Nonetheless, chlorination and filtration systems were installed to guard against any bacterial infestation (Figure 13.1).

FIGURE 13.1 Filtration system of mountain spring water source. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Growing temperate crops in tropical countries presents some unique challenges. With improved economies in many tropical countries, an expanding middle class of people demand clean, safe, and nutritious foods, as they do in other industrialized countries throughout the world. They demand similar diets that include fresh fruits and vegetables.

Such crops, which are not native to the tropics, require specific growing conditions and culture. Strawberries, sweet peppers, eggplants, tomatoes, cucumbers, lettuce, cabbage, celery, cauliflower, beans, watercress, and other herbs are in demand. In many regions of these countries, the climate is not suitable for growing such crops because of excessive temperatures and high humidity. However, in mountainous areas with elevations above 1,500 m (4,900 ft), the temperatures drop sufficiently to allow the growing of cool-season, temperate crops, such as lettuce, strawberries, watercress, cabbage, celery, and cauliflower. Such is the case in Venezuela.

The temperatures in these regions range from 22°C to 28°C (72°F–82°F) during the day and from 16°C to 20°C (61°F–68°F) during the night. Daytime temperatures are at the upper limit of the tolerable range for growing cool-season crops such as lettuce, cabbage, cauliflower, and watercress. Any prolonged variation in daytime temperatures can cause crop failure.

The higher the elevation the crops can be located at the less the chance of experiencing excessive daytime temperatures, which may cause bolting of lettuce, cabbage, and cauliflower or the flowering of watercress. By seeking higher elevations, generally steeper terrain is encountered (Figure 13.2). As a result, conventional farming is very difficult. Small plots of land are cultivated by hand repeatedly year after year. Production declines with fertility, and soil erosion increases with structural breakdown.

13.3 SAND CULTURE IN THE TROPICS

The farm of Hidroponias Venezolanas is located about 40 km from Caracas, in San Pedro de Los Altos. Terraces have been cut into the steep terrain to maximize the available level

FIGURE 13.2 Steep terrain of conventional farming with terraces of hydroponic culture under plastic covers. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.3 View of hydroponic terraces at the farm of Hidroponias Venezolanas. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

ground (Figure 13.3). Each terrace is about one-third of a hectare. As the soil is very rocky and the use of heavy equipment to level the sites is costly, it was decided to construct raised beds of metal frames. The cost of steel and the labor of welding it are relatively low.

The frames of the beds were welded on-site and set into concrete footings as shown in Figure 13.4. The bottoms were constructed of clay bricks and concrete, common building materials of the country (Figure 13.5). The beds were leveled with a thin coat of concrete

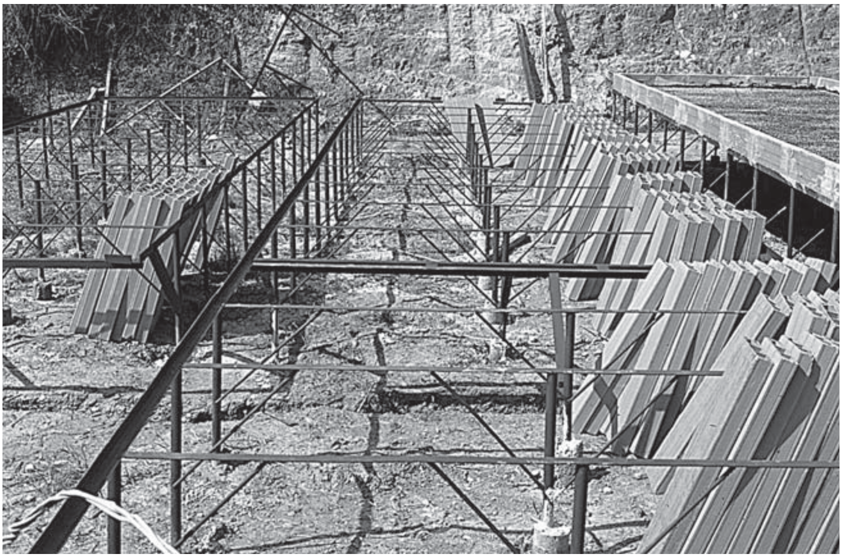

FIGURE 13.4 Steel frames of hydroponic beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.5 Clay brick bottom of hydroponic beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.6 Beds leveled with a coat of concrete. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

and sealed with bituminous paint (Figures 13.6 and 13.7). Drain pipes or clay tiles were placed on the bottom surface to provide adequate drainage (Figure 13.8).

The substrate is quartz (silica) sand with a subirrigation system. Large 50,000-L (13,000-gal) underground cisterns of concrete were built for storage of nutrient solution. Fresh water is pumped from several wells and streams to a number of storage tanks and finally to the one above the hydroponic farm. The water is low in total dissolved salts, a rare and fortunate situation in the tropics. A complex series of piping and plumbing moves the water to the storage tanks. A nutrient solution cistern with a series of beds forms one sector of production. The solution is distributed via pipes and pumps to distribution pipes in each bed (Figure 13.9).

The beds are flooded at one end by entering a PVC header attached to fill-drain lines along the bed length (Figure 13.10). Clay tiles cut in half or PVC pipes with holes placed along the bottom of each bed distribute flow evenly. The drain is plugged manually to allow the solution to rise in the bed to within an inch (2.5 cm) of the sand surface (Figure 13.11). Three pipe plugs of different heights regulate the solution level in the beds. When transplants are first placed into the beds, the tallest pipe plug maintains the level within 1 in. Later, as plants become established, the water level is decreased several times by placing shorter pipe plugs in the drain hole.

Each irrigation cycle takes from 15 to 20 min. The plug is then removed, and the solution flows out of the bed within 10 min, providing good aeration. Four to five irrigation cycles per day are needed for lettuce. To reduce the drain-fill times, new beds are shortened to

FIGURE 13.7 Beds sealed with bituminous paint. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.8 Drain-fill lines in bottom of beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

9 m (29.5 ft), instead of the previous 18–20 m (60–65 ft). The large cistern is divided into five sections of 9,000 L (2,375 gal), with each section having a separate pump and piping to a sector of eight beds (Figure 13.12). This permits filling the beds within 5 min, with a similar drainage time, resulting in improved oxygenation of the plant roots.

Suitable silica sand must be trucked from a distance of over 500 mi and is hence costly. The sand is pure silica of coarse texture normally used in the glass industry. Owing to this

FIGURE 13.9 Distribution pipes from the cistern to the raised beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.10 Nutrient solution enters from main distribution lines to inlet end of the beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

high cost of silica sand, placing a 3- to 4-in. (7.5- to 10-cm) layer of crushed clay bricks on the bottom of the beds over the drain lines reduced sand requirements. Silica sand was placed on the remaining 4–5 in. (10–12.5 cm) of the depth on top of the crushed bricks. The use of crushed clay tiles as a lower medium created problems because of its breakdown into a fine powder over a period of 6 mo. This powder plugged the drainpipes, causing excessive moisture in the roots and crown of the lettuce plants contributing to bacterial soft rot.

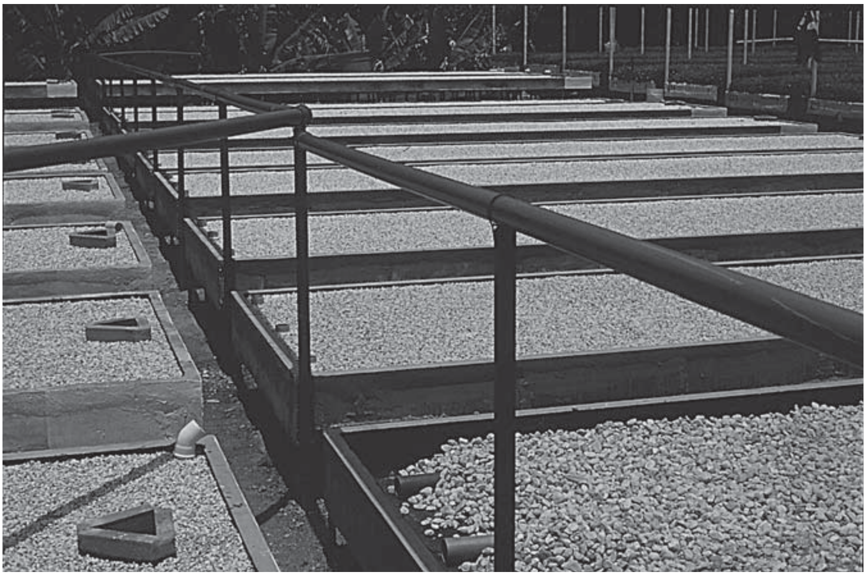

FIGURE 13.11 Inlet mains and drainage ends of beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

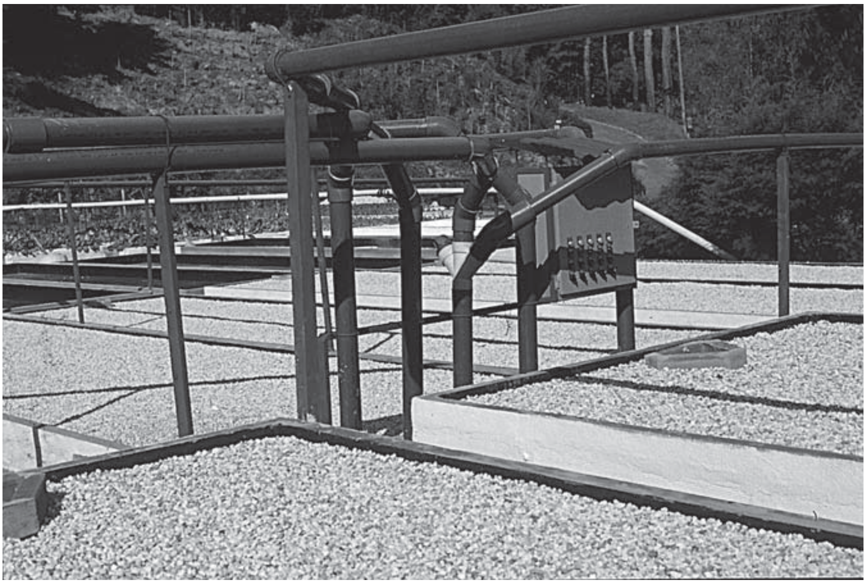

FIGURE 13.12 Distribution system from multisectioned cistern that provides solution to sectors of beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

The solution was to remove the lower layer of crushed clay tile and replace it with coarse granite rock followed by a layer of smaller pebbles before the top layer of sand was added (Figure 13.13).

The availability and cost of construction materials, medium, and fertilizers in a specific location will determine the type of hydroponic system that should be used. In many tropical countries, lumber is scarce and very costly. Generally, steel products, concrete,

FIGURE 13.13 Coarse rock with pea gravel and finally a top layer of coarse sand. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

and clay bricks are readily available and inexpensive. Such is the case in Venezuela, where hydroponic beds are constructed of steel frames, clay bricks, and concrete as outlined above.

In the tropics, where day length and the hours of sunlight vary only slightly from one month to the next, an accurate correlation should exist among electrical conductivity (EC), total dissolved solutes (TDS), concentration of various nutrients, and plant age. There are two seasons in the tropics, a wet season from June through December and a dry season from January through May. While there is more precipitation during the wet season, rainfall is very heavy and over a short period of time each day. Rapid clearing of the sky follows with full sunlight. Therefore, the number of hours of sunlight for any month during the wet season does not differ greatly from that of the dry season. Consequently, the most significant effect on nutrient solutions is that of plant growth stage, rather than the influence of sunlight.

Extremes in rainfall are commonplace. For instance, in the plains of central Venezuela, during the dry season, precipitation is so low that it closely resembles desert conditions with extremely high temperatures over 30°C (86°F), while during the wet season, rainfall is so heavy that the entire region becomes inundated with several feet of water. In such areas, crops can only be grown during the dry season with irrigation.

Even in the mountainous regions the wet and dry seasons are distinct. During the wet season, temperatures are generally a few degrees warmer, and rainfall occurs for several hours almost every day. As a result, crops that cannot tolerate continual moistening are soon damaged and infected with diseases. Such is the case with lettuce, especially head lettuce. Within several weeks of maturity, head lettuce is very sensitive to moisture. Any moisture that penetrates the head causes rotting, which spreads rapidly with high temperatures. Losses of up to 40%–60% are not uncommon.

Since many crops cannot be cultivated during the wet season, short supply raises prices dramatically. An excellent market can be established for hydroponically grown lettuce and other produce if the market can be reliably supplied year-round. Using sand culture in raised beds prevents rainfall from upsetting the growing of crops through excessive root moisture, but moisture onto the plants still causes losses. Several methods help overcome this problem. First, the choice of a very resistant variety that has tightly closed leaves will prevent rainfall from entering the head. Hidroponias Venezolanas has tested over 25 different varieties and found that the best are "Great Lakes 659" and "Montemar." These are resistant to bolting and form large heads. The second possibility was to erect an inexpensive roof above the beds. Placed at several meters above the beds in a saw tooth configuration, the roofs would prevent rainfall, but permit sufficient natural ventilation to keep temperatures within several degrees of the ambient. Fiberglass covers were constructed. The material discolored within a year, and light levels reduced sufficiently to cause bolting at the slightly higher than ambient temperatures.

Experience with the hydroponic farm at CuisinArt Resort & Spa in Anguilla indicates that a polycarbonate material, such as GE's "Lexan," does stand up to the high ultraviolet light of the tropics. After 12 yr, the greenhouse in Anguilla shows very little degradation in light transmissibility of the polycarbonate. The best material for permanent structures in tropical regions would possibly be the twin-wall or triple-wall polycarbonate products, as they would also give higher insulating values than the corrugated, single-layer product. There are other cheaper Chinese products of polycarbonate available, but how they compare with the GE Lexan cannot be predicted. Many of the greenhouse polycarbonate materials, such as "Lexan," have a 10-yr guarantee against yellowing and loss of light transmission.

Growing of head lettuce in areas of high temperatures, 25°C–28°C (77°F–82°F), is difficult because of "bolting," which occurs above these temperatures. With a slight reduction in light from the use of a fiberglass or polyethylene cover, bolting occurs at lower temperatures (25°C–27°C).

For this reason, a temporary cover that could be easily and quickly removed would be beneficial to the growing of many cool-season crops. Polyethylene retractable roof greenhouses now available commercially may be the answer for the tropics. Motorized roll-up roofs may be deployed within several minutes. The roofs cover the crop as soon as rain is detected and open when the threat of rainfall passes. In this way, the crop still can grow under ambient temperatures and light, reducing the incidence of bolting and bacterial soft rot.

In the tropics, year-round warm temperatures generate large insect populations. When crops are grown hydroponically outside without the protection of closed greenhouses, insects quickly invade the crops and rapidly spread with few or no natural predators. The use of pesticides is imperative. Often pesticides are unavailable and those, which are, may soon become ineffective because of the buildup of insect resistance. Without the introduction of new pesticides to overcome such resistance, control diminishes until crop losses occur.

In the past, pesticides applied with a backpack sprayer controlled leaf miners infesting the lettuce. Later, by using sticky traps, spot spraying of infested areas, and removal of infected leaves, adequate control was achieved. Assisting this control is a natural predatory wasp. In the future, predators must be imported or local laboratories established to raise them in order that a good integrated pest management (IPM) program can be the principal method of control. These control measures for pests are discussed in Chapter 14.

Nematodes infest most soils in tropical countries. These are very small microscopic roundworms, sometimes called *eelworms*, which infest the roots of plants. Depending on the species involved, they may cause death of roots, injuries to roots that act as ports of entry for fungal diseases, or swelling of roots so that they cannot function in normal water and mineral uptake. This root damage often causes plants to wilt during the day when water uptake cannot meet evapotranspirational losses. If plants do survive the stress, they become stunted and nonmarketable.

Soil temperature is critical in the development of nematodes. Females fail to reach maturity at temperatures above 33°C (92°F) or below 15°C (59°F). Soil temperatures in the tropics are near optimum levels for nematode development. It takes about 17 d at 29°C (85°F) for females to develop from infective larvae to egg-laying adults. Spreading within the field occurs through movement of infested soil or plant debris by man, water, and wind.

Even with hydroponic culture, nematodes can easily be introduced into a crop by movement through water or wind. Preplanting treatments with steam or chemicals effectively eliminate nematodes from soil and other media such as sand, sawdust, or gravel used in hydroponics. Nematodes are killed with steam sterilization, by heating the medium under moist conditions for 30 min to 49°C (120°F). This and chemical methods of sterilization are described in Chapter 4.

Hidroponias Venezolanas successfully used Basimid, a soil fumigant, for the control of unencysted nematodes in sand culture. However, the pesticide had to be imported from North America, so there could be long delays in obtaining it. Subsequently, steam sterilization generated by a portable steam boiler gave similar results. Perforated pipes were placed several inches below the surface of the medium in the beds. The entire bed was covered with a heavy vinyl or canvas tarpaulin.

Generally, it takes several hours to raise the temperature of the medium throughout the bed to 60°C–82°C (140°F–180°F). It is best to moisten the medium before sterilizing, as the moisture carries the heat uniformly throughout. This process is really pasteurization, not sterilization, as it is best not to use as high a temperature as would be required for sterilization, since only the detrimental organisms must be killed. If lower temperatures between 60°C and 80°C (140°F–180°F) are used, many beneficial organisms will remain alive. It may be disadvantageous to sterilize the medium and kill all organisms, as after sterilization any organisms can be easily introduced into the medium. With pasteurization at slightly lower temperatures, only the pest organisms will be killed. Beneficial organisms can then resist reinoculation by detrimental ones.

Hidroponias Venezolanas no longer uses Basamid or steam sterilization to control nematodes. Between lettuce crops they flood the beds with water for several hours to float the old roots to the surface, removing them by hand. After draining, the beds sit empty for several days. Sunlight raises the temperature of the sand sufficiently to kill any nematodes. In addition, with chlorination and filtration of all the raw water entering the hydroponic systems, these organisms are substantially reduced.

Once this multitude of problems can be resolved, excellent lettuce crops can be grown under tropical conditions using hydroponics (Figure 13.14). When most problems were resolved, each hydroponic bed 2.5 m × 20 m × 25 cm deep (8.4 ft × 65.6 ft × 9.8 in. deep) was capable of producing 310–330 heads of lettuce, each averaging 1 kg (2.2 lb) in weight. In a continuous cropping system, new plants were sown every day so that harvesting could be done at least three times a week. In this way, the market can be supplied year-round. Consistent supply to the marketplace is essential if long-term contracts are to be met. This reliable servicing of the market is the basis for establishing a strong market, with a constant premium price to be received for the hydroponic products.

Head (iceberg) lettuce takes between 70 and 75 d from seeding to harvest. The lettuce seedlings are started in a special propagation area. Seeds are sown into petroleum-based

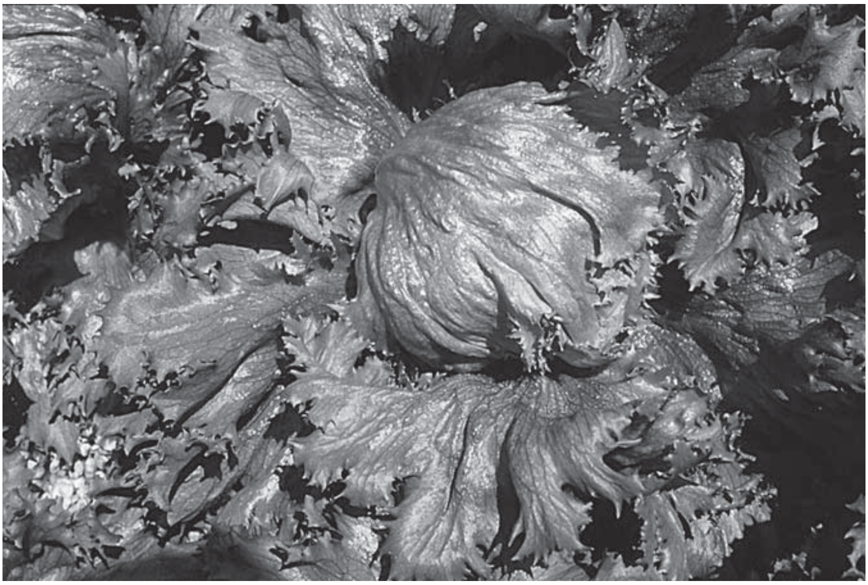

FIGURE 13.14 High-quality head lettuce produced from sand culture. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

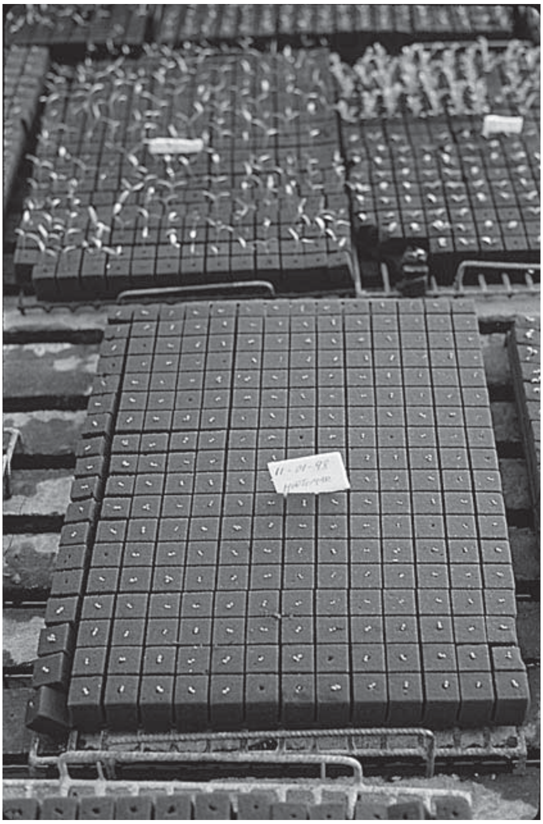

FIGURE 13.15 Propagation of lettuce seedlings grown in “Lelli” cubes. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

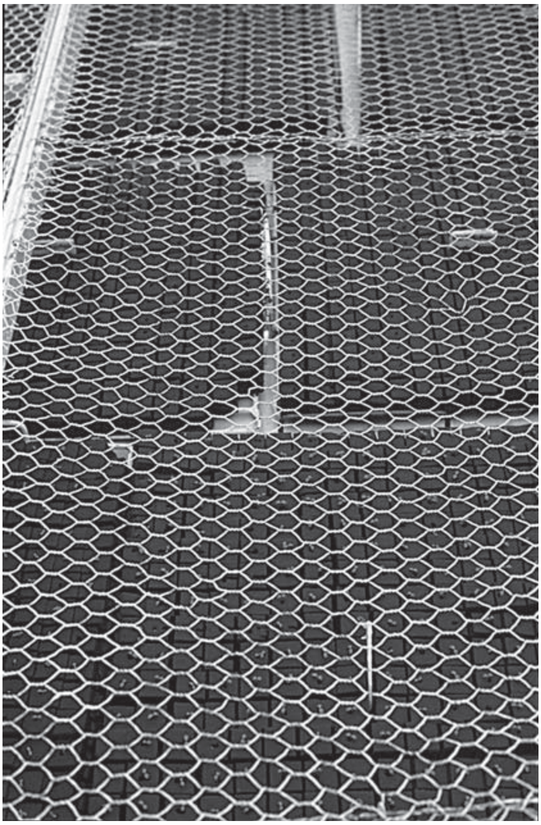

FIGURE 13.16 Initial germination of lettuce under screen cover. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

synthetic “Lelli” cubes, similar to “Oasis” cubes measuring about 1 in. × 1 in. × 1.5 in. high (Figure 13.15). After seeding, the cubes are placed under a screen for 4–5 d until they germinate (Figure 13.16). This prevents birds from eating the seeds. They are separated and spaced out in special channels of an ebb-and-flood bed to continue growing until they are 25–28 d old (Figures 13.17 and 13.18). At 25–28 d they are transplanted directly into the sand culture beds. The lettuce reaches maturity within 42–45 d after transplanting. Yearly production of one hydroponic bed would be eight to nine crops of an average of 320 heads or 2,500–2,800 heads of lettuce.

13.4 EBB-AND-FLOOD WATER CULTURE OF WATERCRESS

The disadvantages of unavailability and high costs of materials and equipment can be overcome by the use of water cultural and nutrient film technique (NFT) systems of hydroponics. While little commercial application of NFT has been carried out in the tropics, it does offer a vast potential by reducing capital costs and dependency on suitable media such as granitic sand or gravel, which is often rare and expensive. Watercress is grown at Hidroponias Venezolanas in raised beds with a modified NFT or ebb-and-flood system. Raised beds of metal frames and clay bricks are constructed as described earlier for sand culture (Figures 13.4 through 13.7). The difference in the bed structure is only the narrower width and shorter length, about 1 m × 8 m (3.3 ft × 26 ft).

FIGURE 13.17 After 15 d the seedlings are separated and placed in ebb-and-flood channels. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.18 At 27–28 d the seedlings are ready to transplant. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Large 50,000-L (13,200-gal) cisterns store the nutrient solution to each sector of beds. No medium is used with the watercress. The solution is maintained at 1–2 cm depth and is circulated every 15 min for 5 min during daylight hours. The solution is pumped through 3-in. (7.5-cm)-diameter main PVC pipes located above the beds (Figure 13.19). Inlet tubes of 0.5-in.-diameter black polyethylene hose direct the solution from the mains to each bed at one end (Figure 13.20). The solution flows to the other end, draining to an 8-in.

FIGURE 13.19 PVC piping distribution system. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.20 Inlet black polyethylene tubes from 3-in. main. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

(20-cm)-diameter catchment pipe that returns the solution to the cistern. This is an ebb-and-flood system.

The nutrient formulation is similar to that of California Watercress as discussed in Chapter 6. Not all of the fertilizers normally used for this formulation are available in Venezuela, so substitutions need to be made. Diammonium phosphate is used in place of monopotassium phosphate as a source of phosphorous. Similarly, iron sulfate is substituted for ion chelate. Both these compounds are less soluble than their counterparts used in North America.

The climate at the farm, whose elevation is 1,300 m (4,265 ft), has moderate temperatures from daily maximums of 26°C–28°C (79°F–82°F) to nightly minimums of 15°C–18°C (59°F–65°F), which are fairly ideal for watercress. Since flowering does not occur, as it does during summer months in California, there is no need to start the plants from seed. Cuttings are taken from existing plants to transplant into new beds. The cuttings are placed into the beds containing about 1–1.5 cm (0.5 in.) depth of solution (Figure 13.21). Within 4 wk the watercress is ready to harvest.

The plants are changed every 6–8 mo, as root buildup in the beds reduces flow of the solution and consequently oxygen to the roots (Figure 13.22). This leads to root decay and diseases, which reduce productivity.

In addition, the plants should be rejuvenated at least once a year through sowing of seeds to maintain vigor. Seed is sown directly into several beds having a mixture of coarse sand and pea gravel. The beds are subirrigated to within 1 cm of the surface to keep the seed moist. Within 5–6 wk the seedlings are removed with their roots intact and transplanted to the production beds as was described for California Watercress in Chapter 6. They are about 4–5 cm (2 in.) tall at that age.

The product that is sold to restaurants is shipped in bulk as 0.5-kg (about 1-lb) bundles in returnable plastic tote bins (Figure 13.23). Several centimeters of water is kept in the bottom of the bins to retain freshness of the watercress. For supermarkets, the watercress is packaged in 100-g (3.5-oz) plastic bags (Figure 13.24). The bulk product is harvested at 25–28 d to provide it with longer stems, which the restaurants use in soups and a dip paste, whereas the packaged watercress that goes to the consumer is harvested from 14 to 16 d to obtain more succulence for fresh salads.

FIGURE 13.21 Watercress cuttings placed in beds to start a new crop. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

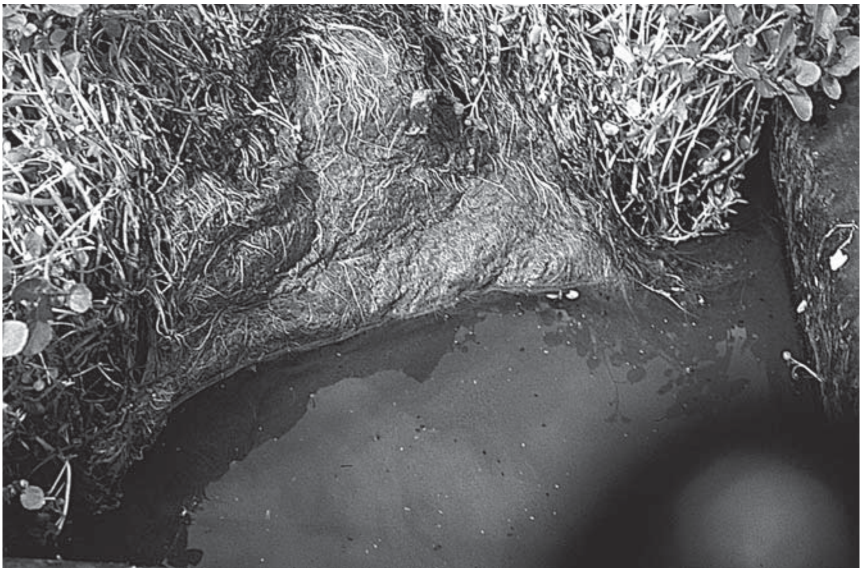

FIGURE 13.22 Large root mass after 6–8 mo of growth impedes flow of solution. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.23 Packing of watercress in returnable plastic tote bins for restaurants. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 13.24 Packaged watercress for supermarket sales. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Monthly production of 6,000–8,000 kg (13,000–17,600 lb) comes from an area of about 0.5 ha (1.25 acres) of beds. This is equivalent to 1.2–1.6 kg/m^2 (0.25–0.33 lb/ft^2). The objective of using improved bed design, higher quality fertilizers, and new methods of nutrient solution circulation is to obtain 2 kg/m^2 (0.4 lb/ft^2) of watercress.

Continued increasing demand for high-quality, clean watercress in the marketplace is forcing the company to expand to more growing terraces. As their volume increases, they have upgraded their packing facilities with more technical weighing and packaging equipment.

13.5 RICE HULLS–COCO COIR CULTURE OF TOMATOES, PEPPERS, AND CUCUMBERS

Three terraces of "greenhouses" of total area of 5,800 m^2 (62,400 ft^2) were constructed in 1996. These are light steel frames with a polyethylene covering to protect the crop from rainfall (Figure 13.25). Tomatoes are the principal crop, with some production of bell peppers and European cucumbers. Similar to lettuce, the plants are seeded in "Lelli" cubes in a propagation area (Figure 13.26) with ebb-and-flood irrigation.

Initially, the plants were grown in 5-gal black polyethylene nursery bags with 85% rice hulls and 15% fine sand. From two 35,000-L (9,250-gal) tanks located above the terraces,

FIGURE 13.25 Inexpensive polyethylene covered structures. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

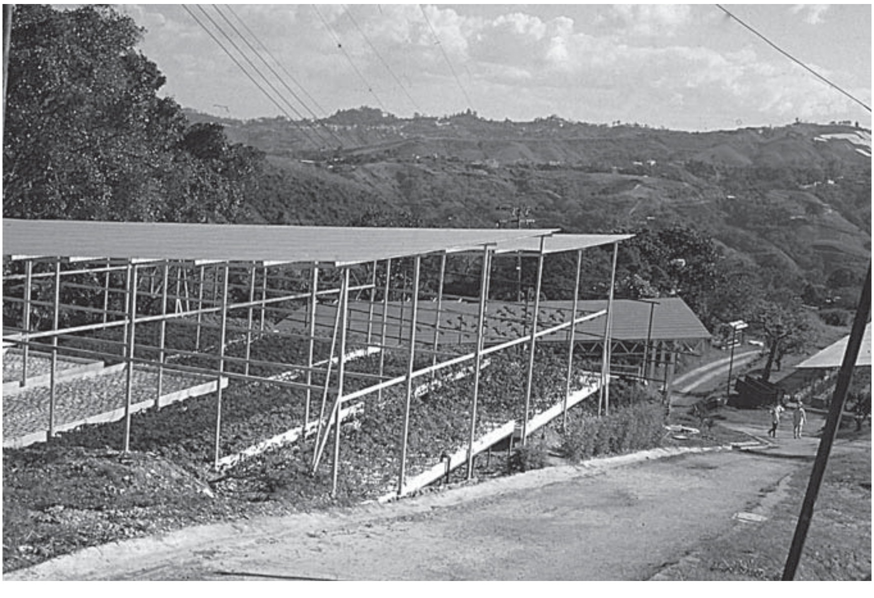

FIGURE 13.26 Tomato seedlings in propagation area. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

the plants were fed by gravity with a drip irrigation system. During the first crop it was discovered that the substrate did not retain sufficient moisture, resulting in blossom-end rot (BER) of many fruits. Even two drip lines per bag did not prevent BER. To overcome this problem, the company located a source of coconut coir that could be shipped in bulk. The substrate was changed to 70% coco coir and 30% rice hulls (Figure 13.27). The cost of both

FIGURE 13.27 Tomatoes growing in 5-gal plastic bags of coco coir and rice hulls. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

coco coir and rice hulls was very low. Coco coir then cost about $15 per cubic meter and rice hulls cost about $10.50 per cubic meter delivered to the farm.

As the plastic nursery bags broke down under the intense tropical sunlight, they were replaced with 5-gal plastic paint buckets (Figures 13.25, 13.28, and 13.29). Small holes were drilled around the base of the buckets for drainage before filling them with the coco coir–rice hull mixture. The cost of the substrate per bucket was about $0.30. They began by growing only one plant per bucket, but later used two plants per bucket as is done with perlite bato buckets as described in Chapter 12.

The plants can be trained in a V-cordon method. The problem of BER was overcome, but there was still a lot of stem disease, especially in the crown area. This disease causes wilting and death of many plants when they begin producing heavily. The problem was related to contamination of the coco coir. The coco coir must be steam sterilized to pasteurize the coco coir and rice hulls before placing the substrate in the buckets. Alternatively, the substrate could be moistened on a concrete slab that was clean and covered with black polyethylene. Sunlight on the black polyethylene cover would quickly raise the temperature of the substrate sufficiently to pasteurize it. The principal tomato variety used was Agora, a Vilmorin seed. It yielded very heavily in the first five to six trusses, but soon succumbed to the wilt disease.

FIGURE 13.28 Five-gallon plastic buckets for growing tomatoes. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Trials with peppers and cucumbers were carried out to determine the best varieties for the tropical climate. Such trials must be ongoing to test new cultivars as they are introduced. Varieties for tropical regions must have resistance to common fungal diseases such as powdery mildew. We have found in Anguilla that "Dominica," a DeRuiter variety, is one of the best European cucumber varieties for resistance against powdery mildew. With continued improvement in sterilization of the substrate and pest control, successful crops may be grown in tropical regions (Figure 13.29).

FIGURE 13.29 Successful tomato crop growing in coco coir and rice hulls. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

High population centers with rising economies increase the percentage of middle-class people who are able to be selective in their food demands. This creates a strong market for high-quality products normally not achieved by conventional soil culture. Hydroponic crops of clean, superior quality find the marketplace willing to pay a premium price. This higher return for products grown hydroponically justifies the high initial capital costs of establishing a hydroponic farm in tropical countries. It will support the imported technology required for successful operation of hydroponics and training of local workers.

13.6 SPECIAL APPLICATIONS

13.6.1 Hydroponics and Resorts and Spas

A unique concept is the combination of a hotel resort complex with a hydroponic greenhouse farm. In the Caribbean and the South Pacific islands it may be difficult to obtain good-quality fresh vegetables. Many of these more isolated, popular tourist locations are in areas of limited agricultural production. On many of the islands, food must be shipped into the countries by air or sea. Fresh, perishable salad crops, such as tomatoes, cucumbers, peppers, lettuce, herbs, and related products are limited or not available.

Hydroponic farms also play a significant role in the operation of health spas associated with such resorts, as is the case with CuisinArt Resort & Spa in Anguilla, British West Indies. The fresh vegetables can be a part of a “wellness” program provided by the spa. Travelers are becoming increasingly aware of the source and quality of the foods eaten in these regions. They realize a sense of security in eating fresh salad crops when they are produced at the site of the resort. To further assist their confidence, the hydroponic farms can offer tours to the resort guests. The guests will even more appreciate their salads once they learn how they have been grown at the resort. In many other regions such as Mexico and Central America, tourists often experience sickness related to unclean salad crops. This can be avoided by growing the salad crops on-site in a hydroponic farm.

In most areas, a light-weight greenhouse structure can be constructed of polyethylene with shade cover on a galvanized steel tubular frame. These have little, if any, environmental control apart from protection against rain and pests.

With an eminent hurricane approaching, the covers and internal components (including all plants) are removed. While the covers and growing systems may be stored safely in a sturdy shed or container, all the plants will have to be harvested or removed. Such practice stalls production from the first hurricane until the end of the season in November. If the first hurricane arrives early in the season, such as August or September, production is curtailed from then until the end of November when it is safe to assume that a further one will not occur that season. It will take several months after that to get a new crop into production. So, in reality the season could be as short as 6–7 mo a year. Of course, during some years certain islands will be spared from a hurricane, but that is a gamble. The result is that the local market cannot depend on fresh vegetable products year-round from such “greenhouse” hydroponic operations.

In areas prone to hurricanes of winds of 150 mph (250 kph) or greater, special heavy, completely enclosed structures are needed to withstand such conditions. This alternative is to build a “hurricane-proof” greenhouse. That was the case with CuisinArt Resort & Spa

FIGURE 13.30 CuisinArt Resort & Spa hydroponic farm. (From CuisinArt Resort & Spa, Anguilla. With permission.)

in Anguilla (Figure 13.30), a unique concept of a hotel combined with a hydroponic greenhouse. The greenhouse is an integral part of the hotel complex in providing fresh salads for its restaurants. It is imperative that the greenhouse will withstand hurricanes. Crops cannot be interrupted by such weather phenomena.

A special greenhouse was engineered to withstand hurricane winds up to 150 mph, so that the crops scheduled to be bearing could be protected during the hurricane season. The greenhouse constructed by AgraTech Greenhouse Manufacturing of Pittsburg, California, has proved its resilience during numerous hurricanes that have occurred over the past 12 yr. To withstand such hurricane winds, the greenhouse superstructure has twice the number of galvanized steel members as a normal greenhouse constructed under North American or European standards. Posts and trusses are located at 6-ft (1.8-m) centers. The structure is set into a perimeter concrete footing and foundation 18 in. (46-cm) wide by over 3 ft (1 m) deep. The roof and sidewalls are covered with corrugated polycarbonate plastic, a very durable material. Each valley of the corrugations is screwed to the purlins running horizontally along the roof across the trusses. The polycarbonate plastic corrugated roof panels resist such strong winds and have stood up to the high ultraviolet light conditions of the tropics over the past 12 yr with little loss of light transmission. Roof vents, cooling pads, and exhaust fans regulate temperatures. As long as the relative humidity in these regions is from 55% to 75%, cooling is possible. This cooling is fairly efficient during the winter months from December through March when humidity levels are lowest.

The CuisinArt Hydroponic Farm greenhouse is 18,000 ft^2 (1,673 m^2) in area. A number of hydroponic systems are used, including perlite bato buckets, raft culture, vertical plant towers, and raised beds with a peat-lite substrate. Crops grown include tomatoes, peppers, European cucumbers, eggplants, Bibb and other lettuces, bok choy, arugula, herbs, and microgreens, as described in Chapters 5 and 12. This diversification is to meet the hotel's fresh salad requirements. In this small greenhouse annual production (2009–2010) was as shown in the following table.

Tomatoes (beefsteak, cherry, roma)	13,037 lb
Peppers (red, orange, yellow)	5,568 lb
European cucumbers	5,018 lb
Persian (Japanese) cucumbers	1,727 lb
Bibb (European) lettuce	23,280 heads
Other novelty lettuce	15,275 heads
Eggplants	650 lb
Bok choy	3,600 heads
Arugula	564 lb
Herbs	1,005 lb

The main area of the greenhouse growing tomatoes, cucumbers, and peppers in bato buckets of perlite contained 1,382 tomato, 109 cucumber, and 692 pepper plants. In addition, herbs, bok choy, and watercress are grown in a series of 66 plant towers located around the perimeter walls of two sides of the greenhouse. Two lettuce ponds, as described in Chapter 5, house 3,328 heads of European Bibb lettuce. The other novelty lettuces, arugula, and basils are grown in raised beds of a total area of 2,200 ft^2 (200 m^2).

Hydroponics can be a part of tourist attractions such as Epcot Center and the Biosphere. It can be incorporated into theme parks and wellness spas and retreats. It is beneficial to the hotel resorts located in areas of nonarable lands and limited sources of fresh water where desalination of sea water can be used with hydroponic culture.

13.6.2 Hydroponic Rooftop Greenhouses

The idea of rooftop gardens has been in use for several decades, but they normally are outside gardens of simple beds or pots with ornamentals or vegetables. Today, there is more focus on the use of hydroponics and greenhouses to produce vegetable crops commercially. The author was first exposed to this concept in 1986 in Taipei, Taiwan, where an investor wanted to erect a hydroponic greenhouse farm on top of a 13-story apartment building in the middle of Taipei. The engineering was done and the erection of the greenhouse was started, but the project had to be stopped because of the wishes of the apartment owners, as they walked their dogs and exercised on the roof of the building.

The idea reemerged in the last few years, and now the world's first commercial rooftop greenhouse is in production in downtown Montreal, Quebec, Canada (Lunau, 2010). This is Lufa Farms. A 31,000-ft^2 (2,881-m^2) facility has been constructed on the top of a two-storey warehouse (Figure 13.31). The author was involved in this project at the early stage of Lufa Farm's birth to oversee the design and development of this multicrop greenhouse and coordinated the startup with Lauren Rathmell, who supervised the establishment of the first crop. Of course, to do such a project requires a building constructed strong enough to meet city building codes of adding the weight of the greenhouse on the roof. The greenhouse is a modern up-to-date glass structure with central hot water heating, high-intensity discharge (HID) lights, CO_2 enrichment, shade/insulation curtains, Argus computer controller, and injection system. The plan is to grow greenhouse vegetable crops year-round. Crops grown

FIGURE 13.31 Rooftop hydroponic greenhouse in downtown Montreal, Canada. (From Lufa Farms, Montreal, Canada. With permission.)

include tomatoes, peppers, cucumbers, eggplants, lettuce, herbs, salad mixes, bok choy, and microgreens.

The greenhouse has two heating zones. There is a cool zone for the lettuce, bok choy, basils, herbs, salad mixes, and microgreens. Lettuce, basils, chard, arugula, bok choy, and some herbs are grown in an NFT system by American Hydroponics (www.amhydro.com). The salad mixes and microgreens are grown in an ebb-and-flood system. The cool zone has evaporative cooling pads and exhaust fans (Figures 13.32 and 13.33). The greenhouse

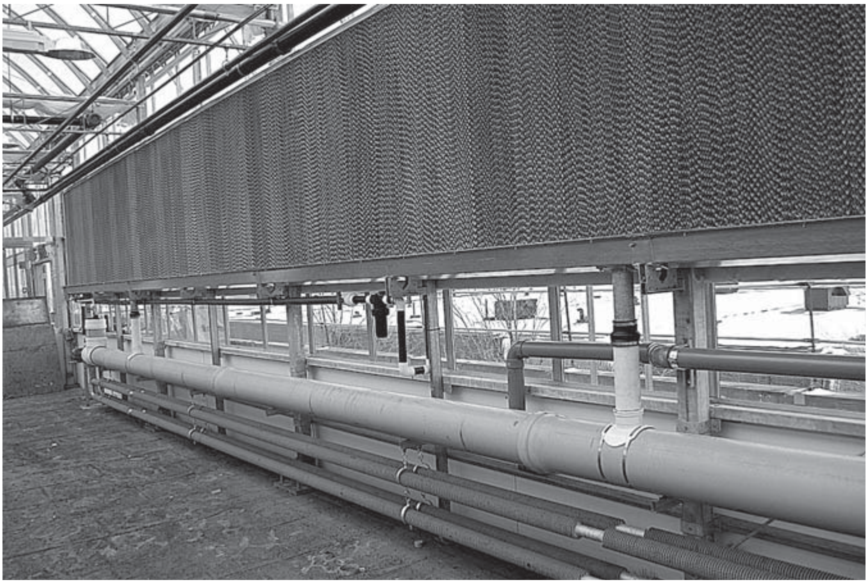

FIGURE 13.32 Evaporative cooling pad. (From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 13.33 Exhaust fans on the side opposite to the cooling pad. (From Lufa Farms, Montreal, Canada. With permission.)

and heating system were designed and built by Westbrook Greenhouse Systems Ltd., Beamsville, Ontario, Canada (www.westbrooksystems.com). All of the heating systems have three hot water boilers located in the greenhouse with hot water pipe distribution (Figure 13.34). Heating pipes include perimeter wall heating, floor heating pipes in the warm zone, and overhead heating in the cool zone.

FIGURE 13.34 Hot water boilers for heating system. (From Lufa Farms, Montreal, Canada. With permission.)

The warm heating zone is for the other section of the greenhouse that is growing tomatoes, peppers, cucumbers, eggplants, and other warm-season herbs. The two zones are separated by a glass partition wall. The vine crops are grown in the new FormFlex raised trays using coco coir slabs as was described in Chapter 12. The greenhouse has CO_2 enrichment in both sections and a full array of HID lighting to enable the growing of these crops year-round.

The tomatoes, peppers, eggplants, and cucumbers were started by a contract nursery propagator. The tomatoes, peppers, and eggplants were grafted to a disease-resistant rootstock. The seedlings are normally grown in the nursery for 55 d, but the first crop had to be extended to 65 d because the construction was several weeks behind schedule. These seedlings were transplanted directly to the coco coir slabs at the 65th day.

Within several weeks of transplanting the plants grow vigorously as the roots enter the coco coir slabs (Figures 13.35 and 13.36). The seedlings were started in rockwool blocks and transplanted 65 d after sowing.

Owing to the diversity of the crops grown, several nutrient systems were designed to enable the use of separate nutrient formulations. All of the leachate is recycled to the fertigation system located in the basement (underground parking) of the building. The leachate is collected in the return tanks where it is filtered to remove any particulate matter and pasteurized by hydrogen peroxide before going to the premix batch tanks where the pH and EC are adjusted by a loop through the injector systems. There are separate injectors for each premix tank. After adjustment that is regulated by the computer controller, the solution is pumped back to the greenhouse irrigation system on the roof. Any loss of water by evapotranspiration of the plants is made up by adding raw water from supply tanks to the batch tanks before solution adjustment by the injectors.

It is very complicated to design these independent nutritional systems for different crops when growing many types of crops together. In such a case, the formulation for a specific

FIGURE 13.35 Eggplants and peppers 2 wk after transplanting. Note: The shade curtains above are drawn to reduce the light during the rooting process. (From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 13.36 Peppers on coco coir slabs on FormFlex raised trays. (From Lufa Farms, Montreal, Canada. With permission.)

crop may not be the most optimum, but often some formulations for specific crops may not differ significantly.

All crops are grown free of synthetic chemical pesticides by using beneficial insects and biological agents, which are natural pesticides. The products are sold as “pesticide free.” Marketing of the product is by “subscribers.” People will join as members to receive a basket of fresh produce weekly. They pay a weekly fee for the basket of vegetables that include tomatoes, peppers, eggplants, cucumbers, lettuce, salad mixes, arugula, and herbs. They may choose the basket mix they prefer from a number of mixtures available.

With success at this site, it is anticipated to construct more rooftop hydroponic greenhouse gardens in the city centers of large population areas on the northeast coast of Canada and the United States where fresh produce often is not readily available, especially during the winter months. In milder climates in the western part of North America, this concept is probably not as feasible, especially when there is usually an abundance of fresh produce from California. Similar application in Europe may be feasible in cities of England, Germany, and northern countries. There, fresh produce in winter would come from Spain, so countries near Spain may have adequate product available during winter, and therefore a rooftop garden in those southern countries probably would not be economically feasible.

Another similar rooftop hydroponic greenhouse has been established by Gotham Greens on a two-story industrial building in Greenpoint, Brooklyn, New York City. They also have a solar array of panels that generates 55 kW of electricity to assist in the electrical needs of the greenhouse (Figure 13.37).

FIGURE 13.37 Gotham Greens greenhouse with solar array. (From Ari Burling & Gotham Greens, Brooklyn, NY. With permission.)

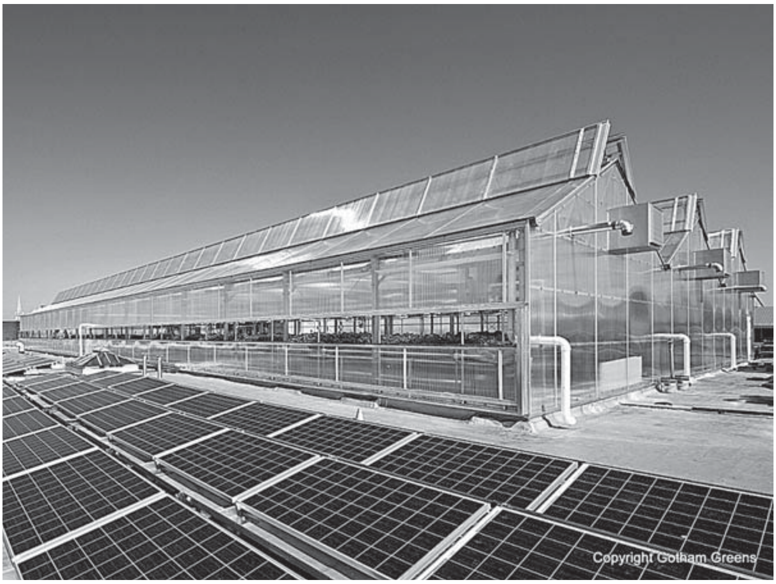

FIGURE 13.38 Gotham Greens 12,000 ft^2 greenhouse in Brooklyn, New York. (From Ari Burling & Gotham Greens, Brooklyn, NY. With permission.)

The greenhouse is 75 ft × 160 ft (22.9 m × 48.8 m) for an area of 12,000 ft^2 (1,115 m^2) (Figure 13.38). It is constructed of galvanized steel, aluminum, and double-wall polycarbonate. Components include natural ventilation, shade curtains, unit heaters, and high-pressure sodium (HPS) lighting.

Gotham Greens greenhouse is growing lettuce and basil with an NFT recirculating system (Figure 13.39). They package for supermarkets such as Whole Foods and other smaller high-quality food markets.

FIGURE 13.39 Gotham Greens growing lettuce and basil in NFT. (From Ari Burling & Gotham Greens, Brooklyn, NY. With permission.)

This concept is certainly the way of the future in providing large population centers with fresh produce year-round. With the rising costs of fuel for transportation and innovations of highly efficient artificial lighting, the economic feasibility of rooftop hydroponic greenhouses on the largely idle roofs will become more common. One step further would be to construct vertical greenhouse buildings within the downtown core of large cities. An article was written on that topic in a recent issue of Scientific American in 2009 (Despommier, 2009). Many conceptual designs have appeared in articles on numerous websites (Figures 13.40 and 13.41).

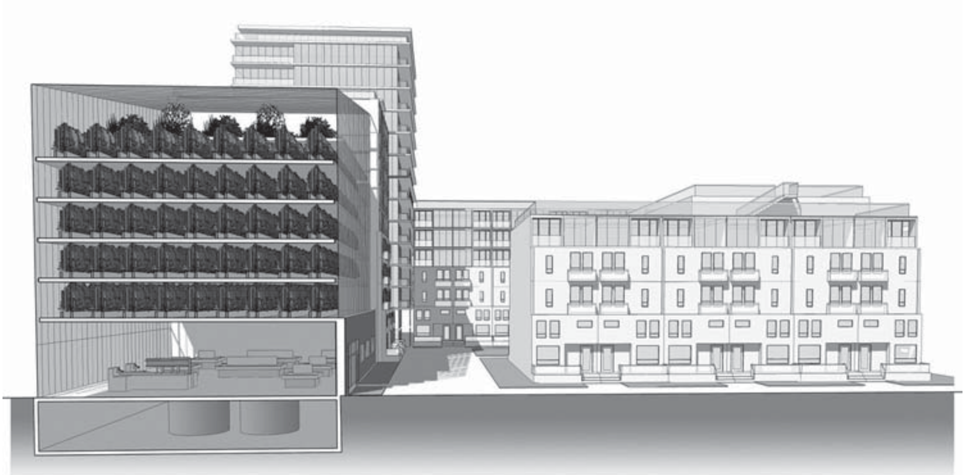

FIGURE 13.40 Conceptual design of a hydroponic farm attached to office buildings and/or residences. (From Gordon Graff, Agro-Arcology, Toronto, Canada. With permission.)

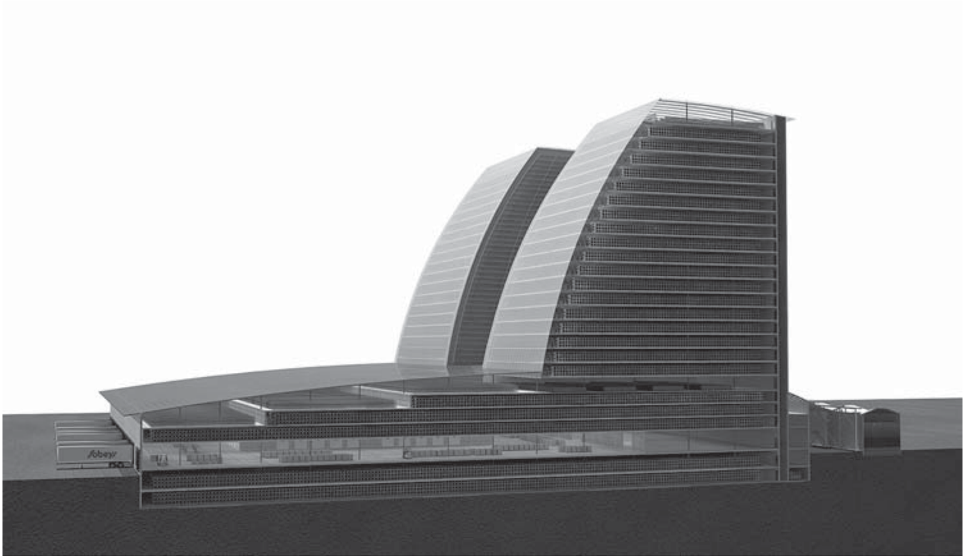

FIGURE 13.41 A conceptual design of a vertical greenhouse. (From Gordon Graff, Agro-Arcology, Toronto, Canada. With permission.)

13.6.3 AUTOMATED VERTICAL HYDROPONIC SYSTEMS

Over the past few decades, hydroponic enthusiasts have designed systems to increase production within a given area. Most are automated vertical production systems that rotate while passing a light source in closed insulated buildings or in greenhouses. One such system is the "Omega Garden" discussed in Chapter 5.

Valcent Products (EU) Limited (www.valcent.eu) is testing an automated vertical hydroponic system at Paignton Zoo in Cornwall, United Kingdom (Bayley et al., 2011). Their vertical system is trademarked as "VertiCrop." They started trials in 2008 growing leafy crops for zoo animals. Kevin Frediani (2010a, 2010b, 2011a, 2011b), the curator of plants and gardens at Paignton Zoo, oversees the research on the VertiCrop growing system. He works with the animal nutritionists to select the right types of crops most suitable for the animals. They feed the animals the total plants including roots, as that decreases waste while increasing fiber to the animals. The growing of their own leafy crops makes it possible to provide the animals with nutritious crops without concern for weather or season availability as they are grown in a greenhouse on-site.

The VertiCrop system is a closed-loop conveyor system suspended by an overhead track that carries 70 hangers that hold eight pairs of growing trays contained in plastic trays (Figure 13.42). There are eight levels stacked 3 m high. The trays are designed for growing microgreens, lettuce, and salad mixes. They are working on LED lighting for the conveyor system to pass in its rotation. The system is automatically irrigated from a central feeding/injection system (Figure 13.43). All leachate is captured, filtered, and recycled through the irrigation system (Figure 13.44). The nutrient solution enters at one side of the system as the trays travel past nozzles located at a centralized irrigation station (Figure 13.45).

Frediani (2010b) claims that in an area of approximately 100 m^2 (1,076 ft^2), 11,200 plants can be grown at any one time. Use of the greenhouse floor area is increased by

FIGURE 13.42 Vertical automated growing system. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

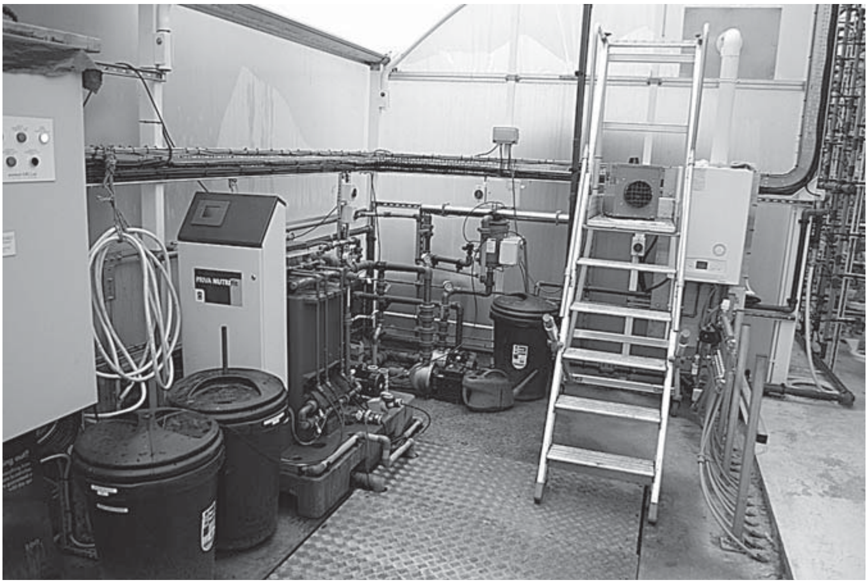

FIGURE 13.43 Priva injection system. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

the conveyor system curving back and forth in a serpentine fashion (Figure 13.46). He further states that up to 250 lettuces per square meter (10.76 ft^2) can be obtained with a 6-m (19.69 ft) high unit and says that it is about 50 times greater than under field growing. This type of growing has potential use in urban food production. Such a system would fit well into the concept of rooftop gardening discussed earlier, as it would increase production within a unit area.

FIGURE 13.44 The drain lines at the back of the trays. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

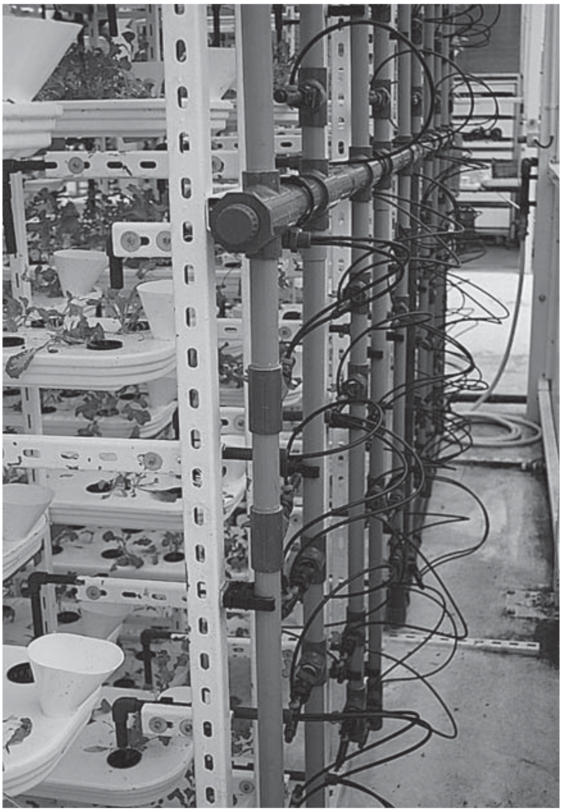

FIGURE 13.45 Irrigation header above passing trays to inject solution to the trays as they pass. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

FIGURE 13.46 VertiCrop system where overhead conveyor curves back to change direction. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

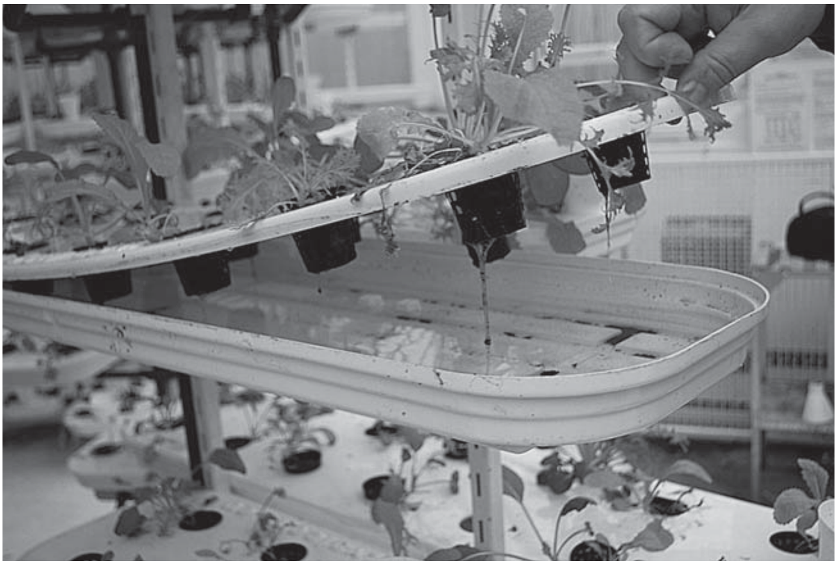

FIGURE 13.47 Plants in mesh pots. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

A specialized machine has been constructed to remove the trays when harvesting and replace them during transplanting to reduce manual labor. Plants are started in growing cubes and transplanted to mesh pots, which are then placed in the trays of the conveyor system (Figure 13.47).

13.6.4 THE SCIENCE BARGE

The Science Barge is a sustainable urban farm designed by New York Sun Works (www.nysunworks.org). The floating barge contains a hydroponic greenhouse powered by solar, wind, and biofuels that grows tomatoes, cucumbers, peppers, lettuce, and herbs. Biofuels include biodiesel and waste vegetable oil. Biofuels are made from food industry by-products. The Cornell Cooperative Extension, New York City, stated in 2005 that New York City restaurants generate sufficient waste oil to supply 10 million gallons of biodiesel fuel annually. The Science Barge tours New York City's public waterfront parks (Figure 13.48). It is a demonstration of renewable energy supporting sustainable vegetable production using rainwater and river water purified by reverse osmosis (RO) for irrigation of the crops. They have a public education program with school groups and the general public.

In 2010, New York Sun Works, a nonprofit organization, opened the Sun Works Center for Environmental Studies at the Manhattan School for Children (Figure 13.49). This is a rooftop greenhouse that functions as a practical classroom on integrated environmental studies offered to students from kindergarten through eighth grade (Figure 13.50) (MacDonald, 2010; MacIsaac, 2010). New York Sun Works wishes to build 100 of these rooftop greenhouse classrooms throughout New York City.

FIGURE 13.48 Hydroponic greenhouse on the Science Barge. (From Manuela Zamora & New York Sun Works, New York, NY. With permission.)

FIGURE 13.49 Rooftop hydroponic greenhouse at the Manhattan School for Children. (From New York Sun Works, New York, NY. With permission.)

FIGURE 13.50 School classroom rooftop hydroponic greenhouse. (From Manuela Zamora & New York Sun Works, New York, NY. With permission.)

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14 Plant Culture

14.1 INTRODUCTION

While this book is an outline and review of soilless culture methods, it is appropriate to discuss briefly some of the methods and products available for the growing of seedlings to be transplanted into a soilless culture system. In order to successfully grow plants, one must start out with vigorous and healthy disease-free seedlings. We shall then proceed to other aspects of successful plant cultures.

14.2 SEEDING

All plants for hydroponic culture should be started from seeds. Some growers may wish to purchase seedlings ready to transplant from specialized transplant growers such as Bevo Agro, mentioned in Chapter 6. Tomato seedlings are 6 wk old, cucumber seedlings 4 wk, and pepper seedlings 8 wk on delivery. However, such a transplanting method using purchased plants is really most applicable to North America or Europe where shipping can be done by ground transportation within several days. The risk of using transplants grown by someone else is that they could have a disease that would be transmitted throughout the crop. However, most propagators practice very stringent sanitation methods. In addition, with grafting becoming the acceptable method of growing most cultivars of tomatoes, peppers, and eggplants, it is much easier to have a specialized propagator do this as most growers are not set up or do not have trained people to do the green grafting. In areas of high sunlight conditions such as desert and tropical regions it is possible to transplant seedlings at an earlier stage. In those locations, it may be beneficial and cheaper to raise one's own seedlings. Cucumbers, for instance, in tropical regions such as Florida and Anguilla can be transplanted at 10–14 d from sowing since they grow very rapidly under the high sunlight of those areas.

A number of methods for sowing seeds are available. One may seed directly into multipack trays using a peat-lite mix or any other suitable substrate as perlite, vermiculite, or granular rockwool. Many types of containers are on the market. Plastic "com-packs" and "multi-pots" are shaped like ice-cube trays with one large compartment to 12 compartments per pack (5.25 in. × 5.25 in. × 2.31 in. deep) (13 cm × 13 cm × 6 cm) (Figure 14.1). These come in 89 packs per 10.5 in. × 21 in. (27 cm × 53 cm) sheet, which fits into a corresponding plastic flat. A similar product (Jiffy strips) is made of peat rather than plastic. In addition, individual plastic and peat pots of various sizes are available. In all of these containers a soilless mix must be used. Most vegetable plants can be grown satisfactorily in 2.25- or 3-in. (5- or 8-cm) square or round pots. In the peat pots and strips, transplanting is done by placing the pot and medium into the beds. The plant roots will grow through the peat container walls.

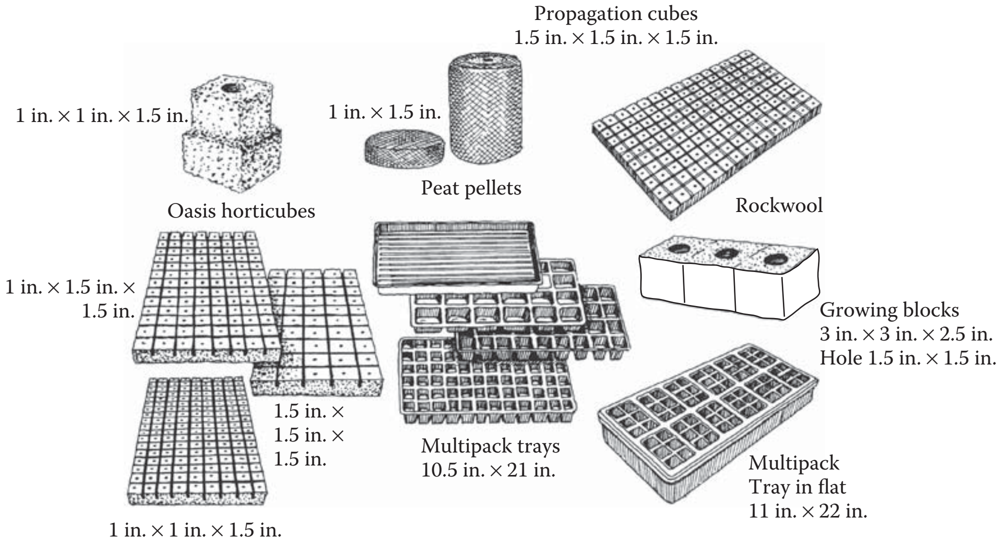


FIGURE 14.1 Seedling propagation cubes, blocks, peat-pellets, and trays. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

An alternative method is to seed directly into Jiffy peat pellets, Oasis "Horticubes," rockwool cubes, or coco coir cubes. Seeds are placed in small precut seeding holes. Peat pellets are compressed peat discs contained by a nylon mesh. These discs are about 1.5 in. (4 cm) in diameter and 0.5 in. (0.6 cm) thick when shipped dry. After soaking in water for 5–10 min they swell to about 1.5 in. (4 cm) in height (Figure 14.1). Seeds are placed in the top and may be covered with their peat medium. They contain sufficient nutrients to carry most plants for 3–4 wk. Plant roots grow out through the nylon mesh. During transplanting, the peat pellet (Jiffy-7) with the plant is placed in the growing bed.

Oasis cubes, rockwool cubes and blocks, and coco coir cubes and blocks are commonly used with nutrient film technique (NFT), rockwool, perlite, coco coir, and sawdust cultures. Use of rockwool blocks originated in Denmark, Holland, and Sweden. They are the most widely used form of growing blocks for tomatoes, cucumbers, peppers, and eggplants. At present, the new coco coir cubes and blocks are being introduced, and it is expected that they will gain market share as more coco coir hydroponic systems are employed.

Rockwool is composed of coke and limestone molten at 1,600°C (2,923°F) and spun into fibers. The fibers are woven into slabs, stabilized with phenolic resin, and provided with a wetting agent. The most widely used rockwool block is manufactured under the tradename "Grodan." Other manufacturers of rockwool products now exist in North America, Europe, and Japan.

Chemically, rockwool blocks are relatively inert as the elements they contain are practically unavailable to plants. While they are slightly alkaline in pH, they are quickly neutralized after a short time of passing nutrient solutions of lower pH through them.

Rockwool blocks have good physical properties of low volume weight, a large pore volume, and a great water-retention capacity. Both rockwool cubes and Oasis cubes are often used with NFT systems. Both these growing blocks are sterile, so that disinfecting measures are unnecessary.

Rockwool cubes/blocks are available as propagation cubes and growing blocks. The propagation cubes come in several sizes. Small cubes of 200 per standard flat dimension measure 1 in. × 1 in. × 1.5 in. high (2.5 cm × 2.5 cm × 4 cm), which are most suitable for lettuce and herbs. Larger cubes of 98 per tray that measure 1.5 in. × 1.5 in. × 1.5 in. (4 cm × 4 cm × 4 cm) are best for tomatoes, peppers, cucumbers, and eggplants (vine crops). The propagation cubes have small holes approximately 0.25 in. (0.6 cm) round and deep for the placement of seeds. Seeds are sown in propagation cubes, which in turn are placed into growing blocks after several weeks of growth. This "pot-in-pot" system permits seedlings to continue growing in the same medium with a minimum of transplanting shock. This does not apply to lettuce and herbs, which are transplanted directly from the propagation cubes into the final production culture.

Growing blocks are wrapped around the perimeter in polyethylene and come in a number of sizes. The most common ones used for vine crops in hydroponics are 3 in. (7.5 cm) and 4 in. (10 cm) square by 2.5 in. (6 cm) deep. There are also tall blocks of almost 4 in. (10 cm) depth for vigorous crops such as cucumbers and melons or for carrying seedlings to a later stage before transplanting. Now, many growers also use double blocks (Grodan Plantop Delta) (Figure 10.24) as described in Section 10.5 to grow two plants per double block. The holes in these blocks are round, of 1.5 in. diameter and 1.5 in. depth (4 cm × 4 cm) to fit the larger propagation cubes of 1.5 in. (4 cm) dimensions.

With most commercial growers purchasing grafted plants from propagators, Grodan has developed special rockwool plugs that fit individually into Grodan Kiem Plug Trays to facilitate automatic seeding, as these propagators sow thousands of seeds at a time. The Kiem plug trays have 240 plugs in each tray. These trays can be placed in ebb-and-flood propagation tables for high-density propagation. After germination, the seedlings can be transplanted to NFT channels or moved on into the larger blocks for growing on.

The Grodan plugs are 2.0 cm in diameter by 2.5 cm in height (0.8 in. × 1 in.). They have several hole configurations of 0.75 cm (0.3 in.) depth that have sloped sides to permit seeds to enter without missing when using automatic seeders. In addition, the sloped sides permit covering of the seeds with vermiculite, which can be added automatically following the sowing. The round plugs fit easily into rockwool cubes having round holes of similar diameter.

Rockwool cubes and blocks must be thoroughly moistened before seeding or transplanting. If not, dry spots will restrict root growth within them. Similarly, Oasis cubes, coco cubes and blocks, and peat pellets must be saturated with water before seeding. This can be accomplished in several ways: overhead sprinkling for 1 h, soaking through hand submersion, or by overhead boom irrigators until the cubes are completely saturated. Seeds can then be placed in the prepunched hole in each cube. When roots appear on the outside of the cubes and true leaves develop, the plants are ready for transplanting. Since the plants are transplanted intact with their cubes, a minimum of transplant setback occurs.

Oasis "Horticubes" are widely used in North America specifically for hydroponic and NFT applications. These cubes have good drainage, making them ideal for seed germination. The "Horticubes" medium is available as 1 in. × 1 in. × 1.5 in. (2.5 cm × 2.5 cm × 3.8 cm) cubes for maximum planting density. Each medium tray is composed of 162 cubes joined at their bases to allow easy separation for transplanting. Their main advantages are that they are sterile, easy to handle, and have a balanced pH.

Sow one seed per propagation cube. Purchase new seed for each crop. Purchase only enough to allow some "overseeding." Pay attention to the percentage germination given on the seed package. From this rating calculate how much extra seed must be sown to meet the crop needs. For example, if the germination is 90%, one must sow 100/90 = 1.11 times the seeds to meet the plant numbers. That is 11% of additional seeds need to be sown in the propagation cubes. At the same time, some seeds will germinate poorly, giving weak seedlings. Add another 5% to compensate for these plants. Large seeds germinate more uniformly. Cucumber seeds are very expensive, so do not sow more than what is necessary to compensate for the germination percentage.

14.3 SEEDLING PRODUCTION

A basic rule in growing seedlings is, “A good seedling gives good production.” The potential production of a plant is set early in its life cycle. A thin, spindly seedling will restrict flow of water and nutrients to the plant as it grows because of its thin stem base. Production will be reduced from what it is genetically capable of under optimum environmental conditions. Weak, spindly seedlings are easily infected by disease and insects and subject to lodging (falling over). This principle applies to all plants.

During germination, the seed embryo is activated and grows using the stored food of the endosperm. Imbibition is the expansion of the seed as it absorbs water. Various biochemical processes take place to activate the embryo and break down the stored food (starch) to make it available to the embryo for growth. Germination requires water, oxygen, specific temperatures, and light (or lack of it). The grower must provide these optimum conditions to permit the seed to germinate rapidly and begin manufacturing its own food through photosynthesis. Rapid, but not succulent, growth will produce a seedling resistant to diseases.

Sterilization of raw water and application of chemical or biological agent sprays can reduce disease infection. However, care must be exercised not to damage the tender seedlings. Use lower rates with applying such sprays to seedlings, and preferably do not do so until several sets of true leaves have formed. During the growing of seedlings, fungus gnats (Figure 14.76) become increasingly present as one starts to add a nutrient solution to the plants. This creates a moist nutrient-rich surface on the cubes, which quickly forms algae that is very favorable to fungus gnats. Fungus gnats lay eggs in the moist surface of the cubes, and larvae that hatch feed on plants’ roots. One bioagent that can be used as a weekly soak to reduce the presence of the fungus gnat larvae is “Gnatrol,” a biological larvicide. The active ingredient of Gnatrol is 37.4% *Bacillus thuringiensis*, subspecies *israelensis*. This is a beneficial bacterium available from Valent Biosciences Corporation.

Application rates for light infestation are 3.2–6.4 oz per 100 U.S. gal, and for heavy infestations, 13–26 oz per 100 gal as a drench, that is, at 28.35 g/oz, 90.7–181 g or 368.5–737 g/378.5 L.

Use sterile growing trays, substrates, and propagation cubes. Prevent clean trays and cubes from being contaminated. Clean propagation benches before use with a 10% bleach solution. If plastic trays are to be reused, sterilize them for at least 0.5 h in 10% bleach solution.

14.3.1 TOMATO SEEDLING CULTURE

The most common substrate is rockwool propagation cubes of 1.5 in. × 1.5 in. × 1.5 in. (4 cm × 4 cm × 4 cm). These cubes have good water retention yet are well drained to provide good oxygenation. They have a water to air ratio of 60%–80% : 40%–20%. Soak the cubes 1 d in advance with raw water of pH 5.5–6.0 and an EC of less than 0.5 mmho.

After sowing the seeds into the preformed holes keep them moist, and then there is no need to cover the seeds. Water the cubes up to several times a day according to light and temperature conditions in the greenhouse. Do not allow them to dry out or to be excessively moist, as this will kill the germinating seeds.

Most commercial growers place the seeded cubes contained in trays in a special seedling section of the greenhouse. This area of the greenhouse has overhead sprinklers controlled intermittently from a time clock or moisture sensor. Overhead traveling boom irrigators, as used in the forest seedling industry, are particularly suitable to provide uniform watering. In this way, seedlings may be placed over the entire greenhouse area rather than leaving pathways for access by workers to manually water. Another method is to use ebb-and-flood benching. The watering cycles can be regulated by moisture sensors or an irrigation controller.

It is important that each watering soaks the medium thoroughly. Water should be applied uniformly over all plants, or uneven growth is likely to occur. Plants should be watered early enough so foliage will dry before dark. Remember that plants require less water during periods of dark, cloudy weather than during periods of bright, warm weather. As plants grow larger, they require more water. Normally, increasing day length and average temperature will increase water needs of plants.

Moveable, rolling benches or less expensive benching of concrete blocks, pipe, lumber, and wire mesh will serve as a temporary seedling area. In northern latitudes, the seedling area must have supplementary artificial lighting such as high-intensity discharge (HID) lights to increase light intensity and day length during winter months. After the seedlings have been transplanted to rockwool or other blocks, they should be kept in the seedling area until they reach about 55 d of age before transplanting to the growing section of the greenhouse. On this final transplanting, temporary benching can be removed and the area used also for production. As mentioned earlier, most growers prefer to purchase transplants at the 6- to 8-wk stage to avoid the labor and cost of raising their own seedlings. Furthermore, tomatoes are grafted to vigorous, disease-resistant rootstocks. Green grafting is a tedious, labor-intensive process, so large growers should avoid it and purchase transplants. Green grafting is discussed in detail later in this chapter.

Drainage is very important during seedling growth. The water or nutrient solution must pass through the growing substrate and drain away from the plants. This provides adequate leaching and at the same time moves oxygen through the medium to the germinating seeds and their subsequent root formation. Do not set propagation cubes on plastic sheeting, as this will accumulate solution underneath the cubes, reducing available oxygen, and promote algae and subsequent fungus gnat infestation. Metal extruded mesh benches will provide good drainage and permit “root pruning” by air so that seedling roots will remain more in the cubes, forming a dense, well-branched root system. These roots will quickly grow into the slabs or other substrate in which the plants are finally placed.

Maintain temperatures from 77°F to 79°F (25°C–26°C) during initial germination. As the seedlings emerge, the cotyledons expand (Figure 14.2). Increase the EC to 1.0–1.5 mmho in the form of a dilute nutrient solution. Lower the day temperature to 73°F (23°C) and night temperature to 68°F (20°C) over several days, and regulate these temperatures for several weeks.

In northerly regions with low levels of sunlight during the winter months, provide supplementary artificial lighting with the use of HID lamps (metal halide (MH) and sodium vapor). Check with lighting specialists and manufacturers as listed in Appendix 5 on the location of light fixtures, spacing, and so on, to obtain 5,500 lx (510 ft-c) intensity at plant surface for 14–16 h/d.

Procedures outlined here are most applicable to northerly regions of the United States, southern latitudes of Canada, and Europe where the conventional cropping period is from mid-December through mid-November. That is, seeds are sown in December and grown in a special seedling area of the greenhouse until transplanted from late December to early January. During winter, day length is short and light intensity is very low. For this reason, supplementary lighting is imperative, and the use of high-EC nutrient solutions is practiced to slow vegetative growth, giving a sturdy plant.

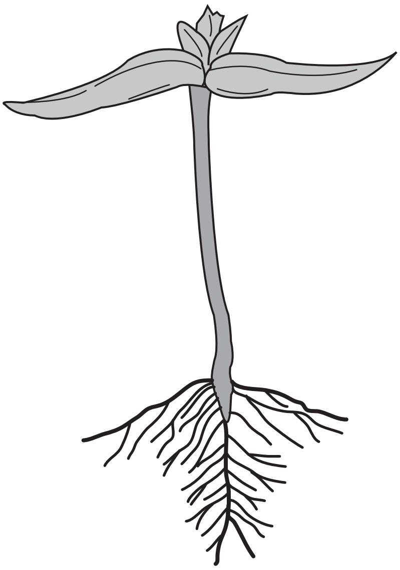


FIGURE 14.2 Seedling in cotyledon and early first-true-leaf stage. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

Once the true leaves have fully unfolded (2–3 wk after sowing), transplant the cubes into 3 in. × 3 in. × 4 in. (7.5 cm × 7.5 cm × 10 cm) deep rockwool blocks. Larger blocks 4 in. × 4 in. × 3 in. (10 cm × 10 cm × 8 cm) are better if the seedlings are to be grown longer in the propagation area. The blocks should be thoroughly watered with a solution having an EC of 2.5–3.0 mmho and a pH of 6.0. For plants not grafted, invert the seedlings at 90° when placing them into the rockwool blocks (Figure 14.3). This procedure will strengthen the stems of seedlings, as adventitious roots will form on the buried part of the stems to increase roots, resulting in a stronger seedling. Stem breakage will be reduced by not watering the seedlings 24 h before transplanting. Space the blocks in a checker-board pattern at 4–6 in. (10–15 cm), depending

FIGURE 14.3 Transplanting tomatoes on side into rockwool blocks. (From CuisinArt Resort & Spa, Anguilla. With permission.)

on the time before transplanting to the slabs or pots of the production area. If the plants are going to be held for 3–4 wk after this transfer to the blocks, space them at about five to six plants per flat (Figure 14.3). Many growers using rockwool or coco coir slabs transplant to double blocks 6 in. × 3 in. × 2.5 in. (15 cm × 7.5 cm × 6.5 cm) (length × width × height). Two seedlings are transplanted per double block. Each slab after transplanting will contain six plants that are trained in a V-cordon configuration strung alternatively to overhead support wires. Optimum temperatures during day and night are 23°C (73°F) and 20°C (68°F), respectively. Maintain CO_2 levels between 500 and 700 ppm (mg/L).

A regular spray program to prevent diseases will assist the plants in becoming very healthy and prepared to cope with transplanting stress. Before transplanting to the slabs, use the beneficial microorganisms “Mycostop” or “RootShield” to prevent *Pythium* and *Fusarium* fungi infection. Hydrogen peroxide at 30–50 ppm in the nutrient solution will help reduce water-borne root rot diseases. Use good sanitation during transplanting. Transport all seedlings in sterilized trays and on sterilized equipment. Do not place them on the floor during transplanting, only directly on top of the slabs or other substrates. A healthy tomato transplant will be as wide as it is high with a thick, sturdy stem when it is transplanted (Figure 14.4).

14.3.2 CUCUMBER SEEDLING CULTURE

Similar to tomatoes, European cucumbers should be sown in 1.5 in. × 1.5 in. × 1.5 in. (4 cm × 4 cm × 4 cm) rockwool propagation cubes. However, as seeds are high in germination (usually 98%), they may be sown directly into rockwool blocks instead of using the cubes first and later transplanting to the blocks. The 4-in. square blocks with small holes of 0.8 in. diameter × 0.6 in. depth (20 mm × 15 mm) are most suitable. Presoaking and subsequent watering procedures during germination to prevent drying must be adhered

FIGURE 14.4 Transplanting 5-wk-old tomato plants to perlite culture. (From CuisinArt Resort & Spa, Anguilla. With permission.)

to as for tomatoes. Presoak the blocks thoroughly with water at 68°F–77°F (20°C–25°C), pH 5.5–6.0, and EC 0.5 mmho.

In areas of high solar radiation, covering the seeds in the holes with some coarse vermiculite will prevent drying of the seeds. This practice will also assist in the shedding of the seed coats. Do not use fungicides during the early stages of germination, as they could slow germination, causing stunting of the seedlings. For both tomatoes and cucumbers, hydrogen peroxide may be used at 30 ppm on the seedlings and up to 50 ppm if algae are present.

Germinate the seeds at air temperatures of 75°F (24°C). They will germinate within 2 d. On germination, maintain the rockwool block temperature at 73°F (23°C) for the next 17 d. Air temperatures during the day should be 79°F (26°C) and at night 70°F (21°C).

In more northerly latitudes where sunlight is limited during winter months, increase the EC to 2.5–2.8 mmho after 7 d. Increase day length to 18 h using supplementary lighting of 5,500 lx (510 ft-c) at plant surface. Regulate carbon dioxide levels between 700 and 800 ppm. As soon as leaves begin to overlap (within 10 d), space the blocks in a checker board fashion to reduce their density by half. This wider spacing will prevent the plants from growing tall and spindly, a condition that easily leads to disease infection. The seedlings may have to be spaced a second time if they are held beyond 3 wk and the leaves once again overlap.

If the seedlings are grown on wire mesh benches, the roots will be air pruned as they grow out of the blocks (Figure 14.5). As mentioned earlier, with tomatoes this forces the plants to form more roots within the blocks and reduces transplant shock as the roots can quickly grow into the slabs when transplanted.

Several days before transplanting, lower the seedling house temperatures to 72°F (22°C) during the day and 68°F (20°C) at night. Depending on seasonal sunlight and supplementary lighting used, an 18- to 28-d-old transplant should have three to four true leaves. In areas of high sunlight, the seedlings may be transplanted at an earlier stage. In Florida, we transplanted when seedlings had two leaves and the third was forming (Figure 14.5). In Anguilla, in the Caribbean, we transplant at the two-leaf stage (about 14 d after sowing).

FIGURE 14.5 European cucumber seedlings in rockwool blocks.

FIGURE 14.6 Cucumber seedlings 27 d from sowing; 7 d after transplanting. (From CuisinArt Resort & Spa, Anguilla. With permission.)

In Anguilla, we sow in rockwool cubes and transplant to rockwool blocks at 5 d. Within 1 wk they root in and grow about 6 in. (15 cm) a day (Figure 14.6), and by 3 wk from transplanting to the buckets the plants will start bearing fruit. They will be kept for 5–6 wk bearing before being replaced with new plants to give a total crop cycle of 10–12 wk. Procedures must be changed somewhat to fit local environmental conditions and seasons due to day length differences.

As with tomatoes, drench the pots or slabs of substrate with "RootShield," a beneficial fungus, before transplanting to prevent *Pythium* and *Fusarium* infection. In addition, use hydrogen peroxide at 30–50 ppm in the nutrient solution to prevent water-borne fungi.

With a 10% bleach solution, sterilize all trays, wagons, and so on to transport the plants into the greenhouse production area. Place an emitter immediately on top of each block to irrigate using the ribbed stakes so that no solution will contact the plant stem, to avoid fungal infection. Place at least one drip line next to each plant off the block to provide extra water, as cucumbers use a large amount of water once the leaves are fully expanded.

14.3.3 PEPPER SEEDLING CULTURE

Similar to tomatoes, pepper seed germination may vary, so one must determine the amount of extra seed needed by using the percentage germination given on the seed package. Add an extra 5%–10%, as germination and vigor are not uniform. Many growers use small, round plug trays (Grodan Kiem plugs) to sow pepper seeds into granular rockwool. This allows them to select the most uniform, vigorous seedlings for transplanting to rockwool blocks. Rockwool cubes may also be used for initial sowing. At about 14–18 d, the peppers in the rockwool cubes can be spaced to double the area by cutting the cubes in strips and making two flats from every one. At the same time, lay the cubes and plants on their sides so that the stems will bend up, as that will make it easier to transplant them on their side into the rockwool blocks (Figure 14.7). Peppers are now also grafted similar to tomatoes; if that is done, do not place them on their sides as was discussed earlier for tomatoes.

The B.C. Ministry of Agriculture recommends soaking pepper seeds with a 10% solution of trisodium phosphate (TSP) for 1 h before sowing to reduce virus infection. However, they warn of possible germination reduction because of the treatments. They also suggest using a 10% skim milk powder solution when handling the seedlings. The milk protein coats the virus making it noninfectious.

Soak the plugs or cubes with raw water of EC 0.5 mmho and pH 5.8. The seeds may be covered with coarse vermiculite or a polyethylene tent to obtain uniform temperature and humidity during germination. This applies especially to more northern regions having poor sunlight conditions during the winter months. After the seedlings emerge, use a dilute nutrient solution.

Germinate seed between 77°F and 79°F (25°C–26°C) and relative humidity (RH) from 75% to 80%. Maintain these temperatures during the day and night. As soon as the seedlings emerge, remove the tent, lower the air temperature to 72°F–74°F (22°C–23°C). Provide supplementary lighting of 5,500 lx (510 ft-c) for 18 h/d. About 4 d after emergence, permit the RH to decrease to 65%–70%.

After 17–18 d from sowing the seed, the seedlings are ready to transplant to 4-in. (10-cm) rockwool blocks when the first true leaves appear (Figure 14.8). Presoak blocks with a nutrient solution having an EC of 2.0–2.2 mmho and a pH of 5.2. Slowly reduce air temperatures to 73°F (23°C) day and night. Space blocks at six per tray to allow enough room for them to grow for 3–4 wk (Figure 14.9).

FIGURE 14.7 Peppers double spaced and placed on their sides.

FIGURE 14.8 Peppers transplanted to blocks at 25 d. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 14.9 Peppers 38 d old ready to transplant to pots or slabs. (From CuisinArt Resort & Spa, Anguilla. With permission.)

Plants need to be supported by bamboo stakes if they are allowed to grow longer than 3–4 wk before transplanting to the production area (Figures 6.74 and 6.75). In northern areas, the peppers may be kept in the rockwool blocks up to 6–9 wk depending on the season. During this late stage of growth in the blocks (4 wk or more after transplanting into the blocks), raise the EC to 3.0–3.2 mmho. Enrich with carbon dioxide at 800 ppm. Similar to tomatoes, during transplanting the peppers may be laid down or inverted to shorten their stems and produce more roots provided they are not grafted.

These recommendations are for more northerly regions of the United States, where peppers are seeded about mid-October for first fruit to set in early January.

14.3.4 Eggplant Seedling Culture

Procedures for sowing and temperature, CO_2, and light requirements are very similar to tomatoes. Transplant the eggplant seedlings to rockwool blocks at about 17–18 d, similar to peppers. Do not bend them down as is done for tomatoes and peppers. Follow the same procedures for presoaking of the cubes and blocks, EC, and pH as for tomatoes. After transplanting to the rockwool blocks, space them six to a tray as for the peppers. Within 2 wk they can be transplanted to the slabs or pots in the production area. By 8 wk from sowing and about 4 wk after transplanting to the pots they have to be trained to two stems and are setting fruit (Figure 14.10). Training of the plants is discussed in Section 14.13.

14.3.5 Lettuce Seedling Culture

For both raft culture and NFT, the best method of sowing seeds is in 1-in. rockwool cubes. Presoak the cubes with raw water similar to that of tomatoes and peppers. Use pelletized

FIGURE 14.10 Eggplants 8 wk from sowing growing in bato buckets of perlite. (From CuisinArt Resort & Spa, Anguilla. With permission.)

seed for automatic seeders. Generally, more uniform germination results from pelletized seed than with raw seed as the clay coating material retains moisture around the seed during the germination process. Always sow extra seed according to the percentage germination. Keep lettuce seed stored in the refrigerator to maintain its viablility. Do not store the seed for more than several months, as it loses its viability within 6 mo.

For specialized small NFT channels, sow the seeds in a coarse vermiculite substrate in 154-celled "creamcup" trays (Figure 14.11). An automatic seeder covers the seeds of the trays with a thin layer of vermiculite. The trays are irrigated on special ebb-and-flood tables (Figure 14.12).

Once the cotyledons are fully expanded and the first true leaves begin to emerge, use a nutrient solution of EC 1.5 and pH 5.4–5.8. Optimum germination temperatures range from 59°F to 68°F (15°C–20°C). Temperatures in excess of 73°F (23°C) may induce dormancy. This may be overcome by placing the seeds on moist paper towels in a refrigerator at 36°F–41°F (2°C–5°C) for 48 h before seeding. At CuisinArt Resort & Spa in Anguilla, we keep the seeds stored in a refrigerator at similar temperatures and have not found any dormancy problems. If dormancy is a problem, keep them at 61°F (16°C) until seedlings emerge. Maintain RH at 60%–80% and carbon dioxide at 1,000 ppm during the day. Use supplementary lighting with a day length of 24 h at seedling emergence during winter months of cloudy weather in the northerly areas.

Transplant to the production area of the greenhouse when three to four true leaves form at an age between 2 and 3 wk (Figure 14.13).

14.3.6 HERB SEEDLING CULTURE

Sow herbs in cubes or multicelled trays depending on the hydroponic growing system. Some herbs such as mint and rosemary are very slow in germinating, taking as long as 6–8 wk

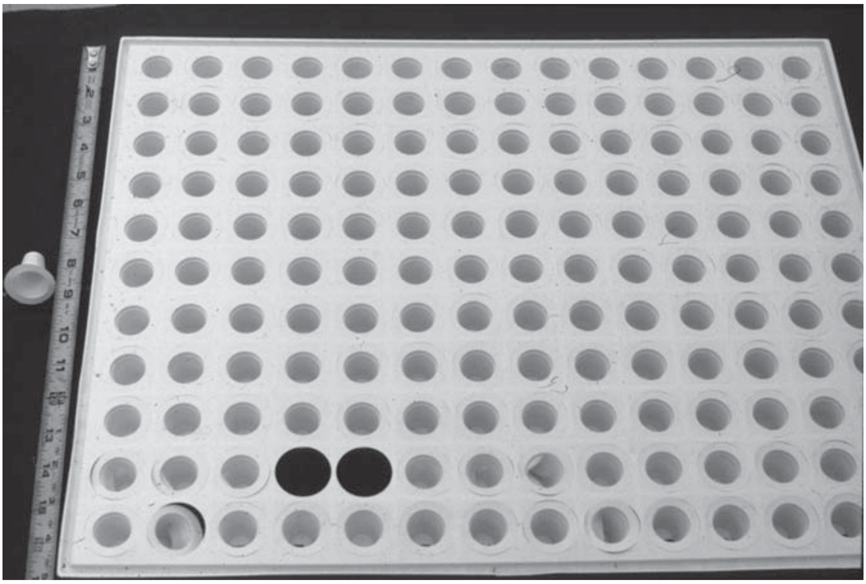


FIGURE 14.11 "Creamcup" trays, 154 celled. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

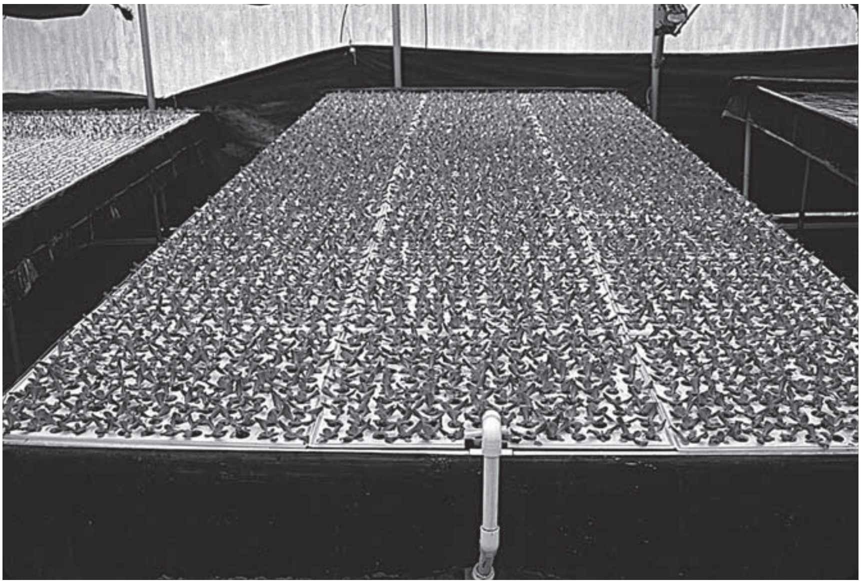


FIGURE 14.12 Ebb and flood seedling table—9 d old. (From F.W. Armstrong Ranch, Oak View, CA. With permission.)

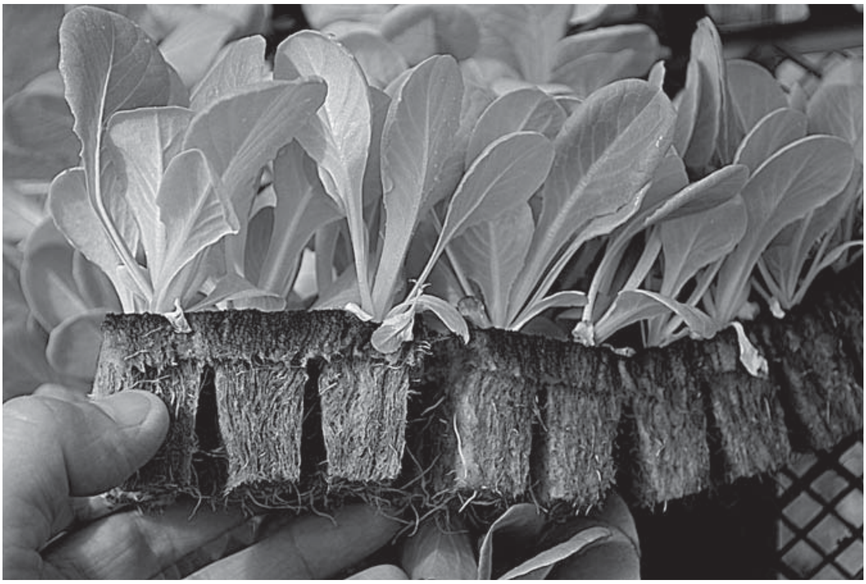


FIGURE 14.13 Bibb lettuce at 20 d in rockwool cubes ready to transplant. (From CuisinArt Resort & Spa, Anguilla. With permission.)

before they are ready to be transplanted. For such slow growing herbs, it may be better to use shoot cuttings to propagate them vegetatively. Cuttings taken from an existing crop will root within several weeks under a mist system with bottom heat. Sow small-seeded herbs such as mint, thyme, oregano, and so on in clumps of 6–10 seeds per cube or cell. Sow three to four seeds of basil and later thin to two per cube after 4 wk by cutting the extras off with a scissors. However, if growing "live herbs," do not thin and seed up to five to six per cube.

Favorable temperatures range from 65°F to 75°F (18°C–24°C). A pH of 5.8–6.2 and an EC of 1.6–2.5 mmho are suitable. Conditions similar to those for lettuce are generally good for herbs. During periods of cloudy weather, it may be necessary to raise the EC to prevent succulent growth. Since herbs are not a large greenhouse crop, one must rely on experience in one's region to determine the more optimum environmental conditions.

14.4 PLANT-GROWING TEMPERATURE

Usually better quality plants are grown when night temperature is 10°F (5.5°C) lower than day temperature. The best temperature range for warm-season crops is 60°F (16°C) at night and 75°F (24°C) during the day. Cool-season crops will do better at 50°F (10°C) night and 60°F (16°C) day temperatures. A 10°F (5.5°C) lower day temperature is best during periods of cloudy weather. These ranges are only guidelines. Specific optimum minimum and maximum temperatures depend on species and even varietal differences. In tomatoes, if the day–night temperature differential is too great, long upright clusters form, which will later kink and possibly break under fruit development.

If the temperature is too low, plant growth will be slower and some purpling of leaves may occur, especially on tomatoes. If the temperature is too high, growth will be soft and "leggy," resulting in poor-quality plants.

The optimum temperature for the tomato plant varies with the stage of plant development (Table 14.1). Tomato plants grown under optimum temperature and light conditions develop large cotyledons and thick stems, with fewer leaves formed before the first flower cluster, greater number of flowers in the first and often the second clusters, and higher early and total yields.

14.5 LIGHT

During cloudy weather, tomato leaves become low in sugars. Leaves and stems become pale and thin, and the fruit clusters may be smaller or fail to set. Excess nitrogen during such a period can be harmful. Supplementary artificial lighting has generally been found to be economically impractical except in the raising of seedlings, as mentioned earlier.

During bright, sunny weather, sugar production in the leaves is high. The leaves are dark and thick, stems are dark green and sturdy, fruit sets well with large clusters, and root systems are vigorous. Nitrogen can be supplied at a heavier rate during this period.

When the weather is cloudy for more than 1 or 2 d, it may be necessary to do the following:

1. Reduce day and night temperatures in the greenhouse 3°F–4°F (2°C).
2. Use as little water as possible but not let the plants wilt.
3. Adjust the nutrient-solution formulation to increase the EC.

These steps will help to keep plant growth balanced between leaf growth and fruit production. If they are not observed, the plants are likely to be very dark green and healthy, but are not likely to set many fruit.

During the seedling stage, plants should be transplanted to wider spacing in flats (at least 2 in. (5 cm) apart) or to individual containers at full cotyledon development or very early first-true-leaf stage (Figure 14.2) to reduce mutual shading. In flats, plants should be set

TABLE 14.1
Night and Day Temperatures from Seed Germination to Fruiting of Greenhouse Tomatoes, European Cucumbers, and Peppers

Growth Stage	Temperature, °C (°F) Night	Temperature, °C (°F) Day
Tomatoes		
Seed germination	24–26 (75–79)	24–26 (75–79)
After emergence, until 1 wk before transplanting	20–22 (68–72)	20–22 (68–72)
For 1 wk	18–19 (64–66)	18–19 (64–66)
After transplanting, until start of harvesting	16–18.5 (61–65)	21–26 (70–79)
During harvesting	17.5–18.5 (63.5–65)	21–24 (70–75)
European Cucumbers		
Seed germination	27–28 (81–82)	27–28 (81–82)
After germination (about 2 d)	24–25 (75–77)	24–25 (75–77)
First transplant to blocks	21–22 (70–72)	23–24 (73–75)
Several days before transplant to greenhouse	20 (68)	22 (72)
After transplant to slabs (use lower temperatures of these ranges as plants reach overhead wires)	16–20 (62–68)	21–24 (70–75)
Peppers		
Seed germination	25–26 (77–79)	25–26 (77–79)
After seed emergence	22–23 (72–73)	22–23 (72–73)
After transplanting	17.5–18 (64–65)	23–23.5 (73–74)
Growth and harvesting	19 (66)	22 (72)

To convert from temperatures in Fahrenheit to those in Celsius, use the following formula: (F−32) × 5/9 = C, where F = degrees in Fahrenheit; C = degrees in Celsius.

out in about 3 wk to avoid spindly development. In individual small containers or growing blocks, plants can develop longer than 3 wk, provided they are spaced out as they grow to avoid crowding. Excellent plants can be grown in 3- or 4-in. (7.6- or 10-cm) pots or blocks, but they require more nursery space than do small containers. At this stage, generally six plants per flat is ideal spacing. Space them sufficiently to prevent leaf overlapping during growth. Good containerized plants have pencil-size stems and are about as wide, from leaf tip to leaf tip, as they are tall (Figure 14.4).

In northerly latitudes, during short, dull days of winter months, supplementary lighting should be used to provide additional intensity of light and to extend the day length. Seedlings at this stage should be provided with 5,500 lx (510 ft-c) intensity of light at plant surface for 14–16 h/d. At present, the most efficient lights for greenhouses are HID plant grow lights. They include MH and high-pressure sodium (HPS) lamps. MH lamps produce light in the blue spectrum and HPS bulbs emit an orange-red glow. MH lights are best for leafy growth to keep plants compact and are used mainly for controlled environments with little natural sunlight, whereas HPS lights increase flowering and are best for supplementary lighting with natural sunlight, as is the case in greenhouses.

HID lights come in 100, 250, 400, 600, 1,000, and 1,500 W. One unit will give adequate lighting for an area of 2 ft × 2 ft, 3 ft × 3 ft, 4 ft × 4 ft, 5 ft × 5 ft, 6 ft × 6 ft, and 8 ft × 8 ft, respectively. If the lights are used as supplementary to natural sunlight, the coverage area can be increased by about 50%.

The height to hang them above the crop is dependent on the wattage. Low-wattage systems (100 and 250 W) should be located at about 2–3 ft (61–91 cm), medium-output systems at 4 ft (1.23 m), and high-wattage systems (1,000 W and above) at about 4–6 ft (1.2–1.8 m).

There are switchable ballasts that allow growers to use either MH or HPS lamps. This enables the grower to change from the MH lamps in the early vegetative stage of growing to HPS lamps as the plants are to be steered toward a generative (flowering–fruit production) stage. An alternative is to also use a small percentage of MH units mixed with the HPS ones if growing under natural sunlight conditions of a greenhouse.

The section of the visible light that is useful for plant photosynthesis ranges from 400 nm of wavelength through 720 nm. The 400–520 nm range includes violet, blue, and green light; 520–610 nm includes green, yellow, and orange bands; and 610–720 nm includes the red band, where there is a large amount of absorption by the chlorophyll pigment during photosynthesis and promotion of flowering.

If supplementary lighting is to be used in the growing area, contact a light manufacturer or their distributors to have them layout the design and choose the best units to use for specific crops. Simply provide them with a plan of the greenhouse and the areas within it with the specific crops. One such lighting manufacturer is P.L. Lighting Systems (www.pllight.com).

14.6 RELATIVE HUMIDITY AND VAPOR PRESSURE DEFICIT (VPD)

Humidity is the quantity of water present in the air as vapor. RH is the amount of humidity present expressed as a percentage of the maximum possible at a given temperature. When air is completely saturated, it has an RH of 100%. Heating of the air reduces the RH, and cooling increases it. Increasing air temperature by 10°C (18°F) almost doubles the water holding capacity and therefore halves the RH. With a full crop in the greenhouse, plants will cool the air temperature by releasing water into the atmosphere by transpiration.

The relationship between RH and temperature affects the crop in a greenhouse. For example, if the greenhouse day temperature is 25°C (77°F) with 50% RH and at night the temperature falls to 15°C (59°F), the RH will rise to 90%. The RH within the crop will be even higher. Such high RH favors diseases. Ventilation is critical to lower the RH. Horizontal air-flow fans (HAF) mix up the air and will reduce the RH within the crop. Raising the temperature and ventilating with overhead vents or exhaust fans will assist in lowering the RH. Outside air can be drawn into the greenhouse by convection tubes and heated before entering the crop. This will reduce the RH. Large convection tubes under plateau gutters with the plants or overhead convection systems can bring in cold outside air that is heated before it reaches the crop.

Broad (2008) explained clearly the relationship between RH and VPD. At present, greenhouse operators measure and control moisture within the atmosphere by using the term vapor pressure deficit (VPD). Atmospheric pressure is typically 14.7 psi or 101 kPa. This is the pressure exerted in the atmosphere by all gases and water vapor. There is a maximum vapor pressure for any given temperature, which is the saturation pressure (100% RH). The VPD is the difference between the actual vapor pressure at a given temperature and the maximum (saturation) vapor pressure. VPD goes in the direction opposite to RH. When RH is high, the VPD is low.

If the VPD is too low, the temperature may be too low and/or the RH is high, causing the crop to be vegetative, soft, and with weak growth. If the VPD is too high, the crop is stressed and may become hard, stunted, and very generative. A good balance between vegetative and generative phases of plants is essential to productivity, as discussed in Section 14.10. VPD, temperature, nutrient formulations, and irrigation cycles are important in manipulating this balance between vegetative and generative phases.

14.7 CARBON DIOXIDE ENRICHMENT

In northern regions, carbon dioxide enrichment in greenhouses has improved productivity substantially. Commercial greenhouse operators claim a 20%–30% increase in tomato yields; better fruit set in early clusters, especially when low light levels would normally reduce fruit setting; and larger fruits. In Ohio, cucumber yields have increased as much as 40%. Lettuce yields have increased 20%–30% per crop, and faster growth rates have allowed production of an extra crop each year.

Carbon dioxide enrichment and supplementary artificial lighting is economically feasible to produce vegetable seedlings and bedding plants. These practices produce sturdier plants in much less time than conventional systems.

For maximum profits, there is an optimum CO_2 concentration that should be present inside the greenhouse, which depends on the stage of growth and species of crop, as well as the location, time of year, and type of greenhouse. Generally, levels at two to five times the normal atmospheric levels (1,000–1,500 ppm CO_2) may be taken as the optimum levels.

On cool days, when greenhouses are being heated and air vents are closed, plants will deplete the CO_2 in the greenhouse atmosphere. In 1 h, plants in a closed greenhouse may lower the CO_2 concentration enough to significantly reduce growth rates. Air venting to maintain CO_2 concentration at outside levels would increase heating costs substantially. In these circumstances, special heaters using propane, natural gas, or fuel oil can supply CO_2 while simultaneously raising temperatures.

Carbon dioxide enrichment may be expected to increase fertilizer and water requirements, since plants will be growing more vigorously. Young tomato plants are especially responsive to CO_2 enrichment. Wittwer and Honma (1969) claimed that growth rates can be increased by 50% and early flowering and fruiting accelerated by a week or 10 d. Effects are carried into the fruiting period. Not only is top growth and flower formation accelerated but root growth is also promoted even more. Carbon dioxide enrichment is of special significance in hydroponic culture since one of the sources of the gas, decaying organic matter in the soil, is not present.

In general, the optimum carbon dioxide levels during the day for tomatoes, cucumbers, peppers, and lettuce are 700–1,000, 800–1,200, 800–1,000, and 1,000–1,200 ppm, respectively.

14.8 TRANSPLANTING

Good-quality transplants are essential to a good greenhouse crop. They must be set into the beds, pots, or on slabs properly and cared for afterward to avoid any check in growth. For the least amount of transplanting shock, plants should be the right age and moderately hardened. Tomato or pepper plants should not have any fruit set.

Containerized plants undergo less transplant shock than bare-root plants because there is little or no disturbance to the root system. The transplanting shock of bare-root plants can be minimized, however, with proper planting and care.

When transplanting tomatoes to gravel medium, the crown area of the stem may be set below the bed surface up to 1–2 in. (2.5–5 cm) to provide better initial support for the plant. This also allows new roots to develop on the buried stem section. With leggy plants, 4–5 in. (10–15 cm) of stem may be buried at an angle. The above-ground portion will grow vertically from where it enters the medium. With rockwool culture, it is common practice to bend the stem from a right angle to a complete inversion when placing seedlings from the propagation cubes to the blocks, but do not do this with grafted plants. With perlite culture, if the seedlings from propagation cubes are planted directly into perlite bato buckets without the use of rockwool blocks, they can be turned at a right angle or inverted into the perlite. This same practice may be used for peppers, but not for cucumbers or lettuce. These vegetables should be transplanted with their crowns positioned at the medium surface, not below it, or severe disease infection can occur in the crown.

Irrigate the plants as soon as possible after they are set to avoid or minimize wilting. In gravel culture, the beds can be flooded while transplanting to maintain a high level of water in the coarse medium. Before planting, keep the containers or flats of plants moist. Properly set container plants will not wilt following transplanting, if their root balls are moist when planted and irrigation follows soon afterward. Bare-root plants may wilt after planting, even though irrigated immediately, but they will recover overnight.

Perlite and coco coir substrates are becoming more popular as discussed in Chapters 11 and 12 because they do not have the disposal problem of rockwool.

14.9 SPACING

Most publications on greenhouse tomato production suggest space allowances of 3.5–4 ft^2 (0.3–0.37 m^2) per plant (12,000–10,000 plants per acre). Plants may be arranged in double or single rows. The most recent method is to use a V-cordon arrangement of training tomatoes and peppers where every other plant is supported to the opposite overhead wire similar to that shown in Figure 14.29 for cucumbers. Plants are arranged in single rows, having double the plants per rockwool or coco coir slab (usually four to five plants per slab). Refer to Chapter 10 for more details. The same plant density is used at 3.5–4.0 ft^2 per plant.

Peppers are spaced similarly to tomatoes, with planting densities of 8,000–10,000 plants per acre (20,000–25,000 plants per hectare). This is equivalent to 3.3–3.5 plants per square meter of greenhouse area. Peppers are trained to two stems per plant, increasing the density to 6.5–7 stems per square meter. Eggplants are arranged at the same density and spacing as peppers, with two stems per plant.

If double rows are used, place three plants per slab, whereas in a single row use five plants per slab. Most growers use single rows, with the plants trained in a V-cordon configuration to the overhead support wires. For double rows, space each row 40 cm (16 in.) apart and 1.46 m (57 in.) between the drainage/irrigation lines. Slabs are spaced 23 cm (9 in.) apart within each row using 100 cm (39 in.) long slabs. In a single-row configuration, rows are 1.8 m (71 in.) apart, and the slabs are placed together end to end within the row.

European cucumbers require a minimum row width of 5 ft (1.5 m). For the spring/summer crop, the plants require 7–9 ft^2 (0.65–0.84 m^2) for each plant, and for the fall crop

9–10 ft^2 (0.84–0.93 m^2). This is a population of 5,000 plants per acre or 12,500 plants per hectare. Plants can be placed in single rows 14–16 in. (35.5–41 cm) apart within the row. Tie plants alternately to overhead wires spaced 2.5–3 ft (0.76–0.9 m) apart in the V-cordon method (Figure 14.29), permitting more uniform light on the plants.

14.10 VEGETATIVE VERSUS GENERATIVE GROWTH

Plants have two phases of growth, vegetative when leaves and stems are growing rapidly, and generative, when they are blooming and forming fruit. In crop production we must maintain a balance between vegetative and generative phases to maximize yields. Initially, when plants are young we emphasize the vegetative phase to get them established with relatively large leaves and stems. This phase is important in establishing sufficient photosynthetic area for the plant to produce sugars that are later used in production of fruits. Once the plant has sufficient leaf area to support fruit formation, we wish to shift it into a more generative phase. In this phase, the sugars are shifted into flower and subsequent fruit formation. In this way, the plant is capable of producing larger and more fruit. For example, as discussed later, in European cucumbers we remove the first eight flowers to keep the plant vegetative, forming large leaves that will later provide photosynthates in forming fruits. As mentioned earlier, with tomato seedlings we want the stems to be pencil thick and the leaves large so that the transplant's area is as wide as high. This initial vegetative growth prepares the plant for later fruit development.

As the plants begin to form fruit, it should be possible to shift their growth to more generative or more vegetative, depending on their growth rate. This can be done by changing certain environmental and nutritional factors. This manipulation of the plant environment to shift it to more vegetative or generative growth is termed *plant steering*. Try to change only one or two factors at a time and look for the desired results. If these changes do not give the needed response, change others. Generally, tomatoes should be steered toward generative growth early in their development. Peppers when young must establish strong vegetative plants before fruit production. This is similar to eggplants. Cucumbers also must establish strong vegetative growth before fruit production. Steering of the plants is accomplished by manipulation of temperatures, irrigation cycles, EC, and pruning. The balance can be influenced by day and night temperatures. The grower must become familiar with the vegetative and generative characteristics and alter the environment and feeding program to acquire the desired result.

With peppers, high light and temperatures direct plants to remain generative. Being too generative will result in small fruit. Maintain six fruits per stem (10–12 fruit per plant). Excessive fruit may stop or slow plant growth, resulting in decreased fruit weight and size. Flowers should not be higher than about 10 cm (4 in.) from the growing tip of the plant. To make the plants more vegetative, raise the night temperatures and reduce the day temperatures, keeping the 24-h average at 20°C–22°C (68°F–72°F). Under lower light intensities of fall months, the 24-h temperature range can be lowered to 20°C (68°F), with night temperatures at 17°C–18°C (63°F–64°F) and day temperatures at 20°C–21°C (68°F–70°F). Maintain carbon dioxide levels between 800 and 1,000 ppm. Under high light conditions, shading of 25%–30% will reduce sunscald and cracking of the fruit.

During fruit production of cucumbers, night temperatures should be maintained at 18°C–19°C (64.5°F–66°F) and day temperatures at 21°C–23°C (70°F–73°F). Therefore, the 24-h temperature will be about 20.5°C–21°C (69°F–70°F).

TABLE 14.2
Tomato Plant Characteristics of Generative versus Vegetative Phases

Characteristic	Too Generative	Too Vegetative
Leaves	Short, dark, and firm	Long, open or springlike curled, light green, and soft
Truses	Stems are thick, sturdy, short, and curved	Thin, long, bent upwards
Flowers	Dark yellow, close to top of the plant, open fast and uniformly within the truss	Light yellow, form far under the top of plant, open poorly, sepals stick together
Fruits	Many fruits (4–6) form quickly with good shape	Few fruits develop slowly, small, with poor shape, may be deformed

TABLE 14.3
Parameters to Shift Tomato Plants toward More Vegetative or More Generative

Parameter	More Vegetative	More Generative
Irrigation cycle length and frequency	Shorter and more frequent	Longer and less frequent
Start irrigation	Earlier	Later
End irrigation	Later	Earlier
Leachate	More leaching, EC lowers	Less leaching, EC rises (cloudy)
Moisture deficit	Lower	Raise
Temperature difference day to night (0°C–5°C) (0°F–9°F)	Smaller	Larger
Carbon dioxide (350–1,000 ppm)	Less	More
EC-irrigation (2.5–4.0 mmho)	Lower	Higher
Truss pruning	More (4 fruits)	Less (5–6 fruits)

Tables 14.2 and 14.3 are based on characteristics of tomatoes, but the general principles apply to other fruit-bearing crops.

14.11 IRRIGATION (FERTIGATION)

Once the plants have been transplanted, the feeding-irrigation system cycles must be set. The time between irrigation cycles depends on a number of factors, as discussed earlier, including the type of growing medium used. Regardless of the hydroponic growing system (rockwool, sawdust, perlite, peat-lite, coco coir), a drip irrigation system with a fertilizer injector is used to provide the plants with water and nutrients. Most hydroponic greenhouses use fertilizer injectors with stock solutions. In the past, two-part stock solutions A and B in separate storage tanks use concentrated nutrient formulations from 100 to 200 times the normal strength. In addition, a stock solution of an acid or a base in the third tank adjusts the pH of the final solution. At present, more growers are setting up the stock solutions separately for each fertilizer salt for the macroelements and a separate one for minor elements. The reason for this is versatility in adjustment of the nutrient formulation. These adjustments are made during changes in sunlight conditions and enables flexibility in steering the plants. The injector dilutes these concentrates proportionally with water in a blending or mixing tank or in large main lines as the solution is pumped through the drip irrigation system.

As described in Chapter 3, new systems utilize computer feedback systems that monitor and adjust the return solution from the crop. Now such recirculation systems are part of the sustainable yields program to conserve water and efficiently utilize fertilizer salts.

Frequency and duration of irrigation cycles depends largely on the substrate water-retention characteristics. Rockwool needs less irrigation than perlite. See Chapter 10 on rockwool culture for specific details. Coco coir irrigation cycles are more similar to a peat-lite substrate, as was described in Chapter 11. More frequent irrigation is needed after transplanting until the plants become established in the substrate. After that, 5–10 irrigation cycles per day may be adequate, depending on environmental conditions and plant stage of growth. Perlite generally needs more frequent irrigation cycles than rockwool as it has less water retention.

14.12 PLANT SUPPORT

Vine crops such as tomatoes, peppers, eggplants, and cucumbers must be trained vertically to maximize production. Training must begin as soon as the plants are transplanted into their final growing system. Support the plants with plastic twine attached to overhead cables. Any vine crop, such as tomatoes, that must be lowered during their crop cycle requires plant hooks, such as "Tomahooks." These hooks have additional string wrapped on them to permit the lowering of the vines as they grow upward (Figure 14.14). The hooks can be purchased already wound with extra string. Additional string needed

FIGURE 14.14 Plant "Tomahooks" attached to overhead support cable. (From CuisinArt Resort & Spa, Anguilla. With permission.)

is at least 20 ft (6 m). Attach the strings to cables located directly above the plant rows at a height of the greenhouse gutters or a maximum of about 5–6 m (16–20 ft) for the new glass Venlo greenhouses having gutters of 7 m (23 ft) or higher as can be seen in Figure 11.9.

The support string is attached to the bottom of the plant by the use of a plant clip below a healthy leaf. This is done during transplanting to begin training the plants vertically. As the plants grow, the string may be wrapped around the stem, always in the same direction (generally clockwise), and occasionally a plant clip may be placed under a leaf petiole to give additional support (Figure 14.15). The string is always wound around the stem of the plant in the same direction to avoid other workers accidentally unwinding the strings. Most growers use this method, but one can also just use plant clips about every foot in plant length as it grows without winding the string around the stem.

Peppers and eggplants should not need to be lowered as long as the support cables are at least 14–15 ft (4.5 m) in height. This is possible in most greenhouses that have a gutter height of 5 m (16 ft) or higher. Lowering peppers and eggplants in lower greenhouses is possible, but must be done with care, as the vines are brittle and break easily. We have found that when doing so only a few leaves should be removed, as the plants get very stressed. Eggplants are even more sensitive to lowering and tend to lose leaves due to senescence afterward.

All vine plants must be clamped to the string before they fall over. Secure the first clamp under a large leaf pulling the twine taut, but not so tight that when released it will pull the leaves up.

Clamping should be positioned as shown in Figures 14.15 and 14.16. Clamps should be placed directly under the leaf petioles, not above them, as such a position gives no support. Clamps should not be placed directly under flower clusters, as the weight of maturing fruit later (in the case of tomatoes) may break off the fruit cluster or fruit may be punctured by the clamps. With peppers it is important that the clamps are not set directly below the small fruit, as when the fruit expands it will grow into the clamp, deforming the fruit as shown in

FIGURE 14.15 Place stem clamps under a strong leaf.

Figure 14.17. Secure plant clips about every foot (30 cm) along the plant stem to give adequate support. The back hinge of the clamp must pinch the string as shown in Figure 14.16.

14.13 SUCKERING AND TRAINING (TOMATOES, CUCUMBERS, PEPPERS, AND EGGPLANTS)

Suckers are the small side shoots that grow between the main stem and the leaf petioles. They must be removed before they grow too large, as they drain the nutrients of the plant, which could otherwise go into fruit development. With tomatoes, they should be removed when they are about 1–2 in. (2.5–5 cm) long (Figures 14.18 and 14.19). At this stage, they can be easily snapped off by hand without creating a large scar of the axillary region (area between stem and petiole). With eggplants and peppers, remove the side shoots at the first or second node (Figures 14.20 and 14.21) depending on the ability of the side shoot to support the fruit.

With tomatoes, remove suckers by hand, which presents less hazard of spreading diseases than using a knife or pruning shears. Rubber or disposable latex gloves should be worn

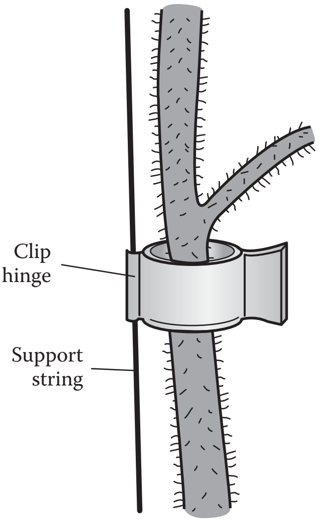


FIGURE 14.16 Correct positioning of plant clips and fastening to support string. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 14.17 Pepper fruit deformed by plant clip.

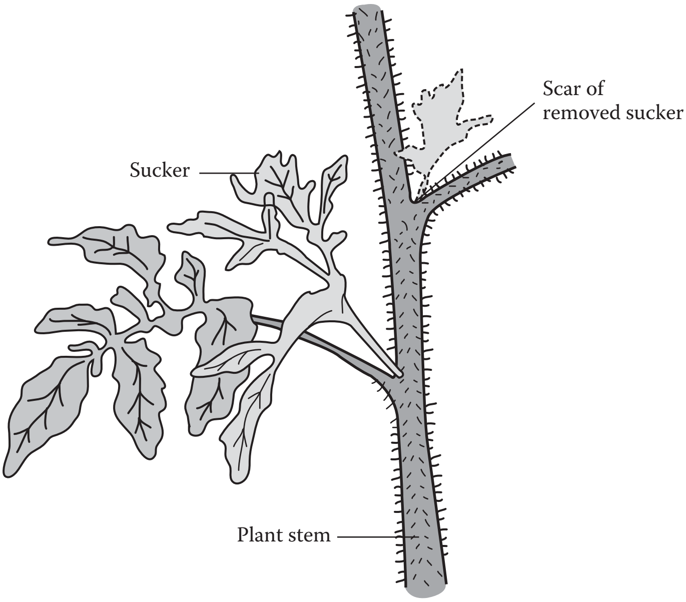


FIGURE 14.18 Removal of tomato suckers at an early stage. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 14.19 Tomato sucker ready to be removed.

FIGURE 14.20 Side shoot of eggplant.

to protect the hands from the acidic sap of the plants. Larger suckers, which may develop because of late suckering, will have to be removed with pruning shears or a knife.

Often, with tomatoes, terminated plants (those no longer having a growing point) will be encountered. Select a vigorous sucker near the growing point and allow it to continue growing, but remove other less vigorous suckers. Some plants may fork or split. Again, select the most vigorous branch and prune off the other growing point (plant apex).

Cucumber side shoots can be removed when they are smaller, more or less the same size as with tomatoes (Figure 14.22). This is a daily task when the plants are growing their principal stem before reaching the overhead supporting cable. Also, all tendrils as shown in Figure 14.23 must be broken off for the entire life of the plant as the tendrils tangle up the leaves and fruit, causing distortion and difficulty in the fruit hanging up, which will cause curved fruit.

As tomato plants mature and the fruits have been harvested from the lower trusses, the older leaves on the bottom of the plant will begin to senesce (yellow) and die. These leaves should be removed to allow better air ventilation and thus lower the RH around the base of the plants. Start taking them off from the time the second truss (fruit cluster) has been completely harvested. After that, continue removing leaves that turn yellow, up to the truss, then bearing mature fruit. In the past, it was recommended to simply snap off the leaves with fingers, but now more growers are using a sharp knife to get a clean surface to minimize scars. Remove all the dead leaves from the greenhouse and dispose of them by burying

FIGURE 14.21 Remove side shoots on peppers at either the first or second node. Note: The main shoot has the plant clips.

them in a pit or haul them to a landfill. This leaf pruning can be repeated many times as the plants mature, usually once a week when the plants are lowered. Generally, no more than three to four leaves should be removed at any time and not more frequently than once per week. The exception is when the plants are to be steered more toward being generative during their early stage once they reach about 3–4 ft (1 m) in height. Removing lower leaves will stress them and shift them to being generative.

As the tomato plants reach the support cables above, unwind the support string and lower the plants 12–16 in. (0.3–0.4 m) each time. Since the lower leaves and fruit have been removed, the stems can be bent to rest on plant stem support wires as described in Chapter 10. Lower the plants slowly to avoid breaking the stems. At all times, about 6–7 ft (1.8–2 m) of foliage and fruit clusters should remain on the upper part of the plant (Figure 14.24).

Flower trusses on beefsteak-type tomatoes may be pruned to select the most uniform four- to five-set fruit on a truss (Figure 14.25). Any misshapen flowers, double set fruit, and often the furthest flower out on the truss are removed. This gives uniform fruit development, shape, size, and color of tomatoes. Blossoms and small fruit should be removed as soon as two or three fruits set to pea size.

With many of the beefsteak varieties, which set fruit heavily, as the fruit develops on the truss, the weight of the fruit causes the truss to buckle or break, resulting in lost production. Truss-support clips and hooks have been developed to prevent such breakage. They are

FIGURE 14.22 Sucker of European cucumber ready to be removed.

inexpensive plastic flexible supports that easily snap onto the truss stem early after fruit set, whereas the hook is attached to the truss and support string as shown in Figures 14.26 and 14.27.

Long English (European) cucumbers are grown in greenhouses since they can be trained vertically and cannot withstand the temperature fluctuations they would encounter under outside conditions.

European cucumbers should be trained under two systems: the renewal umbrella system (Figure 14.28), and the V-cordon system (Figure 14.29). A V-cordon system trains the plants to make best use of available light within the greenhouse. Over each row of plant two support wires are placed 7–10 ft (about 2–3 m) above the floor, or close to gutter height when using carts to work on the plants. At present, the most common method is the "high-wire" system in which cucumbers are planted in raised trays, as described in Chapters 10 and 11, using coco coir or rockwool in the FormFlex trays. Since most greenhouses now have high gutters of 6–7 m (20–23 ft), the plants can be trained to 5–6 m (16–20 ft). The cables are spaced 2.5–3 ft (0.75–1 m) apart. The support strings are then tied alternately to the two overhead wires so that the plants are inclined away from the row on each side (Figure 14.29). Suckering and trimming of cucumbers is necessary to obtain a balance between the vegetative vigor and fruit load of each plant. Suckers, and also all blossoms and fruit, should be removed up to the sixth or seventh true leaf. All tendrils must be removed daily (Figure 14.23).

FIGURE 14.23 Tendrils of cucumbers must be taken off daily.

FIGURE 14.24 Removal of lower leaves and setting of bare stems on support bars. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

FIGURE 14.25 Prune fruit from trusses while fruit is small.

FIGURE 14.26 Truss support hook attached to truss and support string.

FIGURE 14.27 Truss clip on fruit cluster to prevent kinking.

If too many fruits are allowed to form at any one time, and too early, a large portion will abort because the plant may not have sufficient food reserves to develop them. If a heavy load of fruit sets, often malformed or poorly colored fruits develop, which are unmarketable. Remove them at an early stage as shown in Figure 14.22. Multiple fruits in one axil should be thinned to one.

The renewal umbrella system of training plants is achieved by the following steps:

1. The main stem should be stopped at one to two leaves above the support cable. Cut off the growing point at that level. It is better to leave three side shoots, two below the cable and one above it, and then thin out the third one once the side shoots begin to elongate. The reason for this is to have an extra one available in case one does not form properly. Fasten a plant clip under the last leaf below the wire to prevent the top from sliding back down.
2. Do not allow fruit to develop on the main stem up to six to seven leaves to promote vegetative growth that results in large leaves that are capable of manufacturing adequate food reserves for the fruit above.
3. Remove all laterals (side shoots) in the leaf axils on the main stem, except the two to three at the top.
4. Train the top two laterals over the cable to hang down on either side of the main stem. Allow these to grow to two-thirds of the way down the main stem.

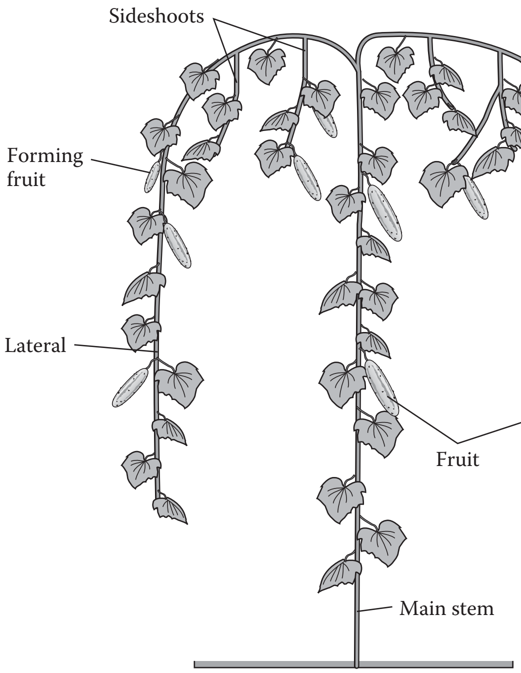


FIGURE 14.28 Renewal umbrella system of training European cucumbers. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

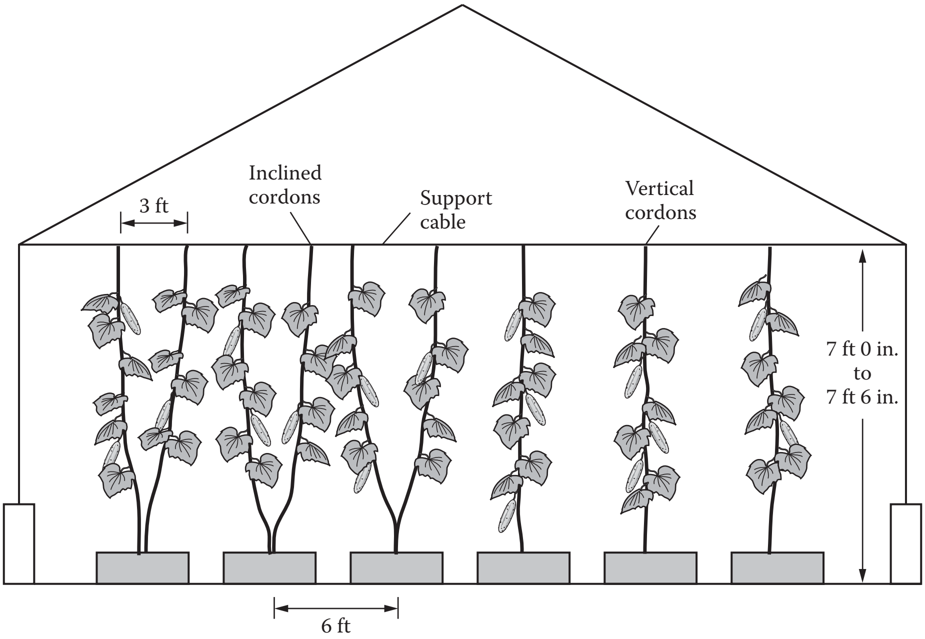


FIGURE 14.29 V-cordon system of training European cucumbers. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 14.30 Attaching plant clips on lateral shoots to support cable and at top of main stem. (From CuisinArt Resort & Spa, Anguilla. With permission.)

Training the main stem and laterals over the support cable can damage the plant if care is not taken. To overcome this problem, use a plant clip after the first axil of the lateral to attach it to the support cable as shown in Figure 14.30.

5. Remove all secondary laterals, except two at the top.
6. While the fruit on the first lateral are maturing, allow the second laterals to grow out and downward.
7. When the fruits on the first lateral have been harvested, remove them completely, allowing the second laterals to develop.
8. Repeating steps 5, 6, and 7 will maintain fruit production.

Some growers carry a cucumber crop for 10 mo using this renewal umbrella system and obtain over 100 cucumbers per plant. However, it is more productive to use two to three crops annually to get more vigorous plants that yield higher. In the warm climates of the semitropics and tropics, it is better to change the crops every 3 mo. In Florida, that was the most productive system of cropping. In Anguilla, we change the crops every 10–11 wk as the plants will grow from seed to first production within 5 wk.

Beit-Alpha (BA) (Japanese cucumbers or Persian pickles) are trained somewhat differently. BA cucumbers are also seedless or burpless, similar to the European cucumbers, but much smaller. They are usually from 5 to 7 in. (12.5–18 cm) in length and 1.25 in. (3.5 cm) in diameter (Figure 14.31). They are sometimes termed *mini cucumbers*. It is important that they are resistant to powdery mildew (PM) (Shaw and Cantliffe, 2003). In our trials of different varieties we found that under the tropical conditions of Anguilla, the most productive and most resistant to PM was “Manar,” a variety of DeRuiter Seeds (Resh, 2009).

Spacing of BA cucumbers is about half of that of the European types, usually about two to three plants per square meter (5–3 ft^2 per plant). In the bato bucket perlite system used in Anguilla at the CuisinArt Resort Hydroponic Farm, the rows are 6 ft apart (1.8 m), and pots are spaced at 16-in. (40-cm) centers within the rows as described in Chapter 12. Two plants

FIGURE 14.31 Beit-Alpha (BA) cucumbers training.

are set in each pot, and they are trained in a V-cordon system. This spacing is equivalent to 3.75 ft^2 per plant.

A 3-mo cropping period is used. In Florida, they recommend three crops per year (Lamb et al., 2001; Shaw et al., 2004). The plants start producing 5 wk after sowing and will produce for about 7–8 wk under tropical conditions.

For the first four to five nodes, remove all side shoots to permit strong initial vegetative growth before bearing fruit. Fruit should be left on the main stem after this level (Figure 14.31). Permit the side shoots to develop to two nodes on the next four to five nodes (Figure 14.32). Above that height, allow the side shoots to develop fully, pinching them when they get within 2 ft (60 cm) of the plant base. Remove all tendrils on the main stem and initial side shoots. Unlike European cucumbers, BA cucumbers are not trained in a renewal umbrella form. BA cucumbers are not pinched when they reach the support cable, but their main stem is trained over the cable and allowed to come back down to within 2–3 ft (about 1 m) of the floor. A plant clip is attached to the main vine and support cable as it comes over the cable (Figure 14.33). This is a very general description of training, as it will vary with specific climatic conditions.

Harvestable fruit weighs between 115 and 120 g or four fruits per pound. If on the average we get eight fruits per plant per week, it is equivalent to 2 lb per plant per week (0.9 kg). While weekly production of European cucumbers averages between 2.5 and 3 lb (1.1–1.3 kg) per plant, the price of BA cucumbers is higher, so revenues may be somewhat better than for European cucumbers. Some reports (Shaw et al., 2004) indicate yields of 60 fruit per 4-mo season, harvesting for 11 wk.

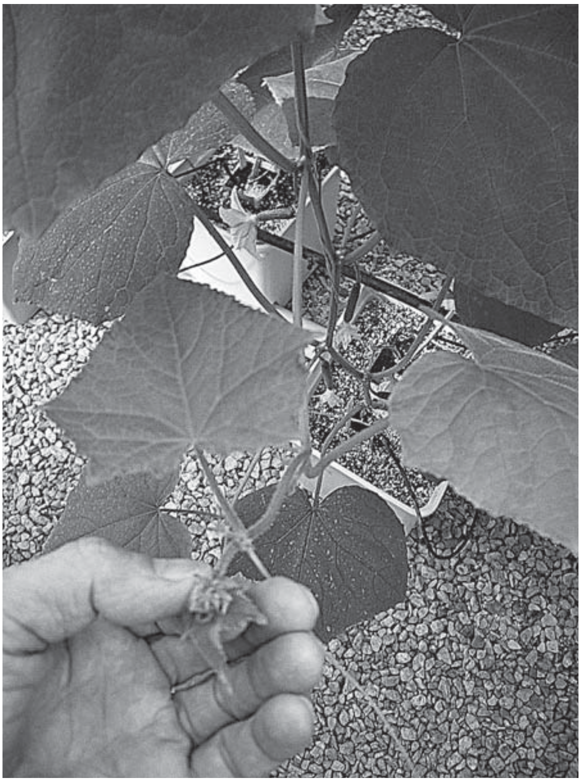


FIGURE 14.32 Pinch side shoots at two nodes on BA cucumbers. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 14.33 Bend growing point of BA cucumber over support cable and attach with a plant clip. (From CuisinArt Resort & Spa, Anguilla. With permission.)

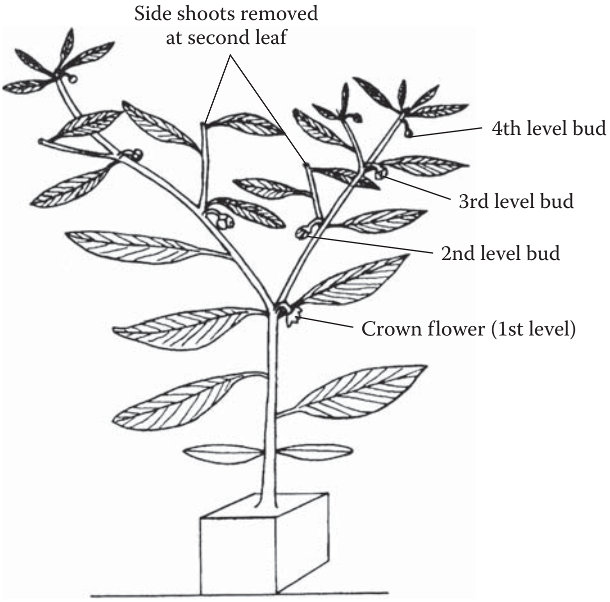


FIGURE 14.34 Position of flower buds and training of pepper plants in their early growth. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 14.35 Initial pruning of pepper.

The BA cucumbers have somewhat thicker skin than European cucumbers, but are still thin enough to not peel them. They do not need to be shrink-wrapped as do European cucumbers to conserve moisture. They will keep up to 14 d when stored at 50°F (10°C) with 95% RH (Sargent et al., 2001).

Researchers (Hochmuth et al., 2004) claim that BA cucumbers will tolerate both higher and lower temperatures of 90°F–100°F (35°C–40°C) and 60°F (15°C), respectively, compared to temperatures for European cucumbers, whose optimum ranges from 65°F to 90°F (18°C–32°C).

Peppers are trained as two stems per plant in a V-cordon system supported by strings attached to overhead wires (Figures 14.34 through 14.38).

While the pepper plant starts out as a single stem, it soon bifurcates to form two stems and then continues to do so producing additional stems. Flower buds form at these division points on the stem (Figure 14.34). The flower in the first division of the stem is called a “crown” bud. Most greenhouse peppers are trimmed to two stems. Additional stems must be pruned to maintain a balance between vegetative growth and fruit development. To encourage vigorous initial vegetative growth capable of supporting later fruit production, flowers must be removed from the first and second stem layers (bifurcations) generally to a height of 16 in. (40 cm). After two stems have formed, remove all side shoots after the second leaf (Figures 14.35 and 14.36). This suckering is necessary every several weeks. The support string should be wound around the main stems in a clockwise direction every 2 wk or plant clips placed every 12 in. (30 cm).

FIGURE 14.36 Side shoot to be removed at second node. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 14.37 Red bell peppers. (From CuisinArt Resort & Spa, Anguilla. With permission.)

Peppers grow slower than tomatoes or cucumbers. Generally, one crop per year is grown. The most common types of peppers grown are the four-lobed, blocky, sweet bell peppers (Figures 14.37 and 14.38). Red is the most popular color, making up 85%, followed by yellow (10%) and orange (5%). This mix of colors varies with market demand. Initially, these greenhouse peppers are green, ripening to the color of the variety. They are indeterminate (staking) varieties, so must be trained vertically in the greenhouse, similar to tomatoes. The plants grow to about 14–16 ft (4.3–4.9 m) in height during a single cropping cycle. In northerly latitudes, sow the seeds in mid-October, transplanting about 6 wk later, with harvesting beginning by March and continuing through mid-November. It takes 4 mo from seeding to first production. In southern latitudes, they can be sown in mid-July to get production by November, continuing until June of the following year. Annual yields should reach at least 23 kg/m^2 (4.7–5 lb/ft^2 or about 17–18 lb per plant).

As most greenhouses have gutters at least 4–5 m (13–16 ft) in height, it should not be necessary to lower peppers. They, however, can be lowered with care to prevent breaking of the very brittle stems. If the plants are lowered, remove three to four leaves first and lower them no more than 10–12 in. (25–30 cm). Unlike tomatoes, only a small number of leaves can be removed without stressing the plants.

Eggplants are becoming a more popular greenhouse crop because of the superior quality over field-grown eggplants. They are not blemished or bruised, since no wind

FIGURE 14.38 Yellow bell peppers in perlite in bato buckets. (From CuisinArt Resort & Spa, Anguilla. With permission.)

damage occurs. The eggplants are also indeterminate varieties. Most are Dutch greenhouse varieties in white or various shades of purple. Some are long and oblong, while others are more round in shape. They must be trained vertically in a V-cordon system similar to peppers as they are grown with two stems (Figure 14.10).

Eggplants grow faster than peppers and can reach a height of 16 ft (5 m) during a season. They are trained in a V-cordon system to the upper support cables. They are trained to two stems per plant very similar to peppers. They are allowed to bifurcate early similar to peppers by selecting the two most vigorous stems (Figure 14.39). Side shoots are removed at the second node so that at least one fruit will develop per side shoot (Figure 14.40). Place plant clips about every 12 in. (30 cm) along the main stem under a strong leaf to attach them to the support string. Eggplants have very large flowers and need to be pollinated. If the greenhouse gutters are less than 16 ft (5 m), the plants can be lowered; however, like peppers they get stressed during this process and often lose lower leaves. At the CuisinArt Resort Hydroponic Farm, we started lowering the eggplants after about 4 mo from sowing (Figure 14.41). As they continued growing to about 12–13 ft (3.6–4 m) (Figure 14.42), the plants began losing the lower leaves, so we cut the main stem back to the base and let two side shoots form as new plants (Figure 14.43). While the side shoots grew well, we found that it is better to run two crops per year to avoid this difficulty of lowering the plants.

FIGURE 14.39 Eggplant at 2 mo from sowing pruned to two stems. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 14.40 Side shoots are cut at the second node. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 14.41 Lowering of eggplants when they reach the support cables. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 14.42 The stems are lowered, and side shoots grow at the base. (From CuisinArt Resort & Spa, Anguilla. With permission.)

FIGURE 14.43 New shoots forming at the base after the old main stems are cut back. (From CuisinArt Resort & Spa, Anguilla. With permission.)

14.14 POLLINATION

Tomatoes, peppers, and eggplants are normally wind pollinated or pollinated by bees when grown outside. In greenhouses, however, air movement is insufficient for flowers to pollinate themselves. Vibration of the tomato flower clusters is essential for good pollination in a greenhouse. This can be done by tapping the flowers with a stick, fingers, or an electric vibrator such as an electric toothbrush. A very useful vibrator is the "Petal Tickler." It is a long vibrator that has high-frequency vibration to effectively dislodge the pollen of the flowers. The vibrator is momentarily held lightly against the flower-cluster branch (Figure 14.44). If environmental conditions are favorable and the flower is receptive, the fine yellow pollen can be seen flowing from the flower upon vibration.

Pollination must be done while the flowers are in a receptive state. This is indicated by their petals curling back in the case of tomatoes, and to a lesser degree in eggplants, the stamens are very prominent (Figures 14.45 and 14.46). Plants should be pollinated at least every other day, since blossoms remain receptive for about 2 d. Pollinating should be done between 11:00 A.M. and 3:00 P.M. under sunny conditions for best results. Research has shown that an RH of 70% is optimum for pollination, fruit set, and fruit development. High humidity keeps the pollen damp and sticky, except around midday, and lessens the

FIGURE 14.44 "Petal Tickler" used to pollinate tomato flowers.

FIGURE 14.45 Tomato flower cluster with receptive flowers.

FIGURE 14.46 Receptive eggplant flower.

chances of sufficient pollen transfer from anthers to stigma. Too dry conditions (RH less than 60%–65%) cause desiccation of pollen.

Greenhouse temperatures should not fall below 60°F (15°C) at night or exceed 85°F (29°C) during the day. At higher or lower temperatures, pollen germination and pollen tube growth are greatly reduced. Chemical growth regulators can be used to induce fruit development under lower-than-optimum temperatures, but these fruits are usually seedless. Open locules and thin outer walls may make the fruit soft and greatly reduce their quality.

If pollination has been done correctly, small beadlike fruit will develop within a week or so. This is called fruit set. When young plants produce their first trusses, pollinate each day until fruit set is visible. It is important to get the fruit set on these first trusses, as it throws the plant into a reproductive state, which favors greater flower and fruit production as the plant ages. After the first few trusses have set, pollinating can be done every other day.

In the past, pollination of tomatoes was done by using vibrators. Pollination of 5 acres (2 ha) of greenhouse tomatoes can take two people full time. Use of bumble bees (*Bombus sp.*) is now the accepted form of pollination of greenhouse tomatoes, a minimum of a 3% increase in yield is achieved according to Gipaanda Greenhouses Ltd. It is important to maintain the correct population levels of bumble bees, as overpopulation may result in the bees overworking the tomato flowers. This is particularly true with peppers, which

FIGURE 14.47 Bumble bee hives for pollination. (From Houweling Nurseries Oxnard, Inc., Camarillo, CA. With permission.)

require a lower population so they will not aggressively enter the blossoms and as a result cause a zipper-pattern scar on the fruit.

Bumble bee hives, costing about $350 each, are available from a number of suppliers (Appendix 5) (Figure 14.47). The population of one hive is sufficient to work one-half acre (0.2 ha) of tomatoes. A 66% sugar–water (by weight) solution with a preservative provides food for the bees, as the tomato flowers do not provide nectar. A supply reservoir sits above the hive. The bees form a round hive inside the box container. A Plexiglas plastic top under the reservoir allows the grower to visually observe the progress of the bee population. A slide stopper is positioned across the entrance to the hive to contain the bees when examining the inside of the hive.

The species of bumble bee is dependent on which are indigenous to the area they are applied. The longevity of the hive is highly dependent on active workers, a viable queen, and developing brood. Optimum temperatures for hives must be less than 85°F (30°C), or the hives shut down. Locate the opening of the hive toward a wall, walkway, or post to assist the bees to find it, as shown in Figure 14.47. The number of hives required for effective pollination ranges from 5 to 7.5 per hectare or 2 to 3 per acre. This is based on hive efficiency (activity of queen). Monitor the pollination by determining the percentage of bruised corolla (all petals together) and sample the blossoms at the postreceptive (folding-up of

FIGURE 14.48 Male flower on European cucumber. Note: No small fruit exists behind the blossom.

petals) stage, which should show 90%–100% bruising. This indicates the number of flowers worked on by the bees. Examination of the sugar–water consumption every 2–3 d should reveal that it is being depleted at a constant or increasing rate.

European and BA cucumbers, unlike the regular North American seeded cucumbers, do not require pollinating to set fruit, and the fruits are therefore seedless. Pollination may occur by bees and from male flowers (Figure 14.48) on the same or neighboring plants in the greenhouse. Pollination causes seeds to form, and the fruits become clubbed at the end and develop a bitter taste. To prevent pollination, bees must not be allowed to enter the greenhouse, and male blossoms should be removed from the plants as soon as they develop. Now, all-female varieties have been developed so the male blossoms seldom develop. However, periodically male plants develop initially and may turn to female as they grow. Remove the male flowers from these plants. The female flower is very distinct with its very small fruit behind the flower (Figure 14.49).

14.15 PHYSIOLOGICAL DISORDERS

Hydroponics has many advantages, but it does not free the grower from the need for alertness in dealing with many physiological disorders common to all forms of food production. Physiological disorders are those fruit-quality defects caused by undesirable temperatures, faulty nutrition, or improper irrigation. Some varieties are more susceptible than others to some of these disorders. Because we are using tomatoes, peppers, eggplants, and cucumbers as examples, we will present as a reference source several disorders common to those fruits.

1. *Blossom-end rot (BER) (tomatoes, peppers).* This disorder appears as a brown, sunburned, leathery tissue at the blossom end of the fruit (Figure 14.50). In the early stages, the affected area will have a green, water-soaked appearance. While the

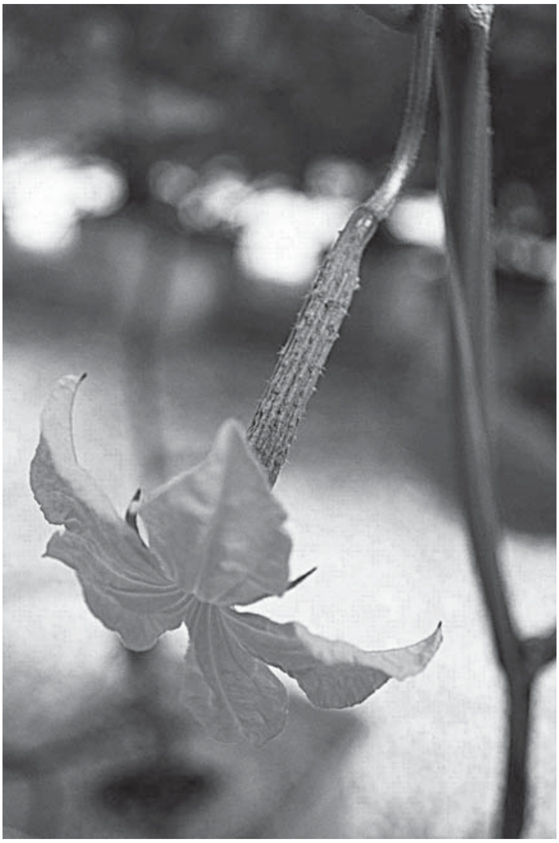


FIGURE 14.49 Female European cucumber flower.

cause of BER is a low supply of calcium to the fruit, the indirect cause is plant stress. This stress may be due to (a) low soil moisture, (b) excess soluble salts in the growing medium, (c) high rates of transpiration, and (d) high soil moisture in heavy soils, which leads to poor root aeration. BER, assuming that calcium levels are sufficient, may be due to low RH (50% or lower) combined with high temperatures (28°C or 82°F or higher). These conditions cause a rapid increase in transpiration that results in high water loss from the leaves, and consequently the calcium travels in the water to the leaves and not to the fruit. Also, high RH in excess of 90% causing insufficient root oxygenation will decrease transpiration and calcium uptake.

BER may be reduced by maintaining night and day RH at 65%–75% and 75%–85%, respectively. Provide good oxygenation to plant roots. Allow more fruit to develop on the first two trusses. Do not remove fruit affected with BER. Apply shade during high light periods of the day. Maintain a good balance between vegetative and generative phases. Researchers claim that the most critical period is about 2 wk after flower development when the rate of fruit growth is greatest (El-Gizawy et al., 1986).

2. *Fruit cracking (tomatoes, peppers, eggplants).* Symptoms are cracks radiating from the stem, almost always on maturing fruit, at any time during ripening (Figure 14.51). This is usually caused by water deficit and excessively high fruit temperatures followed by a sudden change in moisture supply to the plants. Prevention is by avoidance of high fruit temperatures and maintenance of uniform soil (medium)

FIGURE 14.50 Blossom-end rot (BER) of tomatoes.

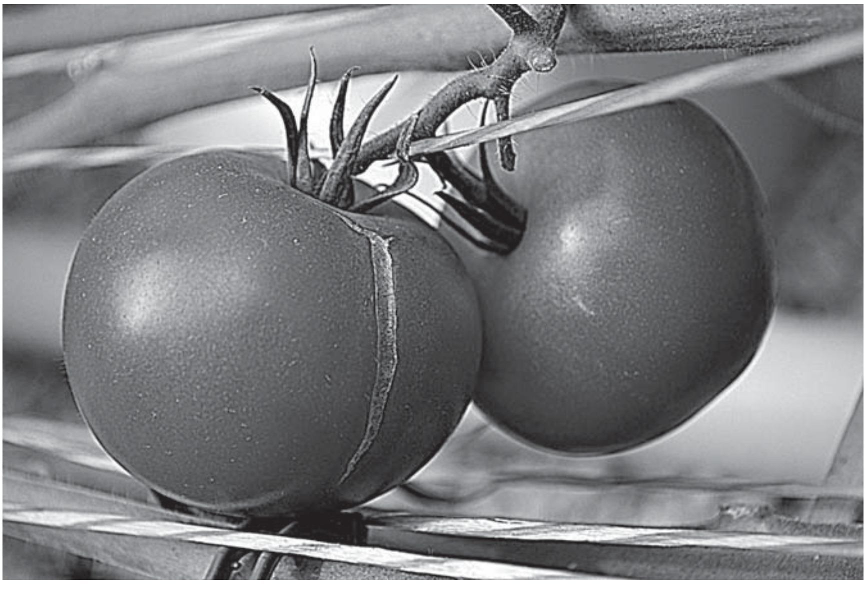


FIGURE 14.51 Fruit cracking of tomatoes.

moisture conditions. Start irrigation cycles from 1 to 2 h after sunrise and the last one 1 h before sunset. One may find that a night irrigation cycle could help.

3. *Blotchy ripening (tomatoes).* This is uneven coloring of the fruit wall in the form of irregular, light green to colorless areas, with brown areas in the vascular tissue inside the fruit. It is associated with low light intensity, cool temperatures, high soil moisture, high nitrogen, and low potassium. It can be avoided under low light intensity conditions by less frequent irrigation cycles and less fertilizer (especially nitrogen).
4. *Green shoulder, sunscald (tomatoes, peppers, eggplants).* These disorders are associated with high temperature or high light intensity (Figure 14.52). Avoid removing leaves that offer protection to fruit clusters during the spring and summer months when sunlight is intense, and keep greenhouse temperatures down. Maintain a good leaf canopy, and use shading under high light. Peppers are particularly susceptible to sun scald.
5. *Misshapen fruit, roughness, and catfacing (tomatoes, peppers).* This is radial wrinkling of the fruit shoulders and walls and fruit-shape distortion due to protuberances and indentations (Figures 14.53 and 14.54). This is caused by poor pollination and environmental factors such as low temperatures and high RH, which cause the flower parts to develop abnormally.

   Low RH during flower set can also contribute to this condition. Remove misshapen fruit early in its development.
6. *Crooking (cucumbers).* This is excessive fruit curvature caused by a slowdown in growth (Figure 14.55). It can be caused by a leaf or stem interfering with the growth of the young fruit or the sticking of a flower petal on the spines of a leaf, stem or another young fruit. Also, tendrils can attach to the young fruit and cause crooking. Other causes include mechanical damage, chilling injury, thrips injury, and gummy stem blight in the fruit. Adverse temperature, excessive substrate

FIGURE 14.52 Sunscald on pepper.

FIGURE 14.53 Catfacing of tomato.

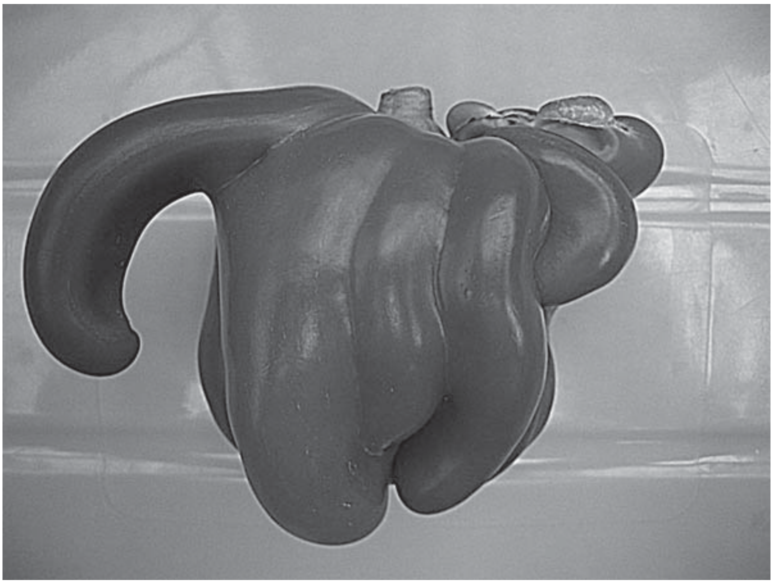


FIGURE 14.54 Catfacing of pepper.

moisture, and poor nutrition have also been suggested as causes. Remove severely curved fruit from the plant immediately.

7. *Fruit abortion (cucumbers).* Abortion of fruit occurs when very young if fruit load is too high, under low light levels, and/or poor root development. The most common cause is poor training of the plant and more than four to five fruits forming on the plant at the same time.

FIGURE 14.55 Crooking of cucumber fruit.

14.16 DISEASES AND INSECTS

Since the control of diseases and insects is very specific, only a brief description of the most common problems are given here. For additional information see articles listed in the bibliography and books having colored photographs (Blanchard, 1997).

14.16.1 Some Common Tomato Diseases

1. *Leaf mold (Cladosporium).* This starts as a small gray spot on the lower side of the leaf and spreads until a definite pale area also develops on the upper surface. Additional infection sites develop, and the initially small spots expand. The basic control measure is sanitation within the greenhouse and careful ventilation and temperature control to prevent high humidity. Some fungicide sprays can be helpful.
2. *Wilt (Fusarium and Verticillium).* Initially, plants wilt on hot days, then eventually they wilt all the time and the leaves become yellow. If the plant is cut just above the soil surface, a darkened ring is visible inside the outer green layer of cells. No spray or cultural treatment will control these diseases. They can be controlled through sterilization of the growing medium and use of resistant or tolerant varieties. Most growers now use grafted tomatoes and peppers to impart resistance to the scion cultivar against these organisms. All cultivars are given a code as to which disease organisms they have resistance against. A good summary of resistance codes is available through Enza Zaden's website, www.enzazaden.com. Whenever one searches for a cultivar it will be followed by the codes to which it is resistant. There are two levels of resistance, high resistance (HR) and intermediate resistance (IR). Those having HR restrict the growth and development of the pest or pathogen. They may exhibit some symptoms or damage under heavy pest or pathogen

pressure. Intermediate resistant varieties, while they do restrict the growth and development of the pest or pathogen, may express greater symptoms or damage compared to highly resistant varieties. Susceptible varieties are unable to restrict growth or development of pests or pathogens and therefore will suffer significant damage from them.

Some varieties are specifically resistant to certain strains of pathogens and not others. This is indicated by the code. The same codes are used for the same pathogens or pests regardless of whether the plant is a tomato, pepper, cucumber, eggplant, or lettuce, as some are common to a number of different crops.

A few typical codes are *Fusarium oxysporum f. sp. cucumerinum* (Foc)—cucumber *Fusarium; Fusarium oxysporum f. sp. lycopersici* (Fol)—tomato *Fusarium; Verticillium dahliae* (Vd)—*Verticillium* wilt of tomato; *Meloidogyne arenaria* (Ma)—root-knot nematode in tomatoes and peppers; *Cucumber mosaic virus* (CMV)—cucumber mosaic; *Tomato mosaic virus* (ToMV)—tomato mosaic.

3. *Early blight and leaf spot (Alternaria and Septoria).* These cause discolored or dead spots on the leaves. Early blight has dark rings on a brown background. Leaf spot has small black dots on the affected area. Both organisms attack the oldest leaves first and cause severe defoliation of the lower part of the plant. Proper ventilation and removal of lower senescing leaves to improve air circulation and reduce RH helps reduce the disease.
4. *Gray mold (Botrytis).* Under high humidity conditions, fungal spores infect wounds such as leaf scare, and a watery rot and fluffy gray growth forms over the affected area. The disease may develop along the stem for several inches and eventually girdle it, killing the plant (Figure 14.56). Proper ventilation to reduce the RH will prevent the spread of the disease. Remove infected plants immediately. Affected areas at early stages of infection can be scraped and covered with a fungicide (Ferbam) paste, or the plant can be sprayed with Ferbam.

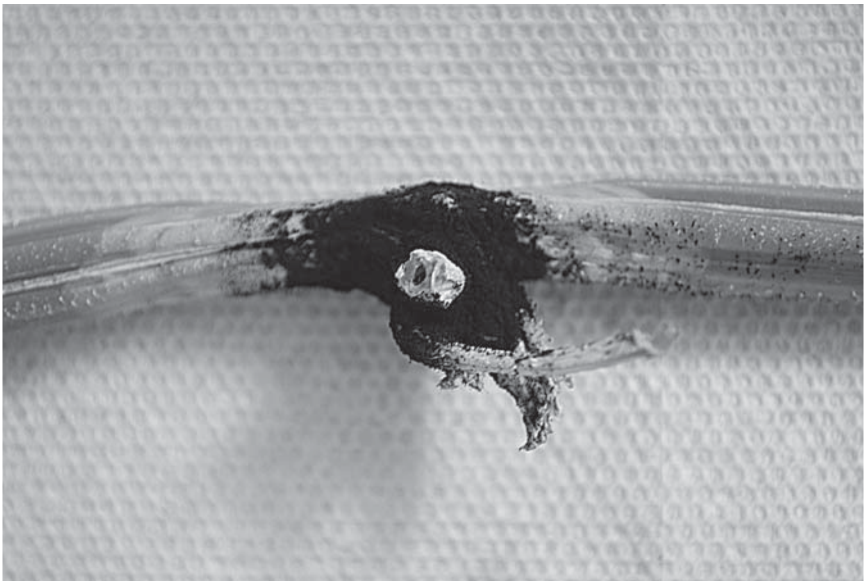


FIGURE 14.56 *Botrytis* on tomato stem.

5. *Virus (tobacco mosaic virus, TMV).* Several viruses will attack tomatoes. TMV is the most common, causing distortion of the leaves and stunting of growth, with resultant yield reductions. Plant juice containing the virus is spread by sucking insects or from the hands or tools of the people working with the crop. Sanitation, control of sucking insects, and no smoking (TMV is present in tobacco) in greenhouses will help avoid infection. At present, most tomato varieties have TMV resistance or tolerance, as is specified by the code ToMV by seed houses. This obviates the need for other TMV protection.

14.16.2 SOME COMMON CUCUMBER DISEASES

1. *Powdery mildew.* Small snow white spots initially appear on the upper surface of the leaves. They quickly spread in size and to other leaves (Figure 14.57). Proper sanitation and adequate ventilation are the primary control measures. Chemical control is also possible. Many growers use elemental sulfur vaporized by heating to form a smokelike cloud in the greenhouse overnight.
2. *Cucumber mosaic virus (CMV).* Some of the same strains of virus found on tomatoes also infect cucumbers. The affected leaves are dwarfed or become long and narrow. No control measure other than prevention through sanitation is known. Control of sucking insects would prevent spreading of the virus to other plants. Now, many cucumber cultivars have resistance to this disease bred into them and are indicated with the code CMV after the variety name.
3. *Wilt (Fusarium).* This is the same wilt disease as found commonly in tomatoes. Proper sterilization of the growing medium between crops and sanitation are the only control measures besides finding varieties resistant to the disease. Before transplanting, it is important to pretreat the substrate with a beneficial fungus such as RootShield (*Trichoderma harzianum,* strain T-22) as a drench or incorporation

FIGURE 14.57 Powdery mildew on cucumbers.

of a granular form into the substrate. This fungus protects against *Pythium, Fusarium, Rhizoctonia, Thielaviopsis,* and *Cylindrocladium* root disease organisms. It attaches to plant roots and releases an enzyme that dissolves the cell walls of these fungal pathogens. RootShield granules are blended into the substrate at a rate of 1.25–1.5 lb/yd^3 (0.57–0.68 kg/0.76 m^3). RootShield WP (wettable powder) is applied as a drench at a rate of 4.5 oz/100 gal (128 g/378 L). It can be applied through low-pressure nozzles, overhead boom sprayers or sprinklers, or subirrigation. For detailed information refer to BioWorks website, www.bioworksinc.com.

4. *Gray mold (Botrytis).* The symptoms and control measure are the same as for tomatoes.
5. *Gummy stem blight (Didymella bryoniae).* Tan-colored lesions appear on petiole stubs and the base of the main stem (Figure 14.58). It also infects flowers and developing fruit, causing shriveled fruit at the flower end and internal browning of tissue. Avoid condensation on plants and guttation (Figure 14.59) by adequate ventilation. Guttation is the escape of water along the leaf margins through special large cells usually in the early morning when root pressure is high and RH is high (VPD is low). Do not leave stubs when pruning, and disinfect pruning knives. Remove crop debris and bury away from the greenhouse. Apply fungicide sprays of Rovral 50 WP or Benlate 50 WP and Manzate 200 at 4- or 7-d intervals, respectively, when infection appears or during high humidity and low light levels. Do not apply within 5 d of harvest. Follow rate and application directions of fungicide label.

FIGURE 14.58 Gummy stem blight on stem of cucumber.

FIGURE 14.59 Guttation on cucumber leaf.

The following are other disorders or damage that may occur:

1. *Pesticide burn*. Often when spraying during high temperatures or under full sunlight without a shading system, even the mildest of bioagents (natural pesticides) can burn plants. The burn will start as a water sinking of the tissue and will be followed with drying and or bleached tissue of leaves (Figure 14.60). This is particularly evident with large, soft-tissue leaves of cucumbers.
2. *Guttation*. This is drops of liquid at the tips and margins of the leaves (Figure 14.59) as mentioned above. This occurs during the night as high root pressure pushes water up from the roots to the leaves and stems, especially under high RH. At night, stomates are closed and transpiration stops. Specialized structures called hydathodes located at the tips and margins of the leaves open, allowing the excess water accumulating in the leaves to escape, forming water droplets. When the water evaporates later in the morning as RH falls and ventilation is present, a film of dried sugars and minerals remains at the edges of the leaves.
3. *Edema*. Similar to guttation, this is a physiological disorder that develops when the plant absorbs water faster than it is lost by respiration. This excess moisture in the plant builds up and causes swellings on the leaves (Figure 14.61). They initially form as pale-green blisters or bumps on the underside of the leaves and progressively swell through to the upper leaf surface. Do not mistake them for some fungal rusts. The cells eventually form larger yellow to brownish spots. This disorder does not affect fruit production in tomatoes, but eventually can damage the leaf area sufficiently to reduce yields if it continues for some time. Conditions that favor it are cloudy weather with high humidity and cool temperatures. To prevent it, cut back on watering cycles during periods of dull weather, increase light if possible by supplementary lighting, and increase ventilation in the greenhouse and around the plants by removing lower leaves on tomatoes. Plants will recover from edema under more favorable growing conditions.

FIGURE 14.60 Pesticide burn on cucumber leaf.

FIGURE 14.61 Edema on cape gooseberry leaves.

14.16.3 INSECTS

Biological control of insect pests is now widely accepted in the greenhouse industry. A number of companies (Appendix 2) sell these biological agents. Biological control refers to the use of living organisms to control other living pest organisms. Integrated pest management (IPM) is the use of beneficial insects and natural pesticides as a pest management program to control pests. There are a number of very good websites that give details on identification of pests and the natural organisms used in their control as outlined in Appendices 2 and 5. An excellent identification reference book is by Malais and Ravensberg, 1992.

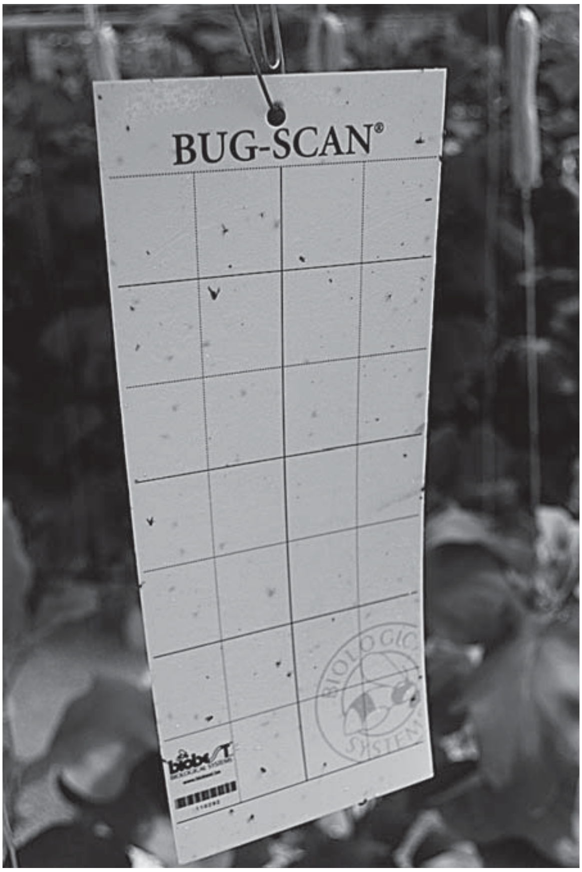


FIGURE 14.62 "Bug-Scan" sticky card.

In IPM, pests can be controlled in a sustainable fashion by using biological, cultural, physical, and chemical methods that minimize environmental risks. For the program to be successful, the crops must be monitored for pests at least once a week using sticky cards (Figure 14.62). Identify and record the pests present on the cards to determine their population dynamics. Set a threshold level at which numbers of any pest warrant action with the IPM program by introducing or reintroducing biological agents to control the pests. This balance between pest and beneficial insect populations must be kept in check by weekly monitoring and identification and introduction of additional beneficial agents as necessary.

There are a number of advantages to using biological control agents. Pests cannot build up resistance against biological agents as easily as they can with pesticides. The cost of biological control is less than that of pesticides. There is no fear of phytotoxicity or persistence of chemicals potentially hazardous to human health. Generally, biological control does not completely eliminate the pest, as a certain level of pest population is necessary to sustain the predator population. For this reason, emphasis is on integrated control, using biological control agents with cultural and chemical control measures. The objective is not complete pest elimination, but pest management, whereby pest populations are maintained at a level below any significant plant damage.

With an IPM program, only certain pesticides must be used, which do not harm the predatory agents. However, highly infested areas may be spot treated by other more poisonous pesticides if pest populations cannot be controlled by the biological agents. Once such infestations are reduced, the use of these chemicals should be restricted. Pesticides such as insecticidal soaps, insect growth regulators or hormones, yellow sticky traps, and bacterial or fungi insecticides may be used with the biological agents without harming them.

The grower must check with government agencies and companies selling biological agents to determine which pesticides may be used without harming the specific predators in their IPM program. For example, if a program of mite control using the predatory mite *Phytoseiulus persimilis* has been introduced into the greenhouse, outbreaks of the two-spotted mite may be controlled using Agri-Mek 0.15 EC (Abamectin 2%), which is harmless to the predatory mite. Yellow sticky traps (Figure 14.62) may be used to monitor pests in the greenhouse. These sticky cards (Bug-Scan) are available commercially from greenhouse suppliers such as Biobest Biological Systems (www.biobest.be), who, like Koppert B.V., supply biological agents and bumble bees for pollination. The Bug-Scan cards have a grid on one side where one can identify and count the insects.

Many of the biological supply houses such as Koppert B.V. (www.koppert.com) will provide a complete pest management program for the grower, in which they monitor and introduce various biological agents to incorporate the IPM program into the greenhouse operation. In this way, their consultants plan, initiate, monitor, and manage the program in its entirety.

1. *Whitefly (Trialeurodes vaporariorum—glasshouse whitefly and Bemisia tabaci—tobacco whitefly).* The whitefly life cycle is 4–5 wk, during which time it undergoes a number of molts in the nymph stage as shown in Figure 14.63. This is the most common pest in the greenhouse tomato crop. It is usually located on the undersides of the leaves. When at rest on a leaf, its triangular white body makes it easy to identify. The insect secretes a sticky substance on the leaves and fruit, in which a black fungus later grows, making it necessary to clean the fruit before marketing. Numerous pesticides such as pyrethrin, Azatin, M-Pede, Pyganic, Fulfil, BotaniGard, and Provado can be used in the IPM program with the beneficial insects to control the whiteflies. However, the insects quickly build up resistance, making it necessary to use different pesticides to obtain reasonable control. Whitefly is also a common pest on cucumbers and peppers.
   Biological control may be achieved by the use of a number of beneficial insects that predatorize or parasitize the pests. These, such as the chalcidoid wasp *Encarsia formosa* (En-Strip; Koppert product name), *Erectmocerus eremicus* (Ercal), *Amblyselus swirskii* (Swirski-Mite), and *Delphastus catalinae* (Delphibug) (Figure 14.64), are some biological control agents available from bioagents suppliers such as Koppert and Biobest. In the case of the wasps, the female lays eggs in the whitefly larvae and also eat early larval stages of the whitefly. The parasitic grub feeds within the larva, which turns black within 2 wk, providing an easy method of determining the success of the predator. Successful control is temperature and humidity dependent, as the predators/parasites have specific optimum temperature and RH ranges under which they reproduce. Optimum conditions, for example, for *E. formosa* to reproduce are a mean temperature of 23°C (73°F) and an RH not exceeding 70%. For specific conditions in a particular area consult with the suppliers as to which of the organisms will best reproduce and control the whitefly. It was found that *Eretmocerus eremicus* (Ercal) and *Amblyseius swirskii* (Swirski-Mite) are more

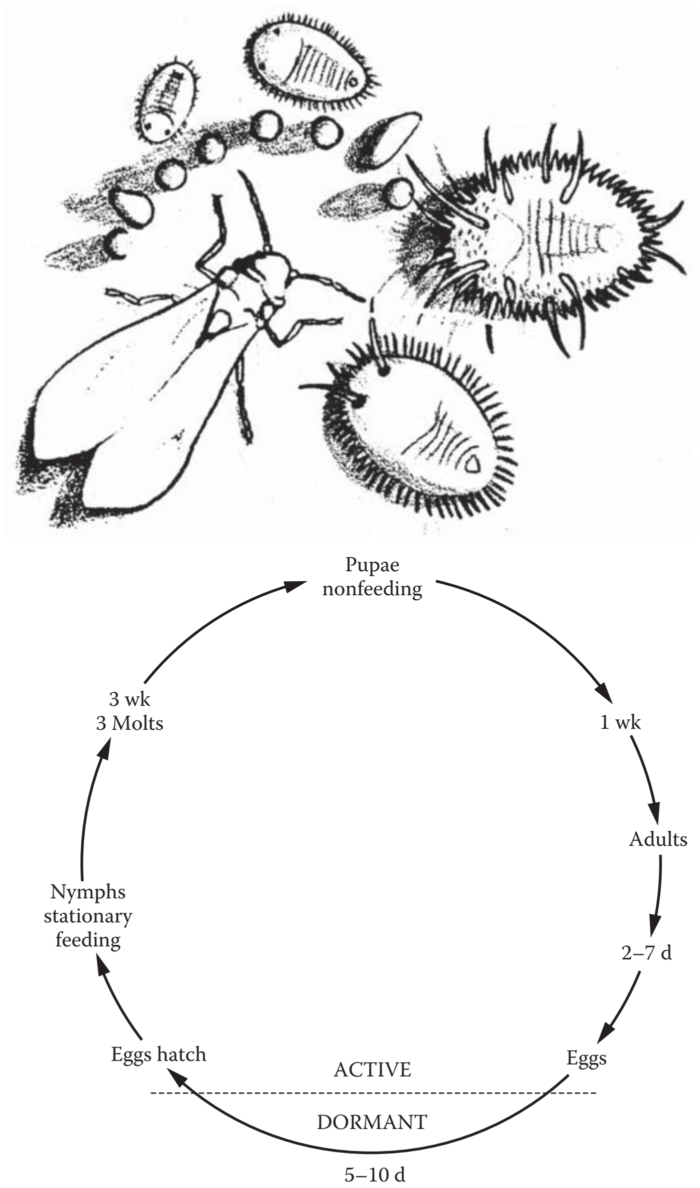


FIGURE 14.63 Life cycle of whitefly. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

suitable for higher temperatures and humidities. *Encarsia* and *Eretmocerus* are purchased as pupae stuck to paper strips (Figures 14.64 and 14.65), which are hung on plants in the greenhouse (Figure 14.66). Each card contains the black pupae from which the parasite emerges. As soon as the first whiteflies are found, a program of repeated introductions of the predators/parasites must be initiated.

To use *E. formosa* successfully, follow these steps:

(i) Do not use residual pesticides for a month before introduction.

(ii) Reduce existing whitefly populations using insecticidal soap or insect hormones, to an average of less than one adult per upper leaf.

FIGURE 14.64 Biological control agents.

FIGURE 14.65 Ercal has *Eretmocerus eremicus* pupae stuck to paper strips.

FIGURE 14.66 Paper strip with *Encarsia* pupae.

(iii) Adjust temperature and humidity to 23°C–27°C (73°F–81°F) and 50%–70%, respectively.
(iv) Introduce *Encarsia* at a rate of 10 per square meter (1 per square foot) of planted area or one to five per infested plant.
(v) Reintroduce *Encarsia* weekly for up to nine introductions.
(vi) Monitor plants weekly for the number of whitefly and black scales.

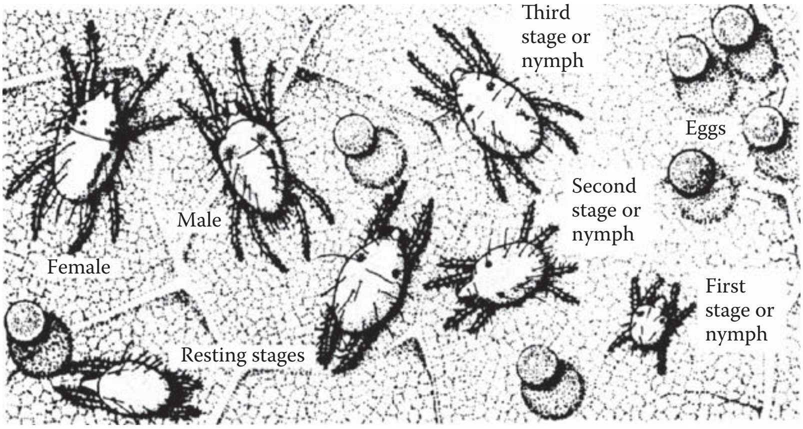
This is a general guideline, so be sure to check with the supplier on the specific procedures for the organisms to be employed.

Several parasitic fungi, *Verticillium lecanii-m* (Mycotal) and *Achersonia aleyroidis*, are now available commercially for controlling whitefly. They are safe to use with *E. formosa*.

In recent years, the sweet potato whitefly *(Bemisia tobaci)* has become a more common pest in greenhouses. A new predator very effective on these whiteflies is the black bug *(Delphastus catalinae* or *D. pusillus)* larvae and adults that can eat as many as 160 whitefly eggs per day. Under higher temperatures, in excess of 80°F (27°C), *E. eremicus*, a parasitic wasp, is more effective in controlling both the greenhouse and sweet potato whiteflies in the second and third larval stages. A mix of *E. formosa* and *E. eremicus* (Enermix) is available to control the whitefly in its second to fourth larval stages.

2. *Two-spotted spider mite (Tetranychus urticae).* Mites are closely related to spiders and ticks, having four pair of legs, unlike insects, which have three pairs of legs. Their life cycle goes through a number of nymph stages, as indicated in Figure 14.67. Their life cycle is from 10 to 14 d, depending on temperature. At 26°C (80°F) the cycle is shortened to 10 d, whereas at lower temperatures the cycle may be up to 2 mo. Low RH also favors their development. Misting plants frequently during dry periods will discourage spider mites, as they dislike high humidity.

   This pest is particularly common on cucumbers. A webbing appearance on the undersides of leaves indicates an already heavy infestation. A magnifying glass is



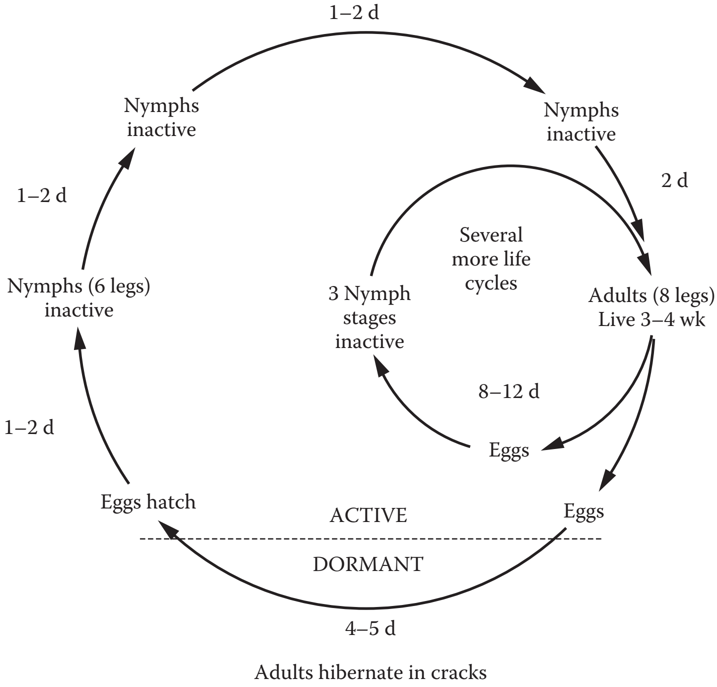


FIGURE 14.67 Life cycle of two-spotted spider mite. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

needed to observe the mite closely in order to see the dark-colored spot on each side of its body. The mite causes a yellowing of leaves, starting as very small yellow pin-sized dots that coalesce to eventually form a very characteristic bronzed appearance. Severe infestations will cause leaves to become entirely bleached, as the mites suck the contents of the leaf cells, leaving a dead shell.

Other mites that are pests of many greenhouse crops such as tomatoes, peppers, and cucumbers include carmine mites *(Tetranychus cinnabarinus)* and broad mites *(Polyhagotarsonemus latus)*. The carmine mite is bright red in color and lacks the spots of the two-spotted spider mite. Damage to plants is similar to that of the two-spotted spider mite.

Broad mites are very small and hard to see with the naked eye. They are translucent and colorless and very small (less than 0.2 mm in length). They can be seen with a hand lens. They are fairly fast moving in the adult stage. Broad mites are particularly damaging to cucumbers and peppers. They are especially damaging to the growing tips and flower buds. They have toxic saliva that causes hardened, distorted growth of the plant tip, and symptoms look similar to a virus infection. Blossoms abort, and growing tips die and blacken, causing stunting of the plants as shown in Figure 14.68 with peppers. Fruit is badly scarred and deformed in peppers and cucumbers (Figure 14.69). If broad mites are not controlled, they will eventually kill the plants.

FIGURE 14.68 Broad mite damage on pepper.

FIGURE 14.69 Cucumber fruit damaged by broad mites.

Mites live on plant refuse and on the greenhouse framework between crops. A thorough eradication and sterilization between crops is necessary. Clear the greenhouse of all plant material and fumigate or spray with appropriate chemicals such as Virkon during power washing of the structure. If populations are very large, they will spread to most crops, including tomatoes, eggplants, lettuce, herbs, and flowers.

Control by chemical miticides must be selected to not damage beneficial insects in an IPM program. Some pesticides that can be used include Agri-Mek 0.15EC (Abamectin), Oberon (Spiromesifen), and M-Pede (Insecticidal Soap).

A predatory mite, *P. persimilis* (Spidex), is available commercially. *Phytoseiulus* differs from the two-spotted mite by its lack of spots, pear-shaped body, longer front legs, and especially its rapid movement when disturbed. In these traits it also differs from carmine mites and is much larger than broad mites. It prefers temperatures in the range of 21°C–27°C (70°F–81°F). Adults develop from eggs in less than a week. This is twice as fast as their prey. However, since bright light and high temperatures are unfavorable to their development, such hot conditions should be avoided, since these conditions also favor spider mites.

Other predatory mites are available: *Metaseiulus occidentalis*, which performs well under cooler temperatures, and *Amblyseius californicus*, which prefers warmer temperatures. A gall midge, *Feltiella acarisuga* (Spidend) *(Therodiplosis persicae)*, lays eggs in spider mite colonies. Koppert has several others: Mirical-N *(Macrolophus caliginosus)*, and Spical *(Neoseiulus californicus)*. *Phytoseiulus macropilis* is effective in controlling carmine mites; predatory mites that effectively control broad mites include *Neoseiulus barkeri* on peppers and *Neoseiulus cucumeris* on cucumbers.

These predators are applied mainly to cucumbers and peppers, but may also be used on tomatoes, beans, gherkins, melons, grapes, strawberries, and various

FIGURE 14.70 *Amblyseius swirskii* introduced with a bran substrate.

FIGURE 14.71 Spical (*Neoseiulus californicus*) is introduced using a shaker bottle.

flower crops. Some of the predators are available in a bran substrate that can be spread on the leaves together with the predators (Figures 14.70 and 14.71).

To use *P. persimilis* or others do the following:

(i) For 1 mo before introduction, do not use residual pesticides.
(ii) Introduce the predator at the first sign of mite damage. If there is greater than 1 mite per leaf, reduce the population with insecticidal soap or Agri-Mek, until only 10% of the leaves are infected.
(iii) Maintain optimum temperatures for the predator and high RH.

(iv) Generally, 8–10 predators per square meter (0.8–1.0/ft^2) should be introduced. Release in early morning onto the mid and upper foliage. Predator mites are available in shaker bottles.

(v) Monitor mite population once per week.

(vi) Reintroduce the predator at monthly intervals. Populations of predators should be roughly maintained at one predator for every five mites. Good control should be achieved within 4–6 wk.

3. *Aphids*. The common aphids are green peach aphid *(Myzus persicae var. persicae)*, tobacco aphid *(M. persicae var. nicotianae)*, cotton aphid *(Aphis gossypii)*, glasshouse potato aphid *(Aulacorthum solani)*, and the potato aphid *(Macrosiphum euphorbiae)*.

   The life cycle varies in length from 7–10 d to 3 wk depending on the temperature and season, as shown in Figure 14.72.

   Aphids are usually clustered in large colonies on new succulent growth, at the base of buds, and on the underside of leaves. The most common greenhouse species is the green peach aphid. The wingless forms are yellowish green in summer and pink to red in the fall and spring. The winged forms are brown. They have a pear-shaped body 1–6 mm in length with four wings, if winged. They excrete “honeydew” from their abdomen, which is a food for ants. The presence of large ant populations on plants often indicates aphid infestation. Aphids feed by sucking out plant sap with their tubelike, piercing mouthpart. This causes distorted leaves when they feed on young leaf buds. Under short food supply, winged females appear and migrate.

   A number of types of aphids, including pink, black, and dark green, feed on most greenhouse vegetables. They suck the juices out of the plant and cause the leaves to become distorted and sticky from a honeydew deposit. Often sooty moulds infect the leaves as a secondary organism, forming a black film on leaves. They also are vectors for viruses. They can be controlled with a weekly spray program using chemicals such as pyrethrin, Azatin, M-Pede, Pyganic, Fulfill, Savona (potassium salts of fatty acids), and BotaniGard.

   Some biological control can be achieved using various lady beetles and the green lacewing, *Chrysopa carnea* (Chrysopa). *Aphidoletes aphidimyza* (Aphidend, marketed by Koppert) is a predaceous midge larva. The adult midge, a small, black, delicate fly lives only a few days. The female lays 100–200 eggs on the underside of leaves close to aphid colonies, which hatch in 3–4 d. A large orange or red larva, up to 3 mm long, matures in 3–5 d and drops to the ground where it forms a cocoon. Pupation takes about 10–14 d, completing a total life cycle of 3 wk.

   The threshold temperature for larval development is approximately 6°C (43°F), with optimum temperatures between 23°C and 25°C (73°F–77°F) at 80%–90% RH. Adult midges feed on aphid honeydew excretions. The larva feeds on aphids, killing from 4 to 65 aphids each.

   Other Koppert products recommended for aphid control include Aphidalia (*Adalia bipunctata*), Aphilin *(Aphelinus abdominalis)*, Aphipar *(Aphidius colemani)*, Ervibank *(Sitobion avenae)*, Evipar *(Aphidius ervi)*, and Syrphidend *(Episyrphus balteatus)*.

   To use *A. aphidimyza* do the following:

(i) Control ants that may protect the aphids.

(ii) Avoid using residual pesticides 1 mo before introduction.

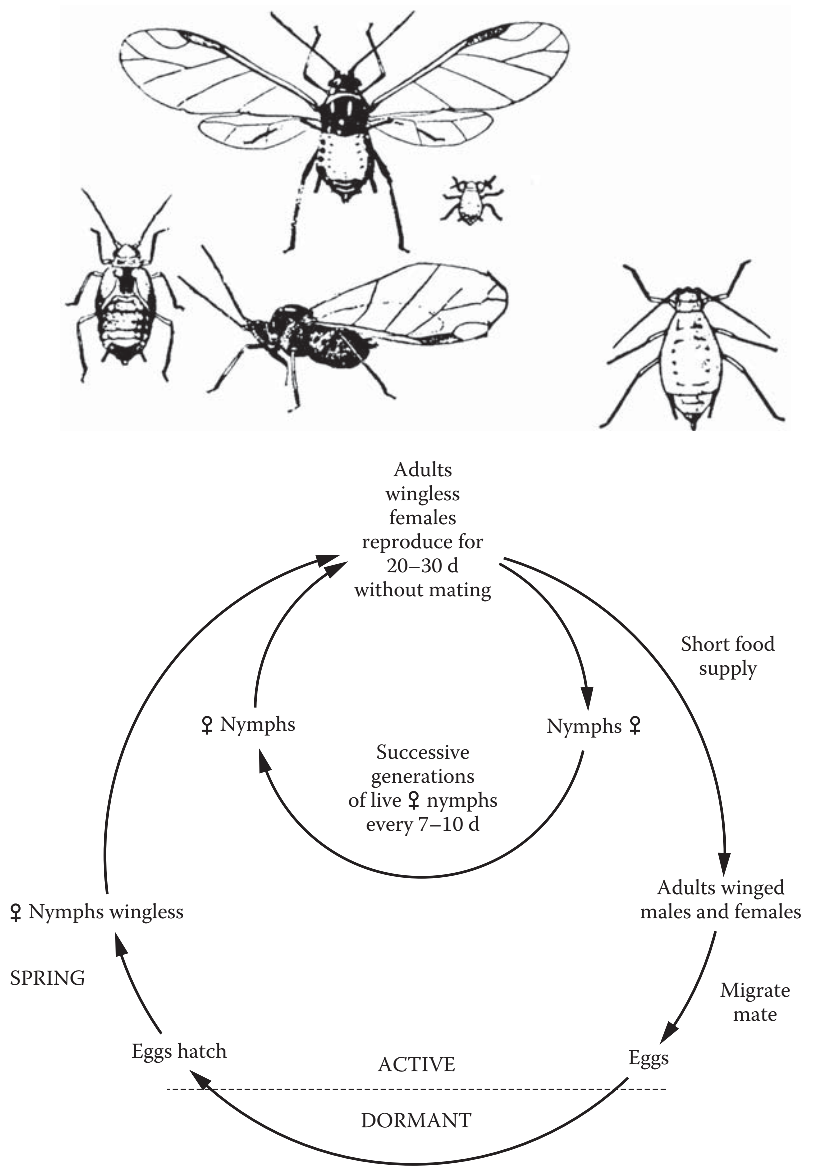


FIGURE 14.72 Life cycle of aphid. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

(iii) Reduce heavy aphid populations with Enstar (insect growth regulator or insecticidal soap. Areas of at least 10 aphids per plant or one aphid per square centimeter should be left to encourage egg laying by the midge.
(iv) Maintain temperatures between 20°C and 27°C (68°F–81°F).
(v) Introduce the predator at a rate of one pupa per three aphids or two to five pupae per square meter (two to five pupae per 10 ft^2) of planted area.
(vi) Spread the pupae in shady areas near aphid-infested plants and repeat introductions in 7–14 d and thereafter as necessary.
(vii) Monitor plants for infestation weekly.

A parasitic fungus, *Verticillium lecanii*, trade name Vertalec, is available commercially as a biological control agent of aphids.

Spot spraying in localized infestations may be done with chemical pesticides such as insecticidal soap, Enstar, and Pirimor, but avoid spraying the *Aphidoletes* larvae. Reintroduction of the predatory larvae will be necessary in areas sprayed with chemical pesticides.

4. *Leaf miners.* The common leaf miners are tomato leaf miner *(Liriomyza bryoniae),* the American serpentine leaf miner *(Liriomyza trifolii)*, the pea leaf miner *(Liriomyza huidobrensis)*, and *Liriomyza strigata.* Adult flies are yellow-black in color and about 2 mm in length. The female deposits its eggs on the leaf, causing a white puncture-protuberance. When the larvae hatch, they eat "tunnels" through the leaf between the upper and lower leaf epidermis, creating "mines." These tunnels may coalesce, resulting in large areas of damage until the entire leaf dries up. The maturing larva drops from the leaves to the ground where it pupates. Within 10 d the adult emerges, the whole cycle from egg to adult fly takes 3 to 5 wk, as shown in Figure 14.73.

   Leaf miners may be controlled chemically with products such as Azatin, Entrust, Distance, and Abamectin 0.15EC (Agri-Mek). These pesticides can be used with an IPM program. There are presently several biological control agents available to control leaf miners. Some products by Koppert include Diminex (*Diglyphus isaea* + *Dacnusa sibirica*) and Miglyphus *(D. isaea).* The two insects, *D. sibirica* and *D. isaea*, parasitize both leaf miner species *L. bryoniae* and *L. trifolii.* A third, *Opius pallipes*, only parasitizes the tomato leaf miner. *Opius* and *Dacnusa* lay eggs in the leaf miner larva. As the leaf miner larva pupates, the parasite emerges instead of the leaf miner. *D. isaea* kills the leaf miner in its tunnel and lays an egg beside it. The wasp (parasite) develops in the tunnel, feeding on the dead larva.

   Leaf samples must be taken from the crop and examined in a laboratory to identify the species of leaf miner, parasites present, and the level of parasitism. If there are insufficient natural parasites present, *Dacnusa* or *Diglyphus* is introduced. The introduction depends on the season, the species of leaf miner, and the level of infestation.

5. *Thrips. Heliothrips haemorrhoidalis,* onion thrips (*Thrips tabaci)*, and flower thrips *(Frankliniella tritici* and *Frankliniella occidentalis).* Thrips are especially attracted to flowers of cucumbers, tomatoes, and peppers. They are particularly attracted to yellow flowers. Adult thrips are 0.75 mm long with feathery wings. They develop outside the greenhouse on weeds and invade the greenhouse. Feeding on leaf undersides, growing tips, and flowers, they cause small bleached dead spots on leaves and damage growing tips and flowers. Nymphs with rasping mouth parts scrape the leaf surface and suck the plant sap, causing a white, silvery, discoloration, resulting in streaks. Thrips feed like spider mites by puncturing and sucking the leaf contents. Damage appears as narrow crevices and a silvery appearance on leaves. They feed in narrow crevices between the calyx and the newly forming fruit of the cucumbers, causing curled and distorted fruits. Thrips similarly damage peppers. Thrips also transmit viruses such as the tomato spotted wilt virus (TSWV).

   Their 2- to 3-wk life cycle begins with the adult female depositing eggs under the leaf surface (Figure 14.74). After 4 d, they hatch into nymphs that feed on the leaves for 3 d before molting into larger, more active nymphs that feed for another

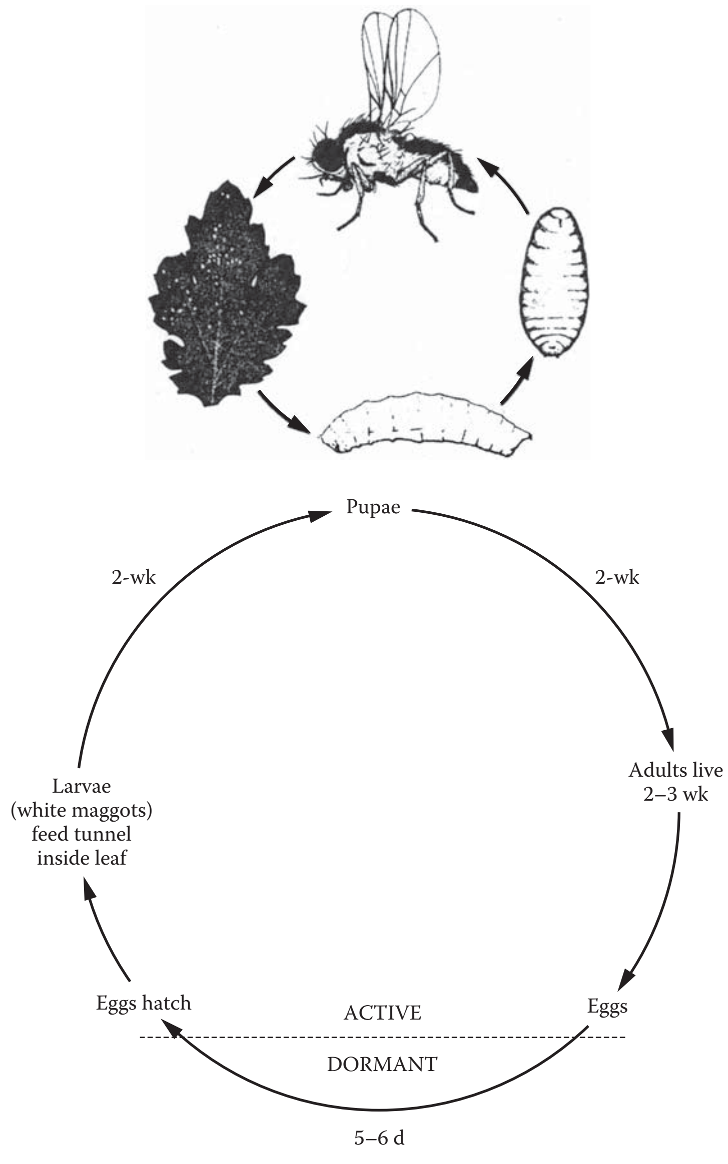


FIGURE 14.73 Life cycle of leaf miner. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

3 d before dropping to the ground to pupate, and emerge as adults within 2 d. They feed for about 6 d before beginning to lay from 50 to 100 eggs over 40 d.

Yellow or blue sticky traps should be used for early detection and monitoring of the pest population. There are a number of pesticides that may be used with an IPM program. Agri-Mek 0.15EC (Abamectin), Entrust, and BotaniGard can assist in their control.

A number of biological agents are recommended to control thrips. *Amblyseius cucumeris,* a predatory mite, controls thrips. The predatory mite is similar in appearance to *Phytoseiulus,* differing only in its lighter pale-pink color and shorter legs. Its life cycle is similar to that of *Phytoseiulus.* The predator mite

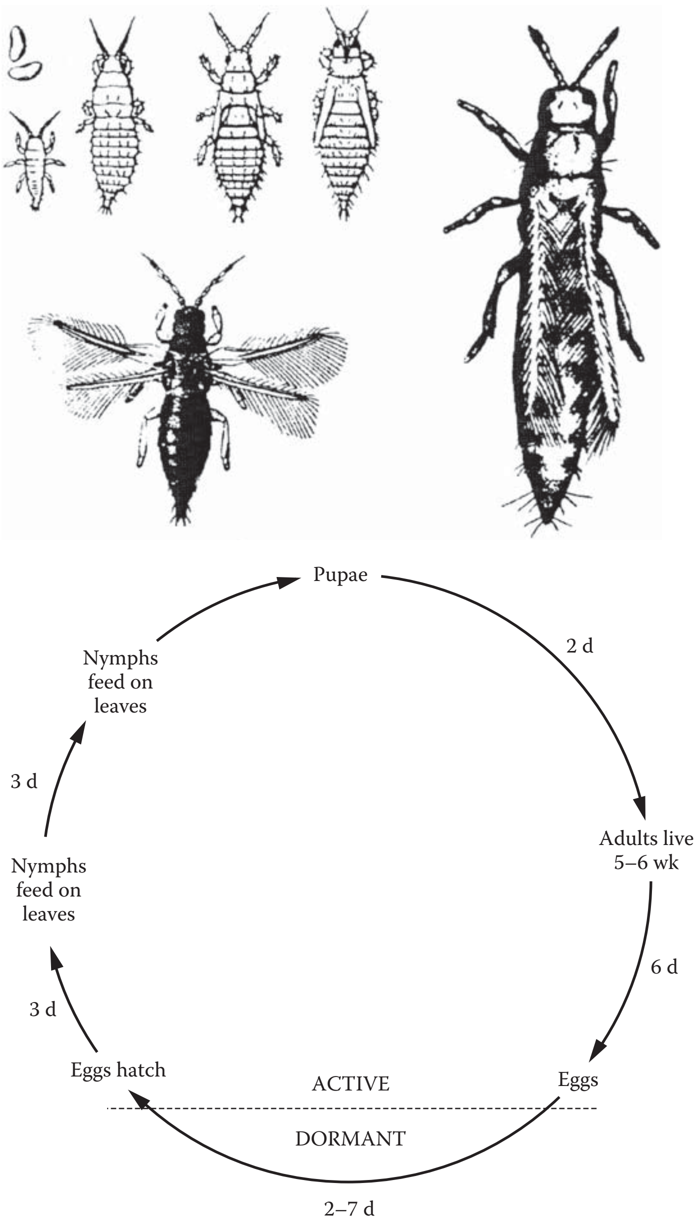


FIGURE 14.74 Life cycle of thrips. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

must be introduced in the crop at an early stage for preventive action so that a large population can be built up in order to control the thrips as soon as they appear. Their introduction and management is similar to that of *Phytoseiulus.* They should be introduced on a weekly basis until population levels reach 100 per plant. *Orius tristicolour*, a pirate bug, controls thrips in peppers and cucumbers. This predator will also feed on pollen, aphids, whitefly, and spider mites when thrip populations are low. *Hypoaspis miles* feeds on thrips' pupae. It is suitable for cucumbers, tomatoes, and peppers.

Other biological control agents available from Koppert include Entomite-A *(Hypoaspis aculeifer)*, Entomite-M *(H. miles)*, Entonem—a parasitic nematode *(Steinernema feltiae)*, Macro-Mite *(Macrocheles robustulus)*, Mycotal *(V. lecanii-m)*, Swirski-Mite *(A. swirskii)*, Thripex *(N. cucumeris)*, and Thripor-I *(Orius insidiosus)*.

6. *Caterpillars and cutworms*. Caterpillars are larvae of butterflies, and cutworms are larvae of moths. These are common in most greenhouse crops. The most important ones found in greenhouses include the tomato looper (*Chrysodeixis chalcites)*, the tomato moth *(Lacanobia oleracea)*, the cabbage moth *(Mamestra brassicae)*, the beet armyworm *(Spodoptera exigua)*, and the silvery moth *(Autographa gamma)*.

   The larvae feed on aerial plant parts. Their presence is indicated by notches in leaves and cut stems and petioles. Cutworms climb up the plant and feed on the foliage at night and are found in the soil or medium during the day. Caterpillars are not nocturnal like cutworms but feed on above-ground plant parts day and night. Their presence is detected by large amounts of excrements on leaves near where they have been feeding.

   Adult moths and butterflies fly into the greenhouse from outdoors and quickly lay eggs on the plants, where they hatch into feeding larvae within several days during high temperatures. Entry of adults should be prevented by using insect screens over shutters, vents, and so on. The time of their life cycle varies with season, temperature, and the species (Figure 14.75).

   Control may be achieved by the use of a number of effective chemical pesticides such as Azatin, Pyganic, Entrust, and Malathion, as well as biological control with parasitic bacterium, *B. thuringiensis*, marketed as Dipel or XenTari. This bacterium must be sprayed on a regular weekly basis, as new growth occurs to protect all surfaces. It is active only upon ingestion by the caterpillar or cutworm. The larvae are paralyzed, so they stop eating a few hours after spraying. They die within 1–5 d. The bacterium is harmless to mammals, fishes, and birds, and leaves no toxic residue in the environment. *Trichogramma evanescens*, a small wasp, effectively controls over 200 species of larvae by laying its eggs in the eggs of the butterflies and moths.

   Other biological control agents available from Koppert include Capsanem *(Steinernema carpocapsae)*, a nematode; Entomite-A *(H. aculeifer)*; Entomite-M *(H. miles)*; and Mirical *(M. caliginosus)*.

7. *Fungus gnats (Bradysia species and Sciara species)*. The larvae of these small, dark gray or black flies feed normally on soil fungi and decaying organic matter, but as populations increase, they attack plant roots. They are legless white worms about 6 mm (0.25 in.) in length with a black head. Adults have long legs and antennae, about 3 mm long, with one pair of clear wings. They attack all seedlings and are favored by the presence of moisture such as exists with capillary mats, seedling cubes, and the growth of algae. They also feed on the tap roots, stem cortex, and root hairs of mature cucumbers. They have a 4-wk life cycle as shown in Figure 14.76. The adults can also transmit mites, nematodes, viruses, and fungal spores. Where larvae chew the roots a port of entry is created for fungal spores to enter the plant.

   Control by the use of yellow sticky traps and chemical pesticides such as Diazinon are effective. Also, avoid moist areas in the greenhouse; keep medium surfaces dry.

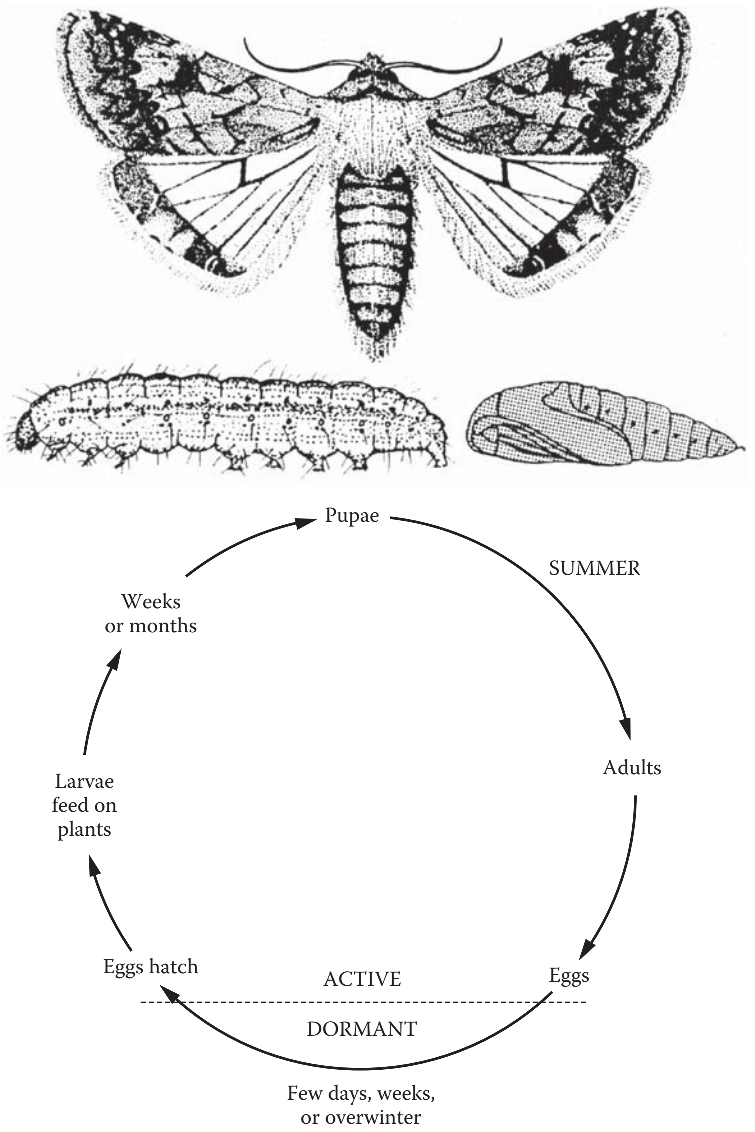


FIGURE 14.75 Life cycle of caterpillars and cutworms. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

Some success has been achieved using a predatory mite that feeds on the eggs and pupae in the soil. The predatory mite, *H. miles* or Entomite-M (Koppert), feeds on fungus gnat eggs and small larvae. Entomite-A *(H. aculeifer)* is also effective. *Bacillus* bacterium may provide some control of the larvae. Vectobac, produced by Abbott Laboratories, is an effective *Bacillus* subspecies against fungus gnats. Similarly, Gnatrol, by Valent BioSciences Corporation, uses *B. thuringiensis,* subsp. *israelensis* to control fungus gnats. It must be applied weekly, similar to XenTari. An insect-parasitizing nematode, *S. carpocapsae* and *S. feltiae* (Entonem by Koppert) controls fungus gnats by entering body openings in the larvae. The nematodes are mixed with water and applied as a drench or spray or through the irrigation system.

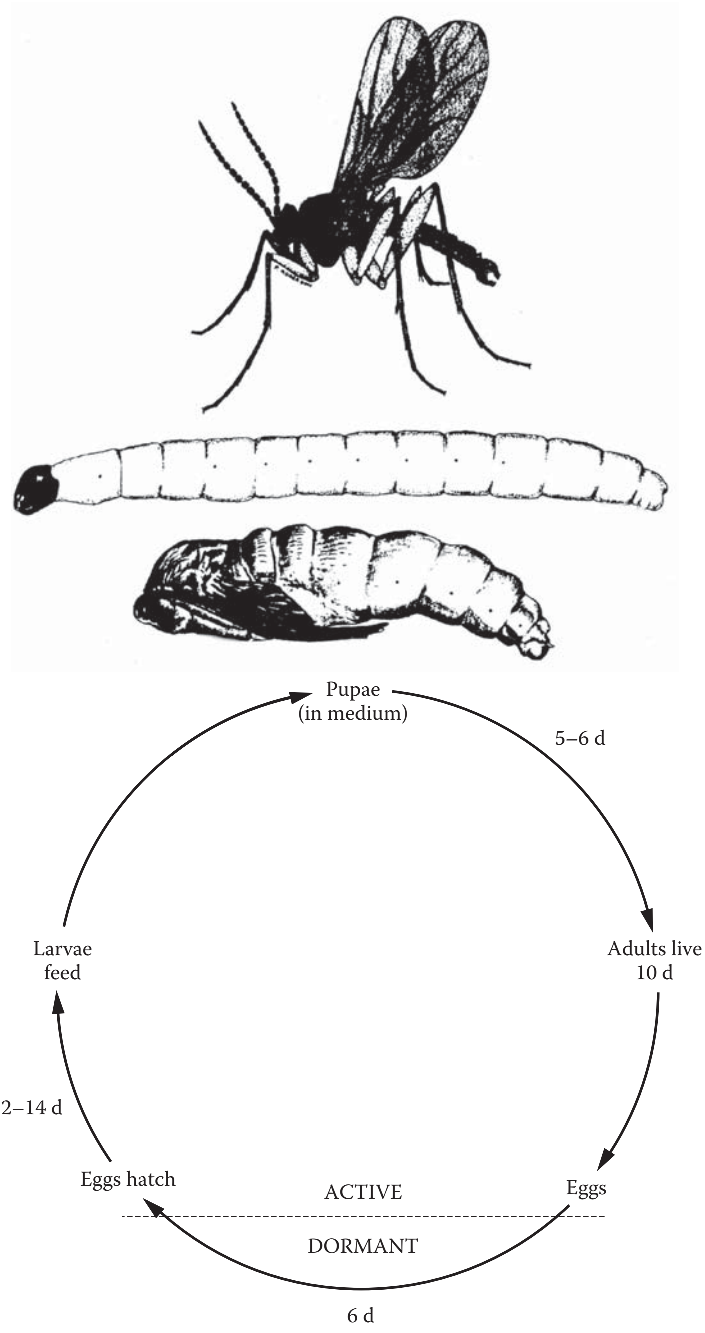


FIGURE 14.76 Life cycle of fungus gnat. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

8. *Mealybugs (Planococcus and Pseudococcus genera).* The citrus mealybug *(Planococcus citri)* is the most prevalent problem. It has been found that mealybugs are particularly troublesome in basils and peppers (Figure 14.77). They multiply rapidly and suck the sap from the plants, creating an environment favorable for secondary fungal infection by sooty moulds. Mealybug infestations build

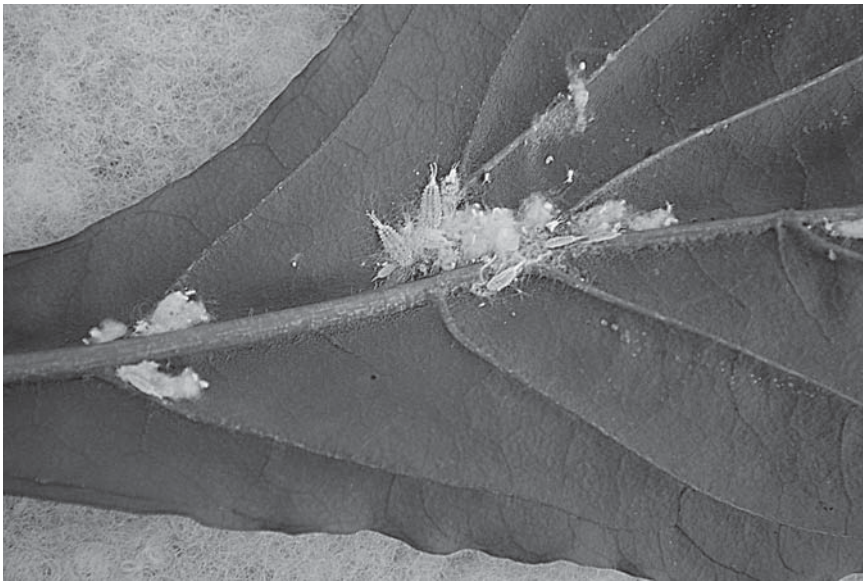


FIGURE 14.77 Mealybugs on pepper leaf.

quickly and cause reduced yields through deformation and yellowing of leaves, leading to leaves and flowers falling off. They excrete honeydew that favors sooty moulds.

Mealybugs have five stages in their life cycle, egg, nymphal stages (two to three), and finally adult. Females in their third larval (nymph) and thereafter develop a white waxlike substance in the form of powder, filaments and projections, or plates that cover their bodies. This protective cover makes it very difficult to control them with pesticides, as the chemicals cannot easily contact the bodies of the mealybugs. Some chemicals used to assist in the control of mealybugs include M-Pede, Azatin, Distance, Bugitol, BotaniGard, Savona, and Enstar II. Mealybugs must be controlled early, as once established, these pesticides do not give effective control. Koppert claims that some biological control agents are available, including Citripar *(Anagyrus pseudococci)*, Cryptobug *(Cryptolaemus montrouzieri)*, Leptopar *(Leptomastix dactylopii)*, and Planopar *(Coccidoxenoides perminutus).*

In general, life cycles of insects can be shortened under optimal temperature and RH conditions. Control of insect pest must be carried out at the most susceptible stage of their life cycle. This is usually the adult or active nymph or larval stages that are feeding. For successful integrated pest control using biological agents, the predator and prey populations must be in balance. Use of selective chemical pesticides for control of localized population outbreaks of the pest is necessary. Before using any chemical pesticides, the grower must check with manufacturers, the supplier of biological agents and/or agricultural extension personnel to determine which may be used safely. Environmental conditions within the greenhouse must be maintained at levels favorable to the predator. Weekly monitoring of predator–prey populations is needed to maintain equilibrium and new introductions of predators made to achieve successful IPM.

Natural insecticides are being introduced for use in all types of IPM programs. One such product is the active ingredient azadirachtin, an extract from the neem tree. It is marketed as Azatin or Neemix and is effective against whiteflies, aphids, thrips, leaf miners, and fungus gnats. A number of microinsecticides, produced by companies such as Emerald BioAgriculture Corporation use bread mold fungi as insecticides: *Beauveria bassiana, Beauveria brongniartii, Metarhizium anisopliae, Verticllium lecanii,* and *Hirsutella thompsoni*. *B. bassiana* is marketed under the name "BotaniGard 22WP." It is effective on whiteflies, thrips, aphids, and other soft-bodied sucking insects. Insects do not develop resistance to it, nor does it have residue problems. It does not harm *Encarsia* and in fact has an additive effect if used together to control whitefly.

The introduction of beneficial agents is a tedious task because they have to be shaken from containers onto plant leaves. Koppert has recently come out with special blowers that deliver the biological agents to the plants, saving up to 80% of the normal time to dispense them. They use airbags to apply predatory mites to the entire crop or specific areas. This blower is operated by batteries, so is very portable. With the dosage pot, the fan evenly releases the carrier material containing the natural enemies. It will carry the material up to 4 m (13 ft) from the airbag and will not harm the biological agents. Mixtures of different natural agents permit their release and uniform distribution in one step.

Hydroponic culture minimizes pests and diseases in the growing medium by efficient sterilization between crops. Pest and diseases of the aerial part of the plant, however, are not deterred by hydroponic culture. Therefore, if proper preventive programs are not followed, severe infestations may occur similar to those in regular soil-culture field conditions.

14.17 VEGETABLE VARIETIES

Many varieties of vegetables are available from seed houses. While both field and greenhouse varieties can be grown in a greenhouse, it is advantageous to use greenhouse varieties whenever possible, since they are often bred to yield very heavily under controlled environmental conditions. That is, in a greenhouse higher yields generally could be expected from greenhouse varieties than from field varieties. In most cases, greenhouse varieties cannot be easily grown under field conditions since they are unable to withstand the temperature fluctuations encountered there.

A number of greenhouse varieties of vegetables perform particularly well in hydroponic culture. These, along with other acceptable greenhouse varieties, are given in Table 14.4. The choice of variety is dependent on season, climate, and market. To initiate a project in a given area, obtain information from seed houses as to which ones should perform best under the specific conditions and then carry out trials with many to eventually find the best performers under the environment. All varieties used in greenhouses are indeterminate or "staking" so that they may be trained vertically by strings attached to overhead support cables. These varieties have resistance and/or tolerance to many common diseases. Each variety name is followed with a code for the diseases they are resistant or tolerant to, as was explained earlier. For example, the variety Caruso with the symbol "TmC_5VF_2" indicates that it is resistant to TMV; *Cladosporium* races A, B, C, D, and E; *Verticillium*; and *Fusarium* races 1 and 2.

TABLE 14.4
Recommended Vegetable Varieties for Greenhouse and Hydroponic Culture

Vegetable		Varieties
Cucumbers	European	*Dominica, *Marillo, *Kasja, Curtis, Pandex, Farbio, Sandra, *Uniflora D, Corona, Fidelio, Bronco, Mustang, Exacta, Jessica, Optima, Flamingo, Accolade, Discover, Crusade, Milligon, *Logica, Camaro, Kalunga
Mini cucumbers	Beit-Alpha (BA)	*Manar, Sarig, Tornac, Picowell, Darius, Suzan, Diva, Tornado, DPSX 419, GVS 18209, *Nimmer
Lettuce	European	*Rex, *Charles, *Deci-Minor, *Ostinata, *Cortina, *Salina, *Milou, *Vegas, *Cortina, Flandria, Astraca, Brighton, Elton, Laurel, Michael, Sumaya, Vincenzo, Volare, Fidel, Skyphos (red)
	Leafy-Novelty	Multigreen1, Multigreen2, *Multigreen3, *Multired1, Multired2, Multired3, Multired4
	Lollo Bionda	Bergamo, Locarno
	Lollo Rossa (red)	*Revolution, Amandine, Soltero
	Oak Leaf (green)	Cedar, Pagero, Torero, Veredes, *Cocarde
	Oak Leaf (red)	*Navara, Versal, Piman, *Oscarde, *Ferrari, *Aruba
	Green Leaf	*Black Seeded Simpson, *Waldmann's, Dark Green, *Domineer, *Malice
	Red Leaf	*New Red Fire, Vulcan, *Red Sails
Tomatoes	Beefsteak	*Caramba, Dundee, Growdena, *Trust, *Dombito, *Caruso, Larma, Perfecto, Belmondo, Apollo, *Match, *Blitz, *Quest, Heritage, *Geronimo, *Matrix, DRW 7749, Rapsodie, Style
	TOV	*Tradiro, *Ambiance, *Clarance, *Tricia, *Success, Endeavour, *Campari, Brillant, Clermon, Lacarno (yellow), *Orangaro (DRK 920) (orange), Brilliant, Grandela
	Cherry/Grape/Plum	*Favorita, *Cello, *Conchita, *Juanita, Monticino, Sweet Hearts, Sweet Million, Dasher, *Zebrino, *Goldita (yellow)
	Cocktail	*Red Delight, Flavorino, Picolino, Goldino (yellow), Orangino (orange)
	Roma	*Granadero, *Naram, *Savantas
	Heirloom	*Brandywine, *Striped German, Green Zebra, Belriccio
	Rootstock	*Maxifort, *Beaufort, *Manfort, Multifort
Peppers (bell types)	Green to red	*Cubico, *Fantasy, *Tango, *Mazurka, *Delphin, *Ferrari, *Zamboni, Fascinato
	Green to yellow	*Lesley, *Luteus, *Goldstar, *Samantha, *Kelvin, Bossanova, Lambourgini, Gold Flame, Crosby, Cigales
	Green to orange	*Paramo, Sympathy, Orangery, *Narobi, *Fellini, Magno
	Green to brown	Hershey
Hot Pepper		*Fireflame
Eggplant	White	*Tango
	Purple	*Taurus

*Varieties particularly suitable to hydroponic culture

Note: Campari can only be grown by license from the seed company.

14.17.1 TOMATOES

Older tomato varieties such as Vendor, Vantage, Tropic, and Manapel have been replaced by the Dutch varieties that are superior in vigor, yields, and disease resistance. As discussed in Chapter 10, many growers are grafting the varieties onto a rootstock resistant to root rots that give higher yields. Peppers and eggplants are also grafted to these resistant rootstocks. The most popular rootstocks include Beaufort, Maxifort, and Manfort.

Over the past decade, cluster or tomato-on-vine (TOV) tomatoes have become very popular and now make up about 65%–70% of the fresh market. The remaining 20%–25% is beefsteak tomatoes and 10% is cocktail, cherry, and specialty tomatoes, including romas. TOV varieties have fruit weight of 90–150 g and include varieties such as Locarno (yellow), DRK 920 (orange), Tradiro (red), Ambiance (red), Success (red), Tricia (red), Endeavour (red), Clermon (red), and Clarance (red). The fruit on a cluster ripens uniformly at the same time, so the entire cluster is cut without removing the individual fruit. They are packaged in special clamshell containers to keep the fruit on the vine while being sold in the market. This type of packaging also differentiates them from conventional field-grown product. Beefsteak fruit weighs from 200 to 250 g and include varieties such as Trust, Quest, Match, Blitz, Geronimo, Matrix, Style, and Rapsodie. Cherry varieties have fruit weights between 15 and 25 g. They include Favorita (red), Conchita (red), Goldita (yellow), Zebrino (green stripes), and Dasher (grape). Specialty varieties including Picolino (red), Flavorino (plum), and Red Delight have fruit size from 30 to 75 g. Roma types include Naram (red), Savantas (red), and Granadero (red), with fruit weights from 100 to 150 g. These are only a few of the many varieties available from seed houses.

14.17.2 CUCUMBERS

It must be noted that the choice of variety is highly dependent on the specific climatic location and market acceptance. The most popular European cucumber varieties now include Dominica, Marillo, Kasja, Flamingo, Accolade, Discover, Logica, Camaro, and Kalunga. It has been found that both Marillo and Dominica are very suitable to tropical conditions under high temperatures and high prevalence of powdery mildew (PM). There are many other varieties available from the various seed producers. Some varieties are more suitable for spring/early summer season, while others are better for summer/fall crops. They are all female, seedless varieties that set fruit without pollination. Some of the best BA varieties for tropical conditions that have most resistance to PM are Manar and Nimmer.

14.17.3 PEPPERS

Peppers are an important greenhouse crop. These are principally the sweet bell peppers, which are green, maturing to red, orange, yellow, or brown (Figure 14.78). The more popular green-to-red varieties are Cubico, Tango, and Fantasy, while the green-to-yellow ones are Luteus, Samantha, Kelvin, and Lesley, especially for tropical or summer conditions. Narobi, Paramo, and Fellini are popular green-to-orange varieties. The hot red “cayenne” types are also becoming a popular greenhouse crop. One of the more productive and good flavored ones found successful in the tropics is Fireflame.

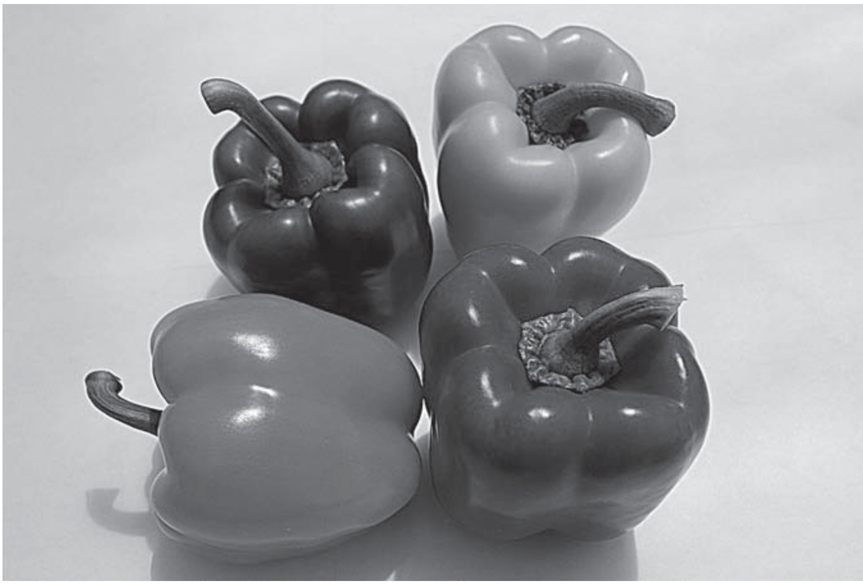


FIGURE 14.78 Greenhouse bell peppers—green, yellow, orange, and red.

14.17.4 EGGPLANTS

Indeterminate eggplants are now available for greenhouse culture. The ones tested with great success are Tango (white), Taurus (dark purple), and Adore (dark purple). Greenhouse eggplants are becoming more common in Europe and beginning now in North America.

14.17.5 LETTUCE

Lettuce grows very well in hydroponic culture. There are four basic types of lettuce: European or Bibb lettuce, looseleaf lettuce, head lettuce or iceberg, and cos or romaine lettuce. While many varieties of each type are available from seed houses, there are a few of each type that are particularly well suited to hydroponic culture and greenhouse environments. The most suitable varieties of European or Bibb lettuce are Deci-Minor, Ostinata, Rex, and Charles. Rex is especially resistant to "bolting" under high temperatures in tropical conditions. They should be planted at 15 cm × 20 cm (6 in. × 8 in.) spacing. Bibb lettuce requires a night temperature of 18°C (65°F), a day temperature of 17°C–19°C (63°F–66°F) on dull days and 21°C–24°C (70°F–75°F) on sunny days. They take about 45–60 d from seeding to maturity, depending on available sunlight.

Looseleaf varieties are generally the easiest to grow. Varieties such as Black Seeded Simpson, Grand Rapids, and Waldmann's Dark Green are very vigorous in hydroponic culture. They require between 45 and 50 d to mature. Their spacing and temperature requirements are similar to European lettuce. Looseleaf varieties require night temperatures of 10°C–13°C (50°F–55°F) and day temperatures of 13°C–21°C (55°F–70°F), depending on sunlight. However, they will tolerate higher temperatures up to 27°C (80°F) without wilting, bolting, or slowing growth. But if higher temperatures occur, "burning" of the leaf tip or margin may result. Some varieties are more tolerant to higher temperatures and resist "tip burn."

Of the many head lettuce varieties available, Great Lakes 659 and Montemar grow best in hydroponics and greenhouse environments. They are most suitable to tropical conditions as mentioned in Chapter 13. They take between 80 and 85 d from seed to mature and will tolerate higher day temperatures up to 27°C–28°C (77°F–78°F) without bolting, provided they receive full sunlight. Head lettuce should be spaced slightly wide apart at 25 cm × 25 cm (10 in. × 10 in.).

Valmaine Cos, Cimmaron (red romaine type), and Parris Island Cos have temperature requirements similar to that of looseleaf lettuce. Several novelty varieties that can tolerate the higher temperatures of the tropics are Red Salad Bowl, Green Salad Bowl, Cocarde, Oscarde, Ferrari, Navara, and Aruba (oakleaf types). Red Sails and New Red Fire are red looseleaf lettuces that tolerate higher temperatures.

Lettuce should be seeded in rockwool cubes, Oasis cubes, or flats of soilless medium as discussed earlier. Transplanting into growing beds should take place once the seedlings are 5–6 cm (2–2.5 in.) in height (about 20–23 d after seeding).

14.18 GREEN GRAFTING

Grafting is now widely accepted in the growing of greenhouse tomatoes, peppers, and eggplants. It is particularly important in tomatoes to give more vigor and disease resistance against Corky Root, TMV, *Fusarium* and *Verticillium* wilts, and nematodes (Black et al., 2003; Rivard and Louws, 2006). The rootstocks increase water and nutrient uptake to give more vigorous plants.

Refer to the seed houses for specific recommendations of which rootstocks to use with a particular variety. In general, use Beaufort with cherry and novelty tomatoes and Maxifort or Manfort with TOV and beefsteak varieties. Be aware of any growth rate differences between the rootstock and variety (scion) to determine whether the rootstock should be sown a few days before or after the scion. For example, Beaufort (rootstock) and Favorita (scion) can be sown at the same time, as they have similar growth rates. If the variety (scion) grows faster than the rootstock, seed the rootstock several days earlier than the variety and vice versa. This is important so that the rootstock and variety (scion) stems have the same thickness when they are ready to graft (approximately 17 d). This is usually when they have two to three true leaves and a stem diameter of about 2 mm.

Sow the rootstock in the final substrate cubes, such as rockwool cubes, which would later be transplanted to rockwool blocks and afterward to the growing system. The variety (scion) can be sown in compact multitrays of 72 cells with a peat-lite medium or coco coir. After grafting, these plant roots will be disposed of. If there are significant size differences among the rootstocks or scions, sort them several days before grafting according to the same stem thickness.

Cut off the rootstocks of a tray with a razor blade at a 45° angle (Figure 14.79). The rootstock should be cut off underneath the cotyledons, if possible. The stem should be at least 2–3 cm (1-in.) long at that location. Too short stems can cause the variety to form aerial roots that could later root into the substrate. This occurs if the aerial roots come in contact with moist substrate. Place silicone or spring-loaded plastic plant clips half way into the cut rootstocks. Cut off the plants of the variety (scion) at the same angle as the rootstock. Be sure that it is the same diameter as the rootstock at that location. It is easier if it is above the cotyledons. Cut off only as many tops (heads) as needed for the prepared rootstocks.

FIGURE 14.79 Cut the scion with a razor or gyproc knife at a 45° angle underneath the cotyledons.

FIGURE 14.80 Place a plant clip on the graft union.

Place the scion in the clips of the prepared rootstocks, being careful that they contact 100% (Figure 14.80). Air or dirt between the two parts will result in failure of the grafting. Lightly mist the plants and place them in a misting chamber. The misting chamber or tunnel must be prepared in advance of the grafting procedure. Spray or mist the inside of the tunnel to increase humidity and close it tightly to prevent drying. Be sure to shade the grafted plants in the tunnel to reduce evaporation.

Optimum temperature for grafting is 22°C–23°C or 72°F–73°F. Avoid temperatures in the tunnel above 28°C–30°C (82°F–86°F).

Keep the tent closed for 3 d; mist the plants lightly if they show any signs of wilting. On the fifth day open the sides of the tunnel to ventilate briefly, and on the sixth day open or roll up the sides a little. On the seventh day remove the tunnel, preferably in the morning; if wilting occurs, cover the plants again in the tunnel. By this time, the graft union should have healed, and the plants will not wilt when removed from the tunnel. Aerial roots may form above the graft union (Figure 14.81). Transplant them to the rockwool blocks several days later, at day 9 or 10. Do not lay the seedlings on their sides in the blocks, as that would cause the scion (variety) to root and defeat the grafting purpose (Figure 14.82).

After the plants have been growing for a number of months and are bearing fruit, the graft union remains visible as a distinct line as shown in Figure 14.83. Grafting clips are available from seed houses. They come in several sizes; the silicone ones are available in 1.5- and 2.0-mm diameters, and the spring-loaded plastic clips are available in sizes ranging from 1.5 to 6 mm in diameter. The choice depends on what size of plant stems will be grafted. It has been found that the 2.0- to 3.0-mm clips are best for grafting tomatoes early.

FIGURE 14.81 Aerial roots may form above the graft union on the scion.

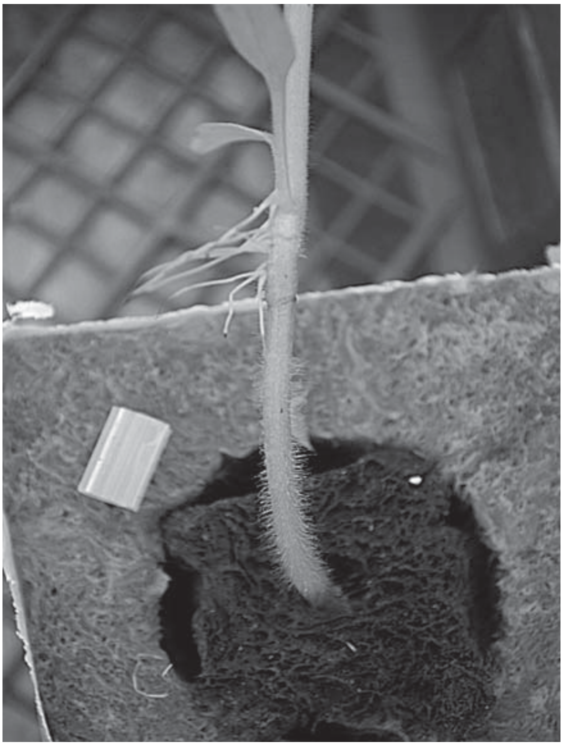


FIGURE 14.82 Place seedling upright in block.

FIGURE 14.83 Graft union remains visible throughout the growth of the plant.

14.19 PLANTING SCHEDULES

A number of planting schedules are possible depending on what crop or combination of crops is to be grown over the entire year. If only tomatoes are to be grown, a spring and fall crop system is used, as shown in Table 14.5. Particularly when growing on a backyard scale, intercropping of lettuce is recommended for the spring crop of tomatoes. This intercropping is not practical for commercial growers. Lettuce should be seeded and transplanted into the beds at the same time. One to two lettuce plants can be placed between each pair of tomato plants. The tomatoes will soon grow above the lettuce, so they will not be shaded by it. While the tomatoes are still small, 12–18 in. (30–45 cm) in height, the lettuce will receive sufficient light to produce well. In this way, a crop of lettuce can be harvested at least 1 mo before the tomatoes will be ready. After this initial intercropping of lettuce, further intercrops can be placed under the tomatoes once the tomatoes are fully mature and several trusses of fruit and all the leaves up to the maturing truss have been removed. This will be about May, as shown in Table 14.5. One intercrop of lettuce could be grown with the fall crop through July and August (Table 14.5).

Intercropping on a commercial scale has already been discussed in Chapter 11. This type of intercropping applies to tomato crops when an older crop is being replaced by younger plants that have been transplanted among the existing mature crop. Other forms of intercropping with different crops are not common practice in commercial greenhouses because of different nutrient and environmental needs of the different crops.

Cucumbers grown year-round may be scheduled in numerous ways. Some growers prefer to grow three to five crops a year, especially under semitropical or tropical conditions (Table 14.6). Others grow only one long crop from December through mid-November using the renewal umbrella system (Table 14.7). Most growers now use a two- to three-crop schedule.

TABLE 14.5
Planting Schedule for a Spring and Fall Crop of Tomatoes (Two Crops Annually) (Backyard Greenhouses Only)

Date	Activity
Dec 20–31	Sow lettuce and tomato seeds in rockwool cubes
Jan 21	Transplant lettuce seedlings into hydroponic system
Feb 1–15	Transplant tomato seedlings into hydroponic system
Mar 1	Harvest lettuce
Apr 1–15	Begin harvesting tomatoes
May 15	Sow lettuce
Jun 1–15	Sow tomato seeds in cubes for the fall crop; terminate tomatoes; transplant lettuce intercrop under existing tomatoes
Jul 1	Harvest lettuce, pull tomato plants of spring crop, clean greenhouse, sterilize, and so on
Jul 15	Transplant fall tomato crop and lettuce intercrop into hydroponic system.
Aug 15–31	Harvest lettuce
Sept 15	Begin harvesting tomatoes
Nov 15	Terminate tomato plants
Dec 20–31	Pull plants of fall crop, clean up, sterilize, and so on, sow lettuce and tomato seeds of spring crop

TABLE 14.6
Three-Crop Schedule for Annual Cucumber Production

Date	Activity
Jan 1	Sow cucumber seeds
Feb 7	Transplant into growing system (first crop)
Mar 7	Begin harvesting cucumbers
Apr 21	Sow cucumber seeds (second crop)
May 15	Pull cucumbers of first crop, clean up, and so on, transplant cucumbers into growing system (second crop)
Jun 21	Begin harvesting cucumbers (second crop)
Aug 15	Sow cucumber seeds (third crop)
Aug 31	Pull cucumber plants of second crop, clean up, and so on
Sept 15	Transplant cucumbers into growing system (third crop)
Oct 15	Begin harvesting cucumbers (third crop)
Dec 20–31	Pull cucumbers of third crop, clean up, and so on

TABLE 14.7
Single Crop of Tomatoes, Eggplants, Cucumbers, or Peppers

Date	Activity
	Tomatoes and Eggplants
Nov 7–14	Sow tomato and/or eggplant seeds
Nov 30	Transplant to larger rockwool blocks under HID supplementary lighting with minimum 5,500 lx (510 ft-c) intensity in seeding area of greenhouse
Dec 14	Set plants in rockwool blocks on top of slabs in greenhouse
Jan 1–7	Transplant tomatoes and/or eggplants into slabs (beds) when flower buds appear
Feb 15–21	First harvest
Nov 21	Last harvest
Nov 21–Dec 7	Remove plants, clean up, and so on
	Cucumbers
Dec 1	Sow cucumber seeds in seeding house
Jan 1–7	Transplant to slabs or beds in greenhouse
Feb 1–7	Begin harvesting cucumbers
Nov 15	Last harvest
Nov 15–Dec 15	Remove plants, clean up, and so on
	Peppers
Oct 1	Sow pepper seeds in seedling house
Oct 21	Transplant peppers to rockwool blocks in seeding greenhouse
Nov 21	Transplant to slabs or beds in greenhouse
Feb 7–15	Begin harvesting peppers
Nov 15–21	Last harvest, remove plants, clean up, and so on

Note: See Chapter 10 for more details on cropping procedures.

Peppers are now a common greenhouse crop grown as a single crop annually from October through November, as shown in Table 14.7.

Eggplants are grown on the same crop schedule as tomatoes as a single annual crop or as two crops per year. The author prefers a two-crop system, as they are difficult to lower and suffer a lot of stress during such a procedure, as described earlier in this chapter.

14.20 CROP TERMINATION

In growing tomatoes, the growing point of each plant should be cut off about 30 d before the expected date for pulling of the plants (Table 14.5). During this 30-d period, remove the many suckers that will develop at the top of the plants.

Several days before starting the clean up, spray the plants to kill any insect infestations. Be careful not to use any pesticides having long-term residual effect, which may harm the beneficial predators of the IPM program of subsequent crops. Stop the flow of water and nutrients to the slabs or beds a few days before physically removing the plants from the greenhouse. Pull out the roots, or cut the base of the stems, but leave the rest of the plant still supported by the string and some clamps. It is easier to remove most of the plant clips before cutting the plants if the clips are to be recycled, otherwise dispose of them with the plants. The plant clips can be reused after soaking and washing them in a bleach solution. By cutting the stems, the plants will lose a lot of water and thus reduce the overall plant weight to be removed from the greenhouse. Dispose of the plants in the garbage or on a compost pile or bury them some distance from the greenhouse to avoid any disease or insect reinfestation of the new crop. After all the plants have been removed from the greenhouse, sweep or vacuum all the floors clean, so that no plant debris remains. The beds, nutrient tanks, and growing medium must be thoroughly sterilized according to measures given in earlier chapters.

Flush irrigation lines with nitric acid at a pH of 1.6–1.7 (60%–70% concentrate diluted 1 part acid to 50 parts water) for 24 h. Make this up in the blending tank and run each station for 2 min to allow the acid solution to thoroughly flush through the system. Let the lines sit full of the acid solution for 24 h. Rinse the lines after 24 h with fresh water and check the pH of the drain water to determine that it is above 5.0 before flushing the lines with a 10% bleach solution. Be careful that the pH is not low because of the presence of acid; if there is any acid remaining it will react with the bleach solution to produce toxic chlorine gas. Flush the lines four times for 2 min every hour over a 4-h period. Leave the final flush in the lines for 24 h. After that, rinse the lines with fresh water.

Power wash the walls, roof, and floor with a sterilant such as Virkon, followed with a 10% bleach solution. Virkon is applied at a rate of 1.0% solution. As Virkon is a powder, mix 1 kg (2.2 lb) per 100 L (26.4 U.S. gal) of water. Once everything has been completely sterilized, the system is ready for its next crop.

A hydroponic system, if properly sterilized and cleaned before each crop, will continuously yield heavy crops over the years, giving its operator higher returns than could be achieved over the long term with soil.

14.21 SPECIAL CONSIDERATIONS

Whether plants are grown hydroponically or in soil, their cultural requirements are the same. Specific information on the growing of various plants is available from gardening books and various extension bulletins issued by universities and agricultural departments. A list of some university extension offices is given in Appendix 2.

Commercial greenhouses are now closely scrutinized by various environmental groups. As a result, use of water, runoff, pesticides, and fertilizer wastes are important aspects to be controlled. Greenhouses are being forced to reuse water, minimize the use of pesticides and fertilizers, and recycle wastes. Recycling of plant materials could be achieved through their use in animal foods. Water and fertilizer usage can be minimized with recirculation hydroponic systems of rockwool, coco coir, and NFT cultures. Pesticide use is largely reduced by employing biological agents in an IPM program. The use of fungicides is being reduced through biological controls and the breeding of disease-resistant varieties. Research in more efficient hydroponic methods, nutrient analyses, and automatic solution adjustment with sterilization of the solution during each passage through the nutrient solution reservoir, all monitored and controlled by a central computer, are some of the present practices in hydroponic culture.

Sustainable cropping systems are now the buzz word in agriculture, and particularly in greenhouse hydroponics. As discussed in Section 11.5, coco coir substrate is the basis for such sustainable agriculture. Greenhouse structures and hydroponic systems that recirculate and adjust their environment and solutions are part of this program. Recently, the use of solar panels in the generation of electricity for the greenhouse is the next step. A company in Germany is presently constructing 5 ha (12.5 acres) of high-tech greenhouses using new solar panels that are mounted on the roof to provide electricity and shading for the greenhouse. A California-based company, Solyndra, has developed this solar panel, which doubles to provide shade through diffusion of light and to generate electricity. They are working with the Regional Center of Experimentation and Agricultural Assistance in Milan, Italy, and the Department of Plant Sciences at the University of California Davis (www.coolerplanet.com).

An article in www.freshplaza.com on May 10, 2011, reported that the company Micothon, which invented an air-assisted spraying technique that gives better penetration and coverage in applying pesticides than conventional spraying systems, is working with Clean Light BV in developing a "Clean Light UV Crop Protection" system for disease management (www.micothon.com and www.cleanlight.nl). Combined with their "Micothon Spraying Robot," it reduces the use of chemicals in greenhouses and helps to protect against fungi, bacteria, and viruses. Micothon claims that with their air-assisted spraying technology one can realize up to 79% better spraying results compared to standard spraying equipment. This gives optimal protection of the crops, with a large reduction in use of pesticides and reduced labor costs from its automated operation. The tube/rail sprayer automatically drives on the heating rail pipes according to the set program of the machine and sprays the entire greenhouse without an operator.

LED grow lights will in the near future provide adequate light over large areas to enable their use in commercial greenhouse operations. They are more efficient in converting energy to light than the present HID lights. However, at present, they are very expensive and do not cover a large surface area to make them economically feasible to use in commercial greenhouses. This lighting in the future may provide an opportunity to construct vertical greenhouses in cities.

This effective control provides hydroponics with the potential of becoming the solution to intensive crop production throughout the world, and in man's future travels to other planets. Hydroponic experiments are now being conducted by several companies sponsored by NASA in its space program. It is to be the method of providing fresh vegetables to astronauts on the space station and future space travel. Experiments on growing plants in space are now scheduled for space flights in the near future. Hydroponic systems have been designed and tested to operate under microgravity environmental conditions of spaceflight. A biomass chamber has been designed for NASA's Controlled Ecological Life Support System (CELSS). Many studies are currently underway to develop equipment and cultural procedures to grow crops hydroponically in space.

Hydroponics is a universal science in that it can be applied to very simple systems such as individual pots of soilless substrate in homes or inexpensive units constructed by individuals themselves in searching for methods of growing basic food crops. This often occurs in poor neighborhoods of countries such as Peru, Colombia, Venezuela, and so on, where people may not have the financial ability to buy nutritious vegetables in the marketplace. It is a key part of the worldwide greenhouse vegetable and ornamental plant industry. It is used in isolated environments such as the McMurdo Research Station in Antarctica to grow vegetables in a closed environment.

Hydroponics is now being incorporated into cities through rooftop hydroponic greenhouse operations, as discussed in Chapter 13. This universal science of hydroponics will continue to enter into new applications in providing highly nutritious vegetables for us under all environmental conditions.

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Appendix 1

Horticultural, Hydroponic, and Soilless-Culture Societies

The largest organization that participates in conferences and symposiums internationally and publishes scientific papers on horticulture is the International Society for Horticultural Science (ISHS) (www.ishs.org). They participate with many hydroponic societies in organizing events on hydroponic culture and horticulture. For example, they recently assisted in the II International Symposium on Soilless Culture and Hydroponics in Pueblo, Mexico, from May 15 to 19, 2011 (www.soillessculture.org). This was a joint event organized by ISHS, the Commission Plant Substrates and Soilless Culture (CMPS), and the Colegio de Postgraduados (CP) in Mexico.

Anyone who is interested in any aspects of horticulture, including hydroponics, may apply for membership in the ISHS. ISHS membership gives one access to publications, symposia, mailing lists, and online services to develop information networks with colleagues having similar interests and concerns in resolving solutions to his or her challenges. This knowledge is shared on an international scale. The ISHS has online forms to apply for membership.

The Hydroponic Society of America (HAS) exists mostly as an online service. They may be contacted at Hydroponic Society of America, P.O. Box 1183, El Cerrito, CA 94530, USA (www.hydroponicsociety.org). Another North American hydroponic society is the Hydroponic Merchants Association (HMA) at 10210 Leatherleaf Ct., Manassas, VA 20111-4245, USA (www.hydromerchants.org).

Other hydroponic societies in the world include the following:

The Australian Hydroponic and Greenhouse Association (AHGA) (renamed Protected Cropping Australia) (PCA). The website is www.protectedcroppingaustralia.com.
In Brazil, the Encontro Brasileiro de Hidroponia (www.encontrohidroponia.com.br).
Centro Nacional de Jardineria Corazon Verde in Costa Rica (www.corazonverdecr.com).
Asociacion Hidroponica Mexicana A.C., Mexico (www.hidroponia.org.mx).
The Singapore Society for Soilless Culture (SSSC): 13-75, 461 Crawford Lane, Singapore 190461.

Others may be found by searching on Google under “Hydroponic Societies” or “Hydroponic Associations.” There are also many forums that one can join to participate in discussions and problem solving with other members.

Appendix 2
Greenhouse Production Resources

RESEARCH EXTENSION SERVICES FOR PUBLICATIONS

Presented here are a few typical sources of information for horticulture, including hydroponics. Nonetheless, the best way to search for information is with specific requests through search engines, such as Google, on the Internet.

Superintendent of Documents: U.S. Government Printing Office: http://www.gpoaccess.gov, http://www.gpo.gov, http://www.bookstore.gpo.gov, http://www.access.gpo.gov.
Wikipedia Cooperative Extension Service: http://en.widipedia.org/wiki/Cooperative_extension_service
Alabama Cooperative Extension System: http://www.aces.edu/
Arizona Cooperative Extension: http://extension.arizona.edu/
University of California Cooperative Extension: http://ucanr.org/
University of Connecticut Extension Services: http://www.extension.uconn.edu/
University of Florida IFAS Extension: http://solutionsforyourlife.ufl.edu/
University of Georgia Cooperative Extension: http://ugaextension.com/
University of Illinois Extension: http://www.extension.uiuc.edu/
Purdue University Extension: http://www.ces.purdue.edu/
University of Kentucky Cooperative Extension Service: http://www.ca.uky.edu/ces/index.htm
Michigan State University Extension: http://www.msue.msu.edu/
Minnesota Extension Service: http://www.extension.umn.edu/
Mississippi State University Extension: http://msucares.com
Rutgers Cooperative Extension: http://www.rce.rutgers.edu/
Cornell Cooperative Extension: http://www.cce.cornell.edu/
North Carolina Cooperative Extension Service: http://www.ces.ncsu.edu/
The Ohio State University Extension: http://extension.osu.edu/
Oregon State University Extension Service: http://extension.oregonstate.edu/
Penn State Cooperative Extension: http://www.extension.psu.edu
Texas A&M University-Texas AgriLife Extension Service: http://texasextension.tamu.edu/
Utah State University Extension: http://www.ext.usu.edu/
Washington State University Extension: http://ext.wsu.edu/
University of Wisconsin Extension: http://www.uwex.edu/ces/

SOME SOIL AND PLANT-TISSUE TESTING LABORATORIES

A&L Southern Agricultural Laboratories, Pompano Beach, FL
A&L Canada Laboratories East, Inc., London, ON: http://www.alcanada.com

A&L Eastern Laboratories, Inc., Richmond, VA: http://al-labs-eastern.com
A&L Great Lakes Laboratories, Inc., Ft. Wayne, IN: http://www.algreatlakes.com
A&L Plains Laboratories, Inc., Lubbock, TX: http://www.al-labs-plains.com
Albion Laboratories, Inc., Clearfield, UT: http://www.AlbionMinerals.com
ALS Laboratory Group, Saskatoon, SK: http://www.alsglobal.com
Agrichem Analytical, Saltspring Island, BC: http://www.agrichem.ca
Agsource Harris Laboratories, Lincoln, NE: http://harris.agsource.com
Analytica Environmental Laboratories, Inc., Thornton, CO: http://www.analyticagroup.com
Brookside Analytical Laboratories, New Knoxville, OH: http://www.blinc.com
Colorado Analytical Laboratory, Brighton, CO: http://www.coloradolab.com
Colorado State Soil, Water and Plant Testing Laboratory, Fort Collins, CO: http://www.extsoilcrop.colostate.edu/SoilLab/soillab.html
Cornell University Analysis Laboratory, Ithaca, NY: http://cnal.cals.cornell.edu/analyses/index.html
Energy Laboratories, Inc., Casper, WY: http://www.energylab.com
Enviro-Test Laboratories, University of Saskatchewan, Saskatoon, SK: http://www.envirotest.com
Exova, Surrey, BC: http://www.exova.com
Griffin Labs Corp. Kelowna, BC: http://www.grifflabs.com
Hill Laboratories, Hamilton, New Zealand: http://www.hill-laboratories.com
Kansas State Research and Extension Soil Testing Laboratory, Manhattan, KS: http://www.agronomy.ksu.edu/soiltesting/
Kinsey's Agricultural Services, Charleston, MO: http://www.kinseyag.com
Les Laboratoires A&L du Canada, Saint Charles sur Richelieu, Quebec: http://www.al-labs-can.com/soil/ser_QCsoil.html
Maxxam Analytics, Burnaby, BC: http://www.maxxam.ca
MB Laboratories Ltd., Sidney, BC: http://www.mblabs.com
Micro Macro International, Inc., Athens, GA: http://www.mmilabs.com
Midwest Laboratories, Inc., Omaha, NE: http://www.midwestlabs.com
Midwestern Bio-Ag, Blue Mounds, WI: http://www.midwesternbioag.com
Northwest Labs, Edmonton, AB and Winnipeg, Manitoba: http://www.norwestlabs.com
Olsen's Agricultural Laboratory, Inc., McCook, NE: http://www.olsenlab.com
Servi-Tech Laboratories, Dodge City, KS: http://www.servitechlabs.com
Scotts Testing Lab, Allentown, PA: http://www.scottsprotestlab.com/plantTesting.php
Soil and Nutrient Laboratory, University of Guelph, Guelph, ON: http://www.uoguelph.ca/labserv
Soil and Plant Analysis Laboratory, University of Wisconsin, Verona, WI: http://uwlab.soils.wisc.edu
Soil & Plant Laboratory, Inc., Anaheim, CA and San Jose, CA: http://www.soilandplantlaboratory.com
Soil Nutrient Analysis Laboratory, University of Connecticut, Storrs, CT: http://soiltest.uconn.edu/
Soil Testing and Plant Diagnostic Services, University of Missouri, Columbia, MO: http://soilplantlab.missouri.edu/
Stratford Agri Analysis Inc., Stratford, ON: http://www.stratfordagri.com

Ward Laboratories, Inc., Kearney, NE: http://www.wardlab.com
Weld Laboratories, Inc., Greeley, CO: http://www.weldlabs.com
Western Laboratories, Parma, ID: http://www.westernlaboratories.com

These are a few of the many laboratories that offer soil, water, nutrient, and plant tissue analyses. There are a number of websites that also offer directories to laboratories such as the following:

Canadian Gardening-How to-Gardening Resources-Testing Your Soil: http://www.canadiangardening.com
Ministry of Agriculture and Lands, Nutrient Testing Laboratories: http://www.agf.gov.bc.ca/resmgmt/NutrientMgmt
Ontario Ministry of Agriculture, Food and Rural Affairs-Nutrient Testing-Accredited Soil Testing Laboratories in Ontario: http://www.omafra.gov.on.ca/english/crops/resource/soillabs.htm
Purdue University-University Related Plant Disease and Soil Testing Services, March 2010: http://www.apsnet.org/members/Documents/SoilLabsandPlantClinics.pdf
ATTRA-National Sustainable Agriculture Information Service-Alternative Soil Testing Laboratories: http://www.attra.org/attra-pub/soil-lab.html

BIOLOGICAL-CONTROL AGENTS

Note: This is not a complete list of companies selling and/or producing biological-control agents.

PRODUCERS

Applied Bio-Nomics Ltd., Sidney, BC: http://www.appliedbio-nomics.com
Associates Insectary, Santa Paula, CA: http://www.associatesinsectary.com
Becker Underwood, Ames, IA: http://www.beckerunderwood.com
Beneficial Insectary, Inc., Redding, CA: http://www.insectary.com
Biobest Canada Limited, Leamington, ON: http://www.biobest.ca
EnviroScience, Inc., Stow, OH: http://www.enviroscienceinc.com
Hydro Gardens-HGI Worldwide, Colorado Springs, CO: http://www.hydro-gardens.com
IPM Laboratories, Locke, NY: http://www.ipmlabs.com
Koppert Biological Systems, Inc., Howell, MI: http://www.koppert.com
Natural Insect Control, Stevensville, ON: http://www.naturalinsectcontrol.com
Pramukh Agriclinic, Madhi, Gujarat, India: Email: pramukhagriclinic@yahoo.co.in
Rincon-Vitova Insectaries, Inc., Ventura, CA: http://www.rinconvitova.com
Sesil Corporation, Chungcheongnam Do, South Korea: http://www.sesilipm.co.kr
Syngenta Bioline, Inc., Oxnard, CA: http://www.SyngentaBioline.com

DISTRIBUTORS

Bio Control S.A., Cartago, Costa Rica: Email: biocontrolsa@ice.co.cr
Distribuciones Imex S.A. de C.V., Jalisco, Mexico: http://www.distribucionesimex.com

EcoSolutions, Inc., Palm Harbor, FL: http://www.ecosolutionsbeneficials.com
Evergreen Growers Supply, Oregon City, OR: http://www.evergreengrowers.com
Global Horticultural, Inc., Beamsville, ON: http://www.globalhort.com
International Technical Services, Wayzatta, MN: http://www.greenhouseinfo.com or: http://www.intertechserv.com
MGS Horticultural, Inc., Leamington, ON: http://www.mgshort.com
Plant Products Co. Ltd., Brampton, ON: http://www.plantprod.com
Richters, Goodwood, ON: http://www.Richters.com
Sound Horticulture, Bellingham, WA: http://www.soundhorticulture.com

SOURCES OF INFORMATION ON BIOLOGICAL CONTROL

Association of Natural Biocontrol Producers: http://www.anbp.org/biocontrollinks.htm
California Department of Pesticide Regulation: Suppliers of Beneficial Organisms in North America: http://www.cdpr.ca.gov/docs/pestmgt/ipminov/bensuppl.htm
Cornell University, College of Agriculture and Life Sciences, Ithaca, NY: http://www.biocontrol.entomology.cornell.edu/
North Carolina State University, Biological Control Information Center, Raleigh, NC: http://www.cipm.ncsu.edu/ent/biocontrol/links.htm
Oregon State University, Integrated Plant Protection Center, Corvallis, OR: http://www.ipmnet.org/
University of Arizona, Controlled Environment Agriculture Center (CEAC), Tucson, AZ: http://ag.arizona.edu/ceac/
University of California, Davis, CA: http://www.ipm.ucdavis.edu/
University of Hawaii Extension, Manoa, Hawaii: http://www.extento.hawaii.edu/kbase/
University of Minnesota, Minneapolis-St. Paul, MN: http://www.entomology.umn.edu/cues/dx/pests.htm
United States Department of Agriculture (USDA): http://www.usda.gov/wps/portal/usda/usdahome?navid=PLANT_HEALTH

REFERENCE

Leppla, N.C. and K.L. Johnson II. 2010. Guidelines for purchasing and using commercial natural enemies and biopesticides in Florida and other states. University of Florida IFAS Extension document IPM-146, Gainesville, FL, http://www.anbp.org/documents/Leppla_Paper_2010.pdf (accessed May 23, 2011).

SPECIAL HYDROPONIC EQUIPMENT

1. *NFT troughs*:
   American Hydroponics, Arcata, CA: http://www.amhydro.com
   CropKing, Lodi, OH: http://www.cropking.com
   Dynacs, Sao Paulo, Brazil: http://www.dynacs.com.br
   Hidrogood Unipessoal Lda., Leiria, Portugal: http://hidrogood.com.pt
   Hortiplan N.V., Belgium: http://www.hortiplan.com/MGS

Hydrocultura, Tlalpan, Mexico: http://www.hydrocultura.com.mx
HydroGarden Wholesale Supplies, Coventry, UK: http://www.hydrogarden.co.uk
Hydroponic Developments Ltd., Tauranga, New Zealand: http://hydrosupply.com
Zwart Systems, Beamsville, ON: http://www.zwartsystems.ca

2. *UV sterilizers*:
   Advanced UV, Inc., Cerritos, CA: http://www.advanceduv.com
   Atlantic Ultraviolet Corp., Hauppauge, NY: http://www.ultraviolet.com
   Aquafine Corporation, Valencia, CA: http://www.aquafineuv.com
   Hortimax, B.V., The Netherlands: http://www.hortimax.com
   Priva America Latina S.A. de C.V., Queretaro, Mexico: http://www.priva.mx
   Priva B.V., The Netherlands: http://www.priva.nl
   Priva International Beijing Ltd., Beijing, China: http://www.priva-asia.com
   Priva North America, Inc., Vineland Station, ON: http://www.priva.ca
   Priva UK, Watford, UK: http://www.priva.co.uk
   Zwart Systems, Beamsville, ON: http://www.zwartsystems.ca
3. *Water chillers*:
   Frigid Units, Inc., Toledo, OH: http://www.frigidunits.com
4. *Vertical plant towers*:
   Hydro-Stacker, Inc., Bradenton, FL: http://www.hydrostacker.com
   Verti-Gro, Inc., Summerfield, FL: http://vertigro.com

Appendix 3
Units of Measurement—Conversion Factors

Parameter	**To Convert →**	**Into →**	**Multiply by**
Length			
25.401	Millimeters	Inches	0.0394
2.5401	Centimeters	Inches	0.3937
0.3048	Meters	Feet	3.2808
0.9144	Meters	Yards	1.0936
1.6093	Kilometers	Miles (statute)	0.6214
Area			
645.160	Square millimeters	Square inches	0.001550
6.4516	Square centimeters	Square inches	0.1550
0.0929	Square meters	Square feet	10.7639
0.8361	Square meters	Square yards	1.1960
0.004046	Square kilometers	Acres	247.105
2.5900	Square kilometers	Square miles	0.3861
0.4046	Hectares	Acres	2.4710
Volume			
16.3872	Cubic centimeters	Cubic inches	0.0610
0.0283	Cubic meters	Cubic feet	35.3145
0.7646	Cubic meters	Cubic yards	1.3079
0.003785	Cubic meters	Gallons (U.S.)	264.178
0.004545	Cubic meters	Gallons (U.K.)	219.976
0.01639	Liters	Cubic inches	61.0238
28.3205	Liters	Cubic feet	0.03531
3.7850	Liters	Gallons (U.S.)	0.2642
4.5454	Liters	Gallons (U.K.)	0.2200
Weight			
28.3495	Grams	Ounces (av.)	0.0353
31.1035	Grams	Ounces (troy)	0.0321
0.4536	Kilograms	Pounds (av.)	2.2046
0.0004535	Metric tons	Pounds (av.)	2204.62
0.907185	Metric tons	Tons (U.S.)	1.1023
1.016047	Metric tons	Tons (U.K.)	0.9842
Multiply by	**← Into**	**← To Convert**	

Appendix 4

Physical Constants of Inorganic Compounds

		Density or	Solubility (g/100 mL)	
Name	**Formula**	**Specific Gravity**	**Cold Water**	**Hot Water**
Ammonium nitrate	NH_4NO_3	1.725	118.3	871
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	1.803	22.7	173.2
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}\cdot 4H_2O$	43	—	—
Ammonium monohydrogen phosphate	$(NH_4)_2HPO_4$	1.619	57.5	106.0
Ammonium sulfate	$(NH_4)_2SO_4$	1.769	70.6	103.8
Boric acid	H_3BO_3	1.435	6.35	27.6
Calcium carbonate	$CaCO_3$	2.710	0.0014	0.0018
Calcium chloride	$CaCl_2$	2.15	74.5	159
Calcium chloride hexahydrate	$CaCl_2\cdot 6H_2O$	1.71	279	536
Calcium hydroxide	$Ca(OH)_2$	2.24	0.185	0.077
Calcium nitrate	$Ca(NO_3)_2$	2.504	121.2	376
Calcium nitrate tetrahydrate	$Ca(NO_3)_2\cdot 4H_2O$	1.82	266	660
Calcium oxide	CaO	3.25–3.38	0.131	0.07
Calcium monophosphate	$Ca(H_2PO_4)_2\cdot H_2O$	2.220	1.8	Decomposes
Calcium sulfate	$CaSO_4$	2.960	0.209	0.1619
Calcium sulfate dihydrate	$CaSO_4\cdot 2H_2O$	2.32	0.241	0.222
Copper sulfate pentahydrate	$CuSO_4\cdot 5H_2O$	2.284	31.6	203.3
Iron (II) hydroxide	$Fe(OH)_2$	3.4	0.00015	—
Iron (II) nitrate	$Fe(NO_3)_2\cdot 6H_2O$	1.6	83.5	166.7
Iron (II) sulfate heptahydrate	$FeSO_4\cdot 7H_2O$	1.898	15.65	48.6
Magnesium oxide	MgO_2	3.58	0.00062	0.0086
Magnesium orthophosphate	$Mg_3(PO_4)_2$	—	Insoluble	Insoluble
Magnesium monohydrogen phosphate heptahydrate	$MgHPO_4\cdot 7H_2O$	1.728	0.3	0.2
Magnesium orthophosphate tetrahydrate	$Mg_3(PO_4)_2\cdot 4H_2O$	1.64	0.0205	—
Magnesium sulfate heptahydrate	$MgSO_4\cdot 7H_2O$	1.68	71	91
Manganese dichloride tetrahydrate	$MnCl_2\cdot 4H_2O$	2.01	151	656
Manganous (II) hydroxide	$Mn(OH)_2$	3.258	0.0002	—
Manganous nitrate	$Mn(NO_3)_2\cdot 4H_2O$	1.82	426.4	Infinite

continued

Name	Formula	Density or Specific Gravity	Solubility (g/100 mL)	
			Cold Water	Hot Water
Manganous dihydrogen phosphate	$Mn(H_2PO_4)_2 \cdot 2H_2O$	—	Soluble	—
Manganous monohydrogen phosphate	$MnHPO_4 \cdot 3H_2O$	—	Slightly soluble	Decomposes
Manganous sulfate	$MnSO_4$	3.25	52	70
Manganous sulfate tetrahydrate	$MnSO_4 \cdot 4H_2O$	2.107	105.3	111.2
Nitric acid	HNO_3	1.5027	Infinite	Infinite
Phosphoric acid (ortho)	H_3PO_4	1.834	548	Very soluble
Phosphoric anhydride	P_2O_5	2.39	Decomposes to H_3PO_4	
Potassium carbonate	K_2CO_3	2.428	112	0.156
Potassium carbonate dihydrate	$K_2CO_3 \cdot 2H_2O$	2.043	146.9	331
Potassium hydrogen carbonate	$KHCO_3$	2.17	22.4	60
Potassium carbonate trihydrate	$2K_2CO_3 \cdot 3H_2O$	2.043	129.4	268.3
Potassium chloride	KCl	1.984	34.7	56.7
Potassium hydroxide	KOH	2.044	107	178
Potassium nitrate	KNO_3	2.109	13.3	47
Potassium orthophosphate	K_3PO_4	2.564	90	Soluble
Potassium dihydrogen phosphate	KH_2PO_4	2.338	33	83.5
Potassium monohydrogen phosphate	K_2HPO_4	—	167	Very soluble
Potassium sulfate	K_2SO_4	2.662	12	24.1
Zinc carbonate	$ZnCO_3$	4.398	0.001	—
Zinc chloride	$ZnCl_2$	2.91	432	615
Zinc orthophosphate	$Zn_3(PO_4)_2$	3.998	Insoluble	Insoluble
Zinc dihydrogen phosphate	$Zn(H_2PO_4)_2 \cdot 2H_2O$	—	Decomposes	—
Zinc orthophosphate tetrahydrate	$Zn_3(PO_4)_2 \cdot 4H_2O$	3.04	Insoluble	Insoluble
Zinc sulfate heptahydrate	$ZnSO_4 \cdot 7H_2O$	1.957	96.5	663.6

Appendix 5
Greenhouse and Hydroponic Suppliers

BIOCONTROL AGENTS

MICROBIALS/BIOAGENTS

ACM-Texas, LLC, Fort Collins, CO: www.ampowdergard.com
AgriDyne Technologies, Inc., (BioSys, Inc.), Rosenberg, TX: www.biosysinc.com
Bayer Corporation, Kansas City, MO: http://usagri.bayer.com
BioBest Canada Ltd., Leamington, ON: www.biobest.ca
BioSafe Systems LLC., East Hartford, CT: www.biosafesystems.com
BioWorks, Inc., Victor, NY: www.bioworksinc.com
Dow AgroSciences LLC: www.dowagro.com
EcoSmart Technologies, Inc., Franklin, TN: www.ecosmart.com
Growth Products, Ltd., White Plains, NY: www.growthproducts.com
International Technology Services, Wayzatta, MN: www.intertechserv.com
McLaughlin Gormley King Company (MGK), Minneapolis, MN: www.pyganic.com
Monterey AgResources, Fresno, CA: www.montereyagresources.com
Mycogen Corporation, San Diego, CA: www.dowagro.com
Natural Industries, Inc., Houston, TX: www.naturalindustries.com
Olympic Horticultural Products Co., (OHP), Mainland, PA: www.ohp.com
Phyton Corporation: www.phytoncorp.com
The Organic Materials Review Institute (OMRI), Eugene, OR: www.omri.org
Valent BioSciences Corporation, Libertyville, IL: www.valentpro.com

POLLINATORS (*BOMBUS SP.*)

Bees West, Inc., Freedom, CA: www.beeswestinc.com
Biobest Belgium N.V., Westerlo, Belgium: www.biobest.be
Biobest Canada Ltd., Leamington, ON: www.biobest.ca
Distribuciones Imex S.A. de C.V., Jalisco, Mexico: www.distribucionesimex.com
International Technical Services, Wayzatta, MN: www.intertechserv.com
Koppert B.V., Berkel en Rodenrijs, The Netherlands: www.koppert.nl
Koppert Canada Limited, Scarborough, ON: www.koppert.com
Koppert Mexico, S.A. de C.V., El Marques, Queretaro, Mexico: www.koppert.com.mx
Koppert Biological Systems, Inc.-USA, Howell, MI: www.koppert.com

GREENHOUSE STRUCTURES, COVERINGS AND EQUIPMENT

Acme Engineering & Mfg. Corp., Muskogee, OK: www.acmefan.com
Advancing Alternatives, Schuylkill Haven, PA: www.advancingalternatives.com
AgraTech, Inc., Pittsburg, CA: www.agratech.com
American Coolair Corp., Jacksonville, FL: www.coolair.com
AmeriLux International, LLC, DePere, WI: www.ameriluxinternational.com
Argus Control Systems Ltd., White Rock, BC: www.arguscontrols.com
AT Films, Inc., Edmonton, AB: www.atfilmsinc.com
Atlas Manufacturing, Inc., Alapaha, GA: www.atlasgreenhouse.com
Berco, Inc., St. Louis, MO: www.bercoinc.com
BFG Supply Co., Burton, OH: www.bfgsupply.com
Biotherm Hydronic, Inc. (TrueLeaf Technologies), Petaluma, CA: www.trueleaf.net
B & K Installation Co. Inc., Homestead, FL: www.bk-installations.com
Bom Greenhouses, Naaldwijk, The Netherlands: www.bomgreenhouses.com
Canadian Hydrogardens Ltd., Ancaster, ON: www.hydrogardens.ca
Climate Control Systems, Inc., Leamington, ON: www.climatecontrol.com
Conley's Greenhouse Manufacturing & Sales, Montclair, CA: www.conleys.com
Cravo Equipment Ltd., Brantford, ON: www.cravo.com
CropKing, Inc., Lodi, OH: www.cropking.com
Dalsem Horticultual Projects B.V., Den Hoorn, The Netherlands: www.dalsem.nl
DeCloet Greenhouse Manufacturing Ltd., Simcoe, ON: www.decloetgreenhouse.com
Delta T Solutions, San Marcos, CA: www.deltatsolutions.com
Evonik Cyro Canada, Inc., Toronto, ON: www.acrylitebuildingproducts.com
Fogco Systems, Inc., Chandler, AZ: www.fogco.com
Foremostco, Inc., Miami, FL: www.foremostco.com
FormFlex Horticultural Systems, Beamsville, ON: www.formflex.ca
Foundation DACE, Nijkerk, The Netherlands: www.dace.nl
Grayhawk Greenhouse Supply, Swanton, OH: www.grayhawkgreenhousesupply.com
Green-Tek, Edgerton, WI: www.green-tek.com
Growers Greenhouse Supplies, Inc., Vineland Station, ON: www.ggs-greenhouse.com
Growers Supply, Dyersville, IA: www.growerssupply.com
Grupo Inverca S.A., Almazora, Spain: www.invercagroup.com
Harnois Greenhouses, St-Thomas-de-Joliette, QC, Canada: www.harnois.com
Herve Savoure, Reston, VA: www.richel-usa.com
Holland Greenhouses, Lansingerland, The Netherlands: www.holland-greenhouses.nl
Jaderloon Co. Inc., Columbia, SC: www.jaderloon.com
JVK Ltd., St. Catharines, ON: www.jvk.net
Kees Greeve B.V., Bergschenhoek, The Netherlands: www.keesgreeve.nl
KGP Greenhouses, Maasdijk, The Netherlands: www.kgpgreenhouses.com
Koolfog, Inc., Palm Desert, CA: www.koolfog.com
Kubo Greenhouse Projects, Monster, The Netherlands: www.kubo.nl
LL Klink & Sons, Inc., Columbia Station, OH: www.LLKlink.com
LS Svensson, Kinna, Sweden: www.ludrigsvensson.com
Ludy Greenhouse Manufacturing Corporation, New Madison, OH: www.ludy.com
Lumite, Inc., Gainesville, GA: www.lumiteinc.com
Lux Lighting Co., Ltd., GuangMing New District, Shenzhen, China: www.growlight.cn

McConkey Co. Inc., Sumner, WA: www.mcconkeyco.com
Mee Industries, Inc., Monrovia, CA: www.meefog.com
Metazet Zwethovve B.V., Wateringen, The Netherlands: www.metazet.com
Nexus Corporation, Northglenn, CO: www.nexuscorp.com
Oregon Valley Greenhouses, Inc., Aurora, OR: www.ovg.com
PARsource Lighting Solutions, Petaluma, CA: www.parsource.com
Paul Boers Ltd., Vineland Station, ON: www.paulboers.com
Plastika Kritis S.A., Crete, Greece: www.plastikakritis.com
P.L. Light Systems, Inc., Beamsville, ON: www.pllight.com
Polygal, Inc., Charlotte, NC: www.polygal.com
Poly-Tex, Inc., Castle Rock, Mn: www.poly-tex.com
Powerplants Australia Pty Ltd., Victoria, Australia: www.powerplants.com.au
Prins Greenhouses, Abbotsford, BC: www.prinsgreenhouses.com
Quasar Light Co., Ltd., Shenzhen Guangdong, China: www.quasarled.com
Richel Group, Eygalieries, France: www.richel.fr
Rough Brothers, Inc., Cincinnati, OH: www.roughbros.com
Smart Fog, Inc., Reno, NV: www.smartfog.com
South Essex Fabricating Inc., Leamington, ON: www.southsx.com
Southwest Agri-Plastics, Inc., Dallas, TX: www.swapinc.com
Structures Unlimited, Sarasota, FL: www.structuresunlimited.net
Stuppy Greenhouse Mfg. Inc., Kansas City, MO: www.stuppy.com
Sunlight Supply, Inc., Vancouver, WA: www.sunlightsupply.com
TrueFog, USA, Desert Hot Springs, CA: www.truefog.com
Val-Co Environmental & Greenhouse Systems, Bird-In-Hand, PA: www.valcogreenhouse.com
Val-Co Greenhouse, Lopik, The Netherlands: www.valcogreenhouse.com
Van der Hoeven B.V., Gravenzande, The Netherlands: www.vanderhoeven.nl
Van Wingerden Greenhouse Company, Mills River, NC: www.van-wingerden.com
Venlo Greenhouse Systems, Inc., Spotsylvania, VA: www.venloinc.com
Verbakel/Bomdas B.V., De Lier, The Netherlands: www.verbakel-bomkas.com
V & V Group, De Lier, The Netherlands: www.venv-holland.nl
Wadsworth Control Systems, Arvada, CO: www.wadsworthcontrols.com
Westbrook Greenhouse Systems, Beamsville, ON: www.westbrooksystems.com
XS Smith, Inc., Washington, NC: www.xssmith.com
Zwart Systems, Beamsville, ON: www.zwartsystems.ca

GREENHOUSE SHADING MATERIALS

Mardenkro North America, Chilliwack, BC: www.mardenkro.com

GROWING MEDIA AND SUPPLIES

Berger Peat Moss, St. Modeste, QC, Canada: www.bergerweb.com
Conrad Fafard, Inc., Agawam, MA: www.fafard.com
CropKing, Inc., Lodi, OH: www.cropking.com
DeWitt Company Inc., Sikeston, MO: www.dewittcompany.com

Dutch Plantin B.V., Helmond, The Netherlands: www.dutchplantin.com
Euro Substrates (Pvt) Ltd., Pitakotte, Sri Lanka (Forteco Coco Coir): www.eurosubstrates.com
Fibrgro Horticultural Rock Wool, Sarnia, ON: www.fibrgro.com
Grodan, Roermond, The Netherlands: www.grodan.nl
Grodan Inc., Milton, ON: www.grodan.com
Hydro-Gardens, Inc., Colorado Springs, CO: www.hydro-gardens.com
Hydrofarm, Horticultural Products, Petaluma, CA: www.hydrofarm.com
Jiffy Products International BV, Hoek Van Holland, The Netherlands: www.jiffypot.com
Michigan Peat Co., Houston, TX: www.michiganpeat.com
Plant Products Co. Ltd., Brampton, ON: www.plantprod.com
Premier Tech Horticulture, Riviere-du-Loup, QC: www.premierhort.com
Saint-Gobain Cultilene B.V., Tilburg, The Netherlands: www.cultilene.nl
Smithers-Oasis North America, Kent, OH: www.smithersoasis.com
Sun Land Garden Products, Inc., Watsonville, CA: www.sunlandgarden.com
Sun Gro Horticulture, Vancouver, BC: www.sungro.com
The Scotts Miracle-Gro Company, Marysville, OH: www.thescottsmiraclegrocompany.com
Whittemore Company, Inc., Lawrence, MA: www.whittemoreco.com

IRRIGATION EQUIPMENT

American Horticultural Supply, Inc., Camarillo, CA: www.americanhort.com
Amiad Filtration Systems Ltd., Oxnard, CA: www.amiadusa.com
H.E. Anderson Company, Muskogee, OK: www.heanderson.com
BFG Supply Co., Burton, OH: www.bfgsupply.com
Climate Control Systems Inc., Leamington, ON: www.climatecontrol.com
CropKing, Inc., Lodi, OH: www.cropking.com
Dosatron International Inc., Clearwater, FL: www.dosatronusa.com
Dosmatic U.S.A./International, Inc., Carrollton, TX: www.dosmatic.com
Dramm Corporation, Manitowoc, WI: www.dramm.com
Growing Systems, Inc., Milwaukee, WI: www.growingsystemsinc.com
Hummert International, Earth City, MO: www.hummert.com
Hunter Industries, Inc., San Marcos, CA: www.hunterindustries.com
Hydro-Gardens, Inc., Colorado Springs, CO: www.hydro-gardens.com
Jain Irrigation Inc., Watertown, NY: www.jainirrigationinc.com
Keeler-Glasgow Company, Inc., Hartford, MI: www.keeleer-glasgow.com
Maxijet, Inc., Dundee, FL: www.maxijet.com
Netafim Irrigation, Inc., Fresno, CA: www.netafimusa.com
Plant Products Co. Ltd., Brampton, ON: www.plantprod.com
Rain Bird Agri-Products Co., Glendora, CA: www.rainbird.com
Roberts Irrigation Company, Inc., Plover, WI: www.robertsirrigation.net
Senninger Irrigation, Inc., Clermont, FL: www.senninger.com
Rain For Rent, Bakersfield, CA: www.rainforrent.com
The Toro Company, Riverside, CA: www.toro.com
Zwart Systems, Beamsville, ON: www.zwartsystems.ca

SEEDS

American Takii, Inc., Salinas, CA: www.takii.com
Asgrow Seed Co./Monsanto Company, Oxnard, CA: www.asgrowandekalb.com; www.monsantovegetableseeds.com
Ball Seed Co., West Chicago, IL: www.ballhort.com
Corona Seeds, Camarillo, CA: www.coronaseeds.com
De Ruiter Seeds, Inc./Monsanto Company, Oxnard, CA: www.deruiterseeds.nl; www.monsantovegetableseeds.com
Ferry-Morse Seed Company, Fulton, KY: www.ferry-morse.com
Harris Moran Seed Company, Modesto, CA: www.harrismoran.com
Harris Seeds, Rochester, NY: www.harrisseeds.com
HPS (Horticultural Products & Services), Randolph, WI: www.hpsseed.com
Hazera Seeds, Inc., Coconut Creek, FL: www.hazerainc.com
A.H. Hummert Seed Co., St. Joseph, MO: www.hummertseed.com
Johnny's Selected Seeds, Winslow, ME: www.johnnyseeds.com
Monsanto Company, Oxnard, CA: www.monsantovegetableseeds.com
Nickerson-Zwaan, Made, The Netherlands: www.nickerson-zwaan.com
Northrup King Co., Minneapolis, MN: www.nk.com
Nunhems USA, Inc., Parma, ID: www.nunhemsusa.com
Ornamental Edibles, San Jose, CA: www.ornamentaledibles.com
PanAmerican Seed Co., West Chicago, IL: www.panamseed.com
Paramount Seeds Inc., Palm City, FL: www.paramountseeds.com
Park Seed Co., Greenwood, SC: www.parkseed.com
Penn State Seed Co., Dallas, PA: www.pennstateseed.com
Richters, Goodwood, ON: www.Richters.com
Rijk Zwaan USA, Inc., Salinas, CA: www.rijkzwaanusa.com
Rijk Zwaan De Lier, De Lier, The Netherlands: www.rijkzwaan.com
Royal Sluis, Inc. (Seminis Vegetable Seeds, Inc.), St. Louis, MO: www.seminis.com
Sakata Seed America, Inc., Morgan Hill, CA: www.sakata.com
Stokes Seeds, Inc., Buffalo, NY or Thorold, ON: www.stokeseeds.com
Syngenta Seeds, Inc. (Rogers Seeds), Boise, ID: www.syngenta-us.com
Thompson & Morgan, Lawrenceburg, IN: www.tmseeds.com

SPROUT SUPPLIES

Caudill Seed Company, Inc., Louisville, KY: www.caudillseed.com
International Specialty Supply, Cookeville, TN: www.sproutnet.com

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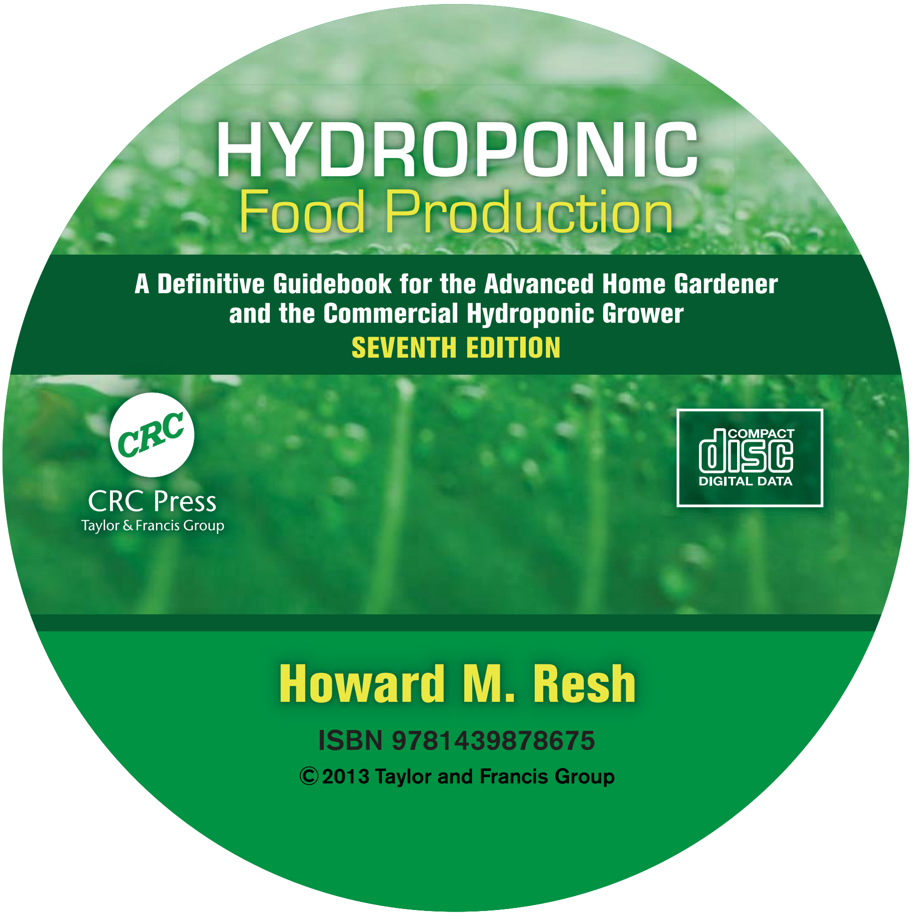

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