Hydroponics

A Practical Guide for the Soilless Grower

Second Edition

AEROPONICS

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J. Benton Jones Jr.

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Preface

This is the third edition of this guidebook; the first edition was published in 1983 and its revision was published in 1997. The two previous editions were primarily devoted to describing various techniques for growing plants without soil. These topics have been revised to reflect advances that have been made in understanding how plants grow and the influence that the rooting and atmospheric environments have on plant performance. In this edition, two new chapters have been added, one on the design and function of a hydroponic greenhouse and the other on hydroponic methods for crop production and management. These two new chapters provide the reader with essential information on greenhouse design and function and then give detailed instructions on how to grow various crops hydroponically, both in the greenhouse and outdoors. Although most hydroponic crops are grown commercially in environmentally controlled greenhouses, hydroponic methods and procedures suited for the hobby grower and techniques for outdoor hydroponics are also included. Organic hydroponics is also one of the new topics included.

Accurate statistics on the acreage of greenhouses devoted to vegetable production are not easily obtainable as no official accounting is made by any governmental or private organization(s). Estimates have been made based on information gathered from various sources suggesting that the acreage of greenhouse vegetable production is approximately 100,000 acres. From best estimates at this time, the acreage of hydroponic vegetable greenhouses probably ranges between 50,000 and 70,000 acres. In a recent Hydroponic Merchants Association (HMA) publication[1], they report that there are 3,000 to 4,000 acres of greenhouse vegetable in production in the United States and Canada, 2,000 to 3,000 acres in Mexico, 30,000 acres in Israel, 10,000 acres in Holland, 4,200 acres in England. Australia, New Zealand and other northern European countries have approxiamately 8,000 acres in greenhouse vegetable production. The HMA also reported that in North America, 95 percent of greenhouse vegetables are grown hydroponically and that the monetary value of produced vegetables is over $2.4 billion dollars today which is increasing at an annual rate of 10%. HMA reports that the largest acreages of hydroponic vegetable production in the United States are in four western states, Arizona (240 acres), California (157 acres), Colorado (86 acres), and Nevada (40 acres), with substantial acreages (from 10 to 40 acres at each location) in Pennsylvania, upstate New York, Virginia, Illinois, Nebraska, and Florida. The primary crop grown is tomato, with herbs, lettuce, and peppers being also grown at some of these locations. The hydroponic growing of flowers and other nonvegetable crops utilizing the same techniques and procedures applied to vegetables is also on the increase. Significant advances continue to be made in the application of hydroponic/soilless culture methods of growing and will continue to be made for controlling the environment within the greenhouse as well as the introduction of plant cultivars better

[1] HMA Media Kit, 2004, Hydroponic Merchants Association (HMA), 10210 Leatherleaf Court, Manassas, VA 20111.

adapted to greenhouse conditions. In order to take full advantage of these advances, growers will need to better control the rooting environment and the nutrient element supply to plants, and adopt those cultural practices that will maximize plant performance. Some of the systems initially devised for growing plants hydroponically are either no longer suitable for use in this developing technology or have been modified to adapt to these advances, making them more efficient in water and nutrient element use. Devising hydroponic growing systems for space application, in confined inhospitable environments, and outdoor growing are the new challenges that are changing our concepts of how best to utilize limited water resources, fully utilize both essential and beneficial elements, and provide for an ideal rooting environment. For many of these new applications, hydroponic/soilless systems must function efficiently without the possibility of failure — a challenge that borders on our current concepts of how plants function under varying environmental conditions.

As with the previous editions, this book begins with the concepts of how plants grow and then describes the requirements necessary for success when using various hydroponic and soilless growing methods. The major focus is on the nutritional requirements of plants and how best to prepare and use nutrient solutions to satisfy the nutrient element requirement of plants using various growing systems and under a wide range of environmental conditions. Many nutrient solution formulas are given, and numerous tables and illustrations included. Various hydroponic/soilless systems of growing are described in detail, and their crop adaptation and advantages and disadvantages are discussed. Included are those procedures required to establish and maintain a healthy rooting environment. Past and current sources of information on hydroponics are listed, including reference books, bulletins, magazine articles, and Internet sites as well as a detailed glossary of key terms.

This book provides valuable information for the commercial grower, the researcher, the hobbyist, and the student — all those interested in hydroponics and how this method of plant production works as applied to a wide range of growing conditions. Students interested in experimenting with various hydroponic/soilless growing systems as well as how to produce nutrient element deficiencies in plants are given the needed instructions. This topic has been expanded considerably with new methods and procedures that will arouse the interests of the curious minded.

The hydroponic literature can be confusing to readers due to the variety of words and terms used as well as the mix of British and metric units. In this book, when required to clarify the text, both British and metric units are given. The words "hydroponic" and "soilless" grower are sometimes combined to give "hydroponic/soilless grower," a combined word that is used when the topic being discussed relates to both, but when specific topics are discussed, then either the word hydroponic or soilless is used. The word "hydroponic" is used when growing systems are purely hydroponic, that is the rooting medium does not specifically interact with the plant, while the word "soilless" is used when systems of growing relate to plant production in which the medium can interact with the plant.

The use of trade names and mention of particular products in this book do not imply endorsement of the products named or criticism of similar ones not named, but rather such products are used as examples for illustration purposes.

J. Benton Jones, Jr.

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Chapter 1

Introduction

The word hydroponics has its derivation from the combining of two Greek words, *hydro* meaning water and *ponos* meaning labor, i.e., working water. The word first appeared in a scientific magazine article (*Science*, Feb 178:1) published in 1937 and authored by W.F. Gericke, who had accepted this word as was suggested by Dr. W.A. Setchell at the University of California. Dr. Gericke began experimenting with hydroponic growing techniques in the late 1920s and then published one of the early books on soilless growing (Gericke, 1940). Later he suggested that the ability to produce crops hydroponically would no longer be "chained to the soil but certain commercial crops could be grown in larger quantities without soil in basins containing solutions of plant food." What Dr. Gericke failed to foresee was that hydroponics would in the future be essentially confined to its application in enclosed environments for growing high cash value crops and would not find its way into the production of a wide range of commercial crops in open environments.

Hydroponic Definitions

The author went to three dictionaries and three encyclopedias to find how hydroponics is defined. *Webster's New World College Dictionary,* Fourth Edition, 1999, defines hydroponics as "the science of growing or the production of plants in nutrient-rich solutions or moist inert material, instead of soil"; the *Random House Webster's College Dictionary,* 1999, as "the cultivation of plants by placing the roots in liquid nutrient solutions rather than in soils; soilless growth of plants"; and *The Oxford English Dictionary,* 2nd Edition, 1989, as "the process of growing plants without soil, in beds of sand, gravel, or similar supporting material flooded with nutrient solutions."

In the *Encyclopedia Americana,* International Edition, 2000, hydroponics is defined as "the practice of growing plants in liquid nutrient cultures rather than in soil," in *The New Encyclopaedia Britannica*, 1997 as "the cultivation of plants in nutrient-enriched water with or without the mechanical support of an inert medium, such as sand or gravel," and in *The World Book Encyclopedia,* 1996 as "the science of growing plants without soil."

The most common aspect of all these definitions is that hydroponics means growing plants without soil, with the sources of nutrients either a nutrient solution or nutrient-enriched water, and that an inert mechanical root support (sand or gravel) may or may not be used. It is interesting to note that in only two of the six definitions is hydroponics defined as a "science."

Searching for definitions of hydroponics in various books and articles, the following were found. Devries (2003) defines hydroponic plant culture as "one in which all nutrients are supplied to the plant through the irrigation water, with the growing substrate being soilless (mostly inorganic), and that the plant is grown to produce flowers or fruits that are harvested for sale." In addition, Devries (2003) states, "hydroponics used to be considered a system where there was no growing media at all, such as the nutrient film technique in vegetables. But today it's accepted that a soilless growing medium is often used to support the plant root system physically and provide for a favorable buffer of solution around the root system." Resh (1995) defines hydroponics as "the science of growing plants without the use of soil, but by use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, or sawdust, to which is added a nutrient solution containing all the essential elements needed by the plant for its normal growth and development." Wignarjah (1995) defines hydroponics as "the technique of growing plants without soil, in a liquid culture." In an *American Vegetable Grower* article entitled "Is hydroponics the answer?" (Anonymous, 1978), hydroponics was defined for the purpose of the article as "any method which uses a nutrient solution on vegetable plants, growing with or without artificial soil mediums." Harris (1977) suggested that a modern definition of hydroponics would be "the science of growing plants in a medium, other than soil, using mixtures of the essential plant nutrient elements dissolved in water." Jensen (1997) stated that hydroponics "is a technology for growing plants in nutrient solutions (water containing fertilizers) with or without the use of an artificial medium (sand, gravel, vermiculite, rockwool, perlite, peat moss, coir, or sawdust) to provide mechanical support." Jensen (1997) defined the growing of plants without media as "liquid hydroponics" and with media as "aggregate hydroponics." Another defining aspect of hydroponics is how the nutrient solution system functions, whether as an "open" system in which the nutrient solution is discarded after passing through the root mass or medium, or as a "closed" system in which the nutrient solution, after passing through the root mass or medium, is recovered for reuse.

Similarly related hydroponic terms are "aqua (water) culture," "hydroculture," "nutriculture," "soilless culture," "soilless agriculture," "tank farming," or "chemical culture." A hydroponicist is defined as one who practices hydroponics, and hydroponicum defined as a building or garden in which hydroponics is practiced.

Historical Past

The growing of plants in nutrient-rich water has been practiced for centuries. For example, the ancient Hanging Gardens of Babylon and the floating gardens of the Aztecs in Mexico were hydroponic in nature. In the 1800s, the basic concepts for the hydroponic growing of plants were established by those investigating how plants grow (Steiner, 1985). The soilless culture of plants was then popularized in the 1930s in a series of publications by a California scientist (Gericke, 1929, 1937, 1940).

During the Second World War, the U.S. Army established large hydroponic gardens on several islands in the western Pacific to supply fresh vegetables to troops operating in that area (Eastwood, 1947). Since the 1980s, the hydroponic technique has become of considerable commercial value for vegetable (Elliott, 1989) and flower (Fynn and Endres, 1994) production, and as of 1995 there are over 60,000 acres of greenhouse vegetables being grown hydroponically throughout the world, an acreage that is expected to continue to increase (Jensen, 1995). In a 2004 Hydroponic Merchants Association publication (see page v), they report over 55,000 acres of hydroponic greenhouse vegetable production worldwide, with about 1,000 acres in the United States, 2,100 acres in Canada, and 2,700 acres in Mexico. In these three countries, 68% of the production is in tomato, 15% in cucumber and 17% in pepper.

Hydroponics in Space

Hydroponics for space applications — providing a means of purifying water, maintaining a balance between oxygen (O_2) and carbon dioxide (CO_2) in space compartments, and supplying food for astronauts — is being intensively researched (Knight, 1989; Schwartzkopf, 1990; Tibbitts, 1991; Brooks, 1992). Hydroponic growing in desert areas of the world (Jensen and Tern, 1971) and in areas such as the polar regions (Tapia, 1985; Rogan and Finnemore, 1992; Sadler, 1995; Budenheim et al., 1995) or other inhospitable regions will become important for providing food and/or a mechanism for waste recycling (Budenheim, 1991, 1993).

Hydroponics/Soilless Culture

Actually, hydroponics is only one form of soilless culture. It refers to a technique in which plant roots are suspended in either a static, continuously aerated nutrient solution or a continuous flow or mist of nutrient solution. The growing of plants in an inorganic substance (such as sand, gravel, perlite, rockwool) or in an organic material (such as sphagnum peat moss, pine bark, or coconut fiber) and periodically watered with a nutrient solution should be referred to as soilless culture but not necessarily hydroponic. Some may argue with these definitions, as the common conception of hydroponics is that plants are grown without soil, with 16 of the 19 required essential elements (see pages 29–33) provided by means of a nutrient solution that periodically bathes the roots.

Most of the books on hydroponic/soilless culture (see References) focus on the general culture of plants and the design of the growing system, giving only sketchy details on the rooting bed design and the composition and management of the nutrient solution. Although the methods of solution delivery and plant support media may vary considerably among hydroponic/soilless systems, most have proven to be workable, resulting in reasonably good plant growth. However, there is a significant difference between a "working system" and one that is commercially viable. Unfortunately, many workable soilless culture systems are not commercially sound. Most books on hydroponics would lead one to believe that hydroponic/soilless culture methods for plant growing are relatively free of problems since the rooting media and supply of nutrient elements can be controlled. Jensen (1997), in his overview, stated, "hydroponic culture is an inherently attractive, often oversimplified technology, which is far easier to promote than to sustain. Unfortunately, failures far outnumber the successes, due to management inexperience or lack of scientific and engineering support." Experience has shown that hydroponic/soilless growing requires careful attention to details and good growing skills. Most hydroponic/soilless growing systems are not easy to manage by the inexperienced and unskilled. Soil growing is more forgiving of errors made by the grower than are most hydroponic/soilless growing systems, particularly those that are purely hydroponic.

Advantages and Disadvantages

In 1981, Jensen listed the advantages and disadvantages of the hydroponic technique for crop production, many of which are still applicable today:

Advantages

a. Crops can be grown where no suitable soil exists or where the soil is contaminated with disease.
b. Labor for tilling, cultivating, fumigating, watering, and other traditional practices is largely eliminated.
c. Maximum yields are possible, making the system economically feasible in high-density and expensive land areas.
d. Conservation of water and nutrients is a feature of all systems. This can lead to a reduction in pollution of land and streams because valuable chemicals need not be lost.
e. Soilborne plant diseases are more readily eradicated in closed systems, which can be totally flooded with an eradicant.
f. More complete control of the environment is generally a feature of the system (i.e., root environment, timely nutrient feeding or irrigation),

and in greenhouse-type operations, the light, temperature, humidity, and composition of the air can be manipulated.

g. Water carrying high soluble salts may be used if done with extreme care. If the soluble salt concentrations in the water supply are over 500 ppm, an open system of hydroponics may be used if care is given to frequent leaching of the growing medium to reduce the salt accumulations.
h. The amateur horticulturist can adapt a hydroponic system to home and patio-type gardens, even in high-rise buildings. A hydroponic system can be clean, lightweight, and mechanized.

Disadvantages

a. The original construction cost per acre is great.
b. Trained personnel must direct the growing operation. Knowledge of how plants grow and of the principles of nutrition is important.
c. Introduced soilborne diseases and nematodes may be spread quickly to all beds on the same nutrient tank of a closed system.
d. Most available plant varieties adapted to controlled growing conditions will require research and development.
e. The reaction of the plant to good or poor nutrition is unbelievably fast. The grower must observe the plants every day.

Wignarajah (1995) gave the following advantages of hydroponics over soil growing:

1. All of the nutrients supplied are readily available to the plant.
2. Lower concentrations of the nutrient can be used.
3. The pH of the nutrient solution can be controlled to ensure optimal nutrient uptake.
4. There are no losses of nutrients due to leaching.

Wignarajah (1995) gave only one disadvantage of hydroponic systems, "that any decline in the O_2 tension of the nutrient solution can create an anoxic condition which inhibits ion uptake." His recommendation is that only aeroponics solves this problem since it provides a "ready supply of O_2 to the roots, hence never becomes anoxic."

The Hydroponic Techniques

In 1983, Collins and Jensen prepared an overview of the hydroponic technique of plant production, and more recently, Jensen (1995) discussed probable future hydroponic developments, stating that "the future growth of controlled environment agriculture will depend on the development of production systems that are competitive in terms of costs and returns with open field agriculture" and that "the future of hydroponics appears more positive today than any time over the last 30 years." In a brief review of hydroponic growing activities in Australia, Canada, England, France, and Holland, Brooke (l995a) stated that "today's hydroponic farmer can grow crops safely and in places that were formerly considered too barren to cultivate, such as deserts, the Arctic, and even in space." He concluded, "hydroponic technology spans the globe." Those looking for a brief overview of the common systems of hydroponic growing in use today will find the article by Rorabaugh (1995) helpful.

Proper instruction in the design and workings of a hydroponic/soilless culture system is absolutely essential. Those not familiar with the potential hazards associated with these systems or who fail to understand the chemistry of the nutrient solution required for their proper management and plant nutrition will normally fail to achieve commercial success with most hydroponic/soilless culture systems.

The technology associated with plant production, hydroponic or otherwise, is rapidly changing, as can be evaluated by reviewing the various bibliographies on hydroponics (Anon., 1984; Gilbert, 1979, 1983, 1984, 1985, 1987, 1992). Those interested in hydroponics must keep abreast of the rapid developments that are occurring by subscribing to and reading periodicals, such as the magazines *The Growing Edge*;[1] and *Maximum Yield Hydrogardening*[2] by membership and participation in groups devoted to the hydroponic/soilless growing of plants; and by becoming acquainted with the books, bulletins, and developing computer, video, and Internet (i.e., e-mail: hydrosoccam@aol.com) sources of hydroponics information. It could be that the problem today is not the lack of information on hydroponics (there are over 400,000 Web sites about hydroponics, for example), but the flood of information, much lacking a scientific basis, that leads to confusion and poor decision-making on the part of users.

"Is Hydroponics the Answer?" was the title of an article that appeared in 1978 (Anon., 1978) that contained remarks by those prominent at that time in discussions of hydroponic topics. In the article was the following quote: "Hydroponics is curiously slow to receive the mass grower endorsement that some envisioned at one time." Carruthers (1998) provided a possible answer for what has been occurring in the United States, stating, "the reasons for this slow growth can be attributed to many factors, including an abundance of rich, fertile soil and plenty of clean water." At the 1985 Hydroponics Worldwide: State of the Art in Soilless Crop Production conference, Savage (1985a) in his review stated, "many extravagant claims have been made for hydroponics/soilless systems, and many promises have been made too soon, but the reality is that a skilled grower can achieve wondrous results." In addition, he sees "soilless culture technology as having reached 'adulthood' and rapid maturing to follow." In addition, Savage (1985a) stated that "soilless and controlled environment crop production take special skills and training; however, most failures were not the result of the growing method, but can be attributed to

[1] *The Growing Edge*, P.O. Box 1027, Portland, OR 97339; tel: (503) 757-0027; Web site: www.growingedge.com.

[2] Maximum Yield Hydro Gardening, 11–1925 Bowden Rd., Nanaimo, B.C. Canada V95 1H1; tel: (250) 729-2677; fax: (205) 729-2687; Website: www.maximumyield.com.

poor financial planning, management, and marketing." More recently, at the 2003 South Pacific Soilless Culture Conference, Alexander (2003b) reported on current developments, stating "hydroponics is growing rapidly everywhere and within the next 5 to 10 years will be established as a major part of our agricultural and horticultural production industries."

Wilcox (1980) wrote about the "High Hopes of Hydroponics," stating that the "future success in the greenhouse industry will demand least-cost, multiple-cropping production strategies nearer to the major population centers." More recently, Naegely (1997) stated that the "greenhouse vegetable business is booming." She concluded, "the next several years promise to be a dynamic time in the greenhouse vegetable industry." Growth in the hydroponic-greenhouse industry was considerable in the 1990s, and its continued future expansion will depend on developments that will keep "controlled environmental agriculture" (CEA) systems financially profitable (see pages 305–307). Jensen (1997) remarked, "while hydroponics and CEA are not synonymous, CEA usually accompanies hydroponics — their potentials and problems are inextricable."

"Hydroponics for the New Millennium: A Special Section on the Future of the Hydroponic Industry" is the title of a series of articles by six contributors who addressed this topic from their own perspectives; the final comment was, "it really is an exciting time to be in the worldwide hydroponic industry, whether it's for commercial production or a hobby" [*Growing Edge* 11(3):6–13, 2000]. Jones and Gibson (2002) stated that "the future of the continued expansion of hydroponics for the commercial production of plants is not encouraging unless a major breakthrough occurs in the way the technique is designed and used." Those factors limiting wide application are cost, the requirement for reliable electrical power, inefficiencies in the use of water and nutrient elements, and environmental requirements for disposal of spent nutrient solution and growing media. Just recently, Schmitz (2004) remarked that "hydroponics is also seen as too technical, too expensive, too everything."

The Future of Hydroponics

What is not encouraging for the future is the lack of input from scientists in public agricultural colleges and experiment stations that at one time made significant contributions to crop production procedures, including hydroponics. The early hydroponic researchers, Dr. W.F. Gericke and D.R. Hoagland for example, were faculty members at the University of California. Today, there are only a few in universities who are still active in hydroponic investigations and research. The current status of Agricultural Cooperative Extension programs varies considerably from state to state. In the past, state specialists and county agents played major roles as sources for reliable information, but today these services are being cut back. Also, few of these specialists and agents have any expertise in hydroponics or extensive experience in dealing with greenhouse management questions. Edwards (1999), however, sees a positive role that county extension offices play, providing assistance to those seeking information, stating that "the Extension office is often the first place these people contact."

The science of hydroponics is currently little investigated, and much of the current focus is on the application of existing hydroponic techniques. Hydroponics, as a method of growing, is being primarily supported by those in the private sector who have a vested interest in its economic development. An example is the Hydroponic Merchants Association (HMA),[1] an association of those who manufacture, distribute, and market hydroponic growing systems that “exists to serve the interests of those who have made hydroponics, aquaponics, greenhouse growing, and other associated trades their livelihood” (Peckenpaugh, 2002f). Most of the hydroponic scientific advancements made today are by those who are investigating how this technique can be made to work for plant production in outer space (Hankinson, 2000a).

Another disturbing factor is that the Hydroponic Society of America[2] has not been active since 1997 when it published its last Proceedings. The Society was founded in 1979 and had been holding annual meetings and publishing proceedings from 1981 through 1997. Also, the International Society of Soilless Culture,[3] an organization that had held meetings and published proceedings in the past, has not been active for several years.

The role that commercial and scientific advancements have on society cannot be ignored when considering what is occurring in hydroponics today. The ease of movement of produce by surface and air transport, for example, allows for the growing of food products at great distances from their point of consumption. The advent of plastics has had a enormous impact on hydroponics because growing vessels, liquid storage tanks, drip irrigation tubing and fittings, greenhouse glazing materials, and sheeting materials, essential components in all hydroponic/greenhouse operations, are derived from a wide range of plastic materials that vary in their physical and chemical characteristics (Garnaud, 1985; Wittwer, 1993). The use of computers and computer control of practically every aspect of a hydroponic/greenhouse operation have revolutionized decision-making and managerial control procedures. Although one might conclude that hydroponic crop production is becoming more and more a science, there is still much art required that makes this method of plant production a challenge as well as an adventure.

The role of the Internet, the superhighway of information technology and communication, has changed and will continue to change how we educate ourselves and obtain the information and devices needed to establish and manage hydroponic/greenhouse systems. The ability to instantly send word and picture messages opens to the most isolated the world of information and resources added to the Internet daily. A grower with a plant problem,

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1 Hydroponic Merchants Association, 10210 Leatherland Court, Manassas, VA 20111; tel: (703) 392-5890; fax: (503) 257-0213; www.hydromerchants.org.

2 Hydroponic Society of America, P.O. Box 1183, El Centro, CA 94530; tel: (510) 232-2323; fax: (510) 232-2384; Web site: www.hsa.hydroponics.org.

3 International Society of Soilless Culture. (There is no current address for the Society and the Web site is not currently being supported.)

whether cultural or nutritional, the result of a disease or insect, can send photographs to an expert for identification and solution. The Internet is "awash" with innumerable Web sites on practically any subject. What might prove to be the challenge is how to separate the reliable from the unreliable while wading through the mass of material that exists.

This book describes various systems of hydroponic/soilless growing and the requirements essential for success. The common procedures for both inorganic and organic media as well as purely hydroponic culture are included, with emphasis on the essential requirements for each technique. Although the importance of these factors is discussed in some detail in this text, the reader is advised to seek other resources for general information on plant production, greenhouse design and construction, environmental control, cultivar selection, general plant cultural practices, and pest management.

Elemental Compound and Ion Symbol Designation

In this text, all elements are designated by their symbols, whereas reagents and compounds are named and their symbol compositions shown when first mentioned in that portion of the text. The symbols for those elements, compounds, and ions found in this text are as follows:

Element	*Symbol*	*Element*	*Symbol*
Aluminum	Al	Nickel	Ni
Antimony	Sb	Nitrogen	N
Arsenic	As	Oxygen	O
Boron	B	Phosphorus	P
Bromine	Br	Platinum	Pt
Cadmium	Cd	Potassium	K
Chlorine	Cl	Rubidium	Rb
Chromium	Cr	Selenium	5e
Cobalt	Co	Silicon	Si
Copper	Cu	Silver	Ag
Fluoride	F	Sodium	Na
Indium	In	Strontium	Sr
Iodine	I	Sulfur	S
Iron	Fe	Titanium	Ti
Lead	Pb	Uranium	U
Lithium	Li	Vanadium	V
Magnesium	Mg	Yttrium	Y
Manganese	Mn	Zinc	Zn
Molybdenum	Mo		

Compound/Ion	*Symbol*
Acetate	$C_2H_3O_2^-$
Ammonium	NH_4^+
Arsenate	AsO_4^{2-}
Bicarbonate	HCO_3^-
Borate	BO_3^{3-}
Carbon dioxide	CO_2
Carbonate	CO_3^{2-}
Cyanide	CN^-
Dihydrogen phosphate	$H_2PO_4^-$
Monohydrogen phosphate	HPO_4^{2-}
Nitrate	NO_3^-
Nitrite	NO_2^-
Phosphate (ortho)	PO_4^{3-}
Silicate	SiO_4^-
Sulfate	SO_4^{2-}
Water	H_2O

In those situations where there may be confusion if only the symbol is used, both the element, compound, or ion and its symbol will be used.

Chapter 2

How Plants Grow

The ancient thinkers wondered about how plants grow. They concluded that plants obtained nourishment from the soil, calling it a "particular juyce" existent in the soil for use by plants. In the 16th century, van Helmont regarded water as the sole nutrient for plants. He came to this conclusion after conducting the following experiment:

> Growing a willow in a large carefully weighed tub of soil, van Helmont observed at the end of the experiment that only 2 ounces of soil was lost during the period of the experiment, while the willow increased in weight from 5 to 169 pounds. Since only water was added to the soil, he concluded that plant growth was produced solely by water.

Later in the 16th century, John Woodward grew spearmint in various kinds of water and observed that growth increased with increasing impurity of the water. He concluded that plant growth increased in water that contained increasing amounts of terrestrial matter, because this matter is left behind in the plant as water passes through the plant.

The idea that soil water carried "food" for plants and that plants "live off the soil" dominated the thinking of the times. It was not until the mid- to late-18th century that experimenters began to clearly understand how, indeed, plants grow.

A book entitled *The Principle of Agriculture and Vegetation,* published in 1757 by the Edinburgh Society and written by Francis Home, introduced a number of factors believed to be related to plant growth. Home recognized the value of pot experiments and plant analysis as means of determining those factors affecting plant growth. His book attracted considerable attention and led experimenters to explore both the soil and the plant more intensively.

Joseph Priestley's famous experiment in 1775 with an animal and a mint plant enclosed in the same vessel established the fact that plants will "purify" rather than deplete the air, as do animals. His results opened a whole new area of investigation. Twenty-five years later, DeSaussure determined that plants consume CO_2 from the air and release O_2 when in the light. Thus, the process that we today call "photosynthesis" was discovered, although it was not well understood by DeSaussure or others at that time.

At about the same time, and as an extension of earlier observations, the "humus" theory of plant growth was proposed and widely accepted. The concept postulated that plants obtain carbon (C) and essential nutrients (elements) from soil humus. This was probably the first suggestion of what we would today call the "organic gardening" concept of plant growth and well-being. Experiments and observations made by many since then have discounted the basic premise of the "humus theory" that plant health comes only from soil humus sources.

In the middle of the 19th century, an experimenter named Boussingault began to carefully observe plants, measuring their growth and determining their composition as they grew in different types of treated soil. This was the beginning of many experiments demonstrating that the soil could be manipulated through the addition of manures and other chemicals to affect plant growth and yield. However, these observations did not explain why plants responded to changing soil conditions. Then came a famous report in 1840 by Liebig, who stated that plants obtain all their C from CO_2 in the air. A new era of understanding plants and how they grow emerged. For the first time, it was understood that plants utilize substances in both the soil and the air. Subsequent efforts turned to identifying those substances in soil, or added to soil, that would optimize plant growth in desired directions.

The value and effect of certain chemicals and manures on plant growth took on new meaning. The field experiments conducted by Lawes and Gilbert at Rothamsted (England) led to the concept that substances other than the soil itself can influence plant growth. About this time, water experiments by Knop and other plant physiologists (a history of how the hydroponic concept was conceived is given by Steiner [1985]) showed conclusively that K, Mg, Ca, Fe, and P, along with S, C, N, H, and O, are all necessary for plant life. It is interesting to observe that the formula devised by Knop for growing plants in a nutrient solution can still be used successfully today in most hydroponic systems (Table 2.1).

Table 2.1 Knop's Nutrient Solution

Reagent	*g/L*
Potassium nitrate (KNO_3)	0.2
Calcium nitrate [$Ca(NO_3)_2 \bullet 4H_2O$]	0.8
Monopotassium phosphate (KH_2PO_4)	0.2
Magnesium sulfate ($MgSO_4 \bullet 7H_2O$)	0.2
Ferric phosphate ($FePO_4$)	0.1

Keep in mind that the mid-19th century was a time of intense scientific discovery. The investigators named above are but a few of those who made significant discoveries that influenced the thinking and course of scientific biological investigation. Many of the major discoveries of their day centered on biological systems, both plant and animal. Before the turn of the 19th century, the scientific basis of plant growth had been well established, as has been reviewed by Russell (1950). Investigators had proven conclusively that plants obtain carbon (C), hydrogen (H), and oxygen (O) required for carbohydrate synthesis from CO_2 and H_2O by the process later called photosynthesis,[1] that N was obtained by root absorption of NH_4^+ and/or NO_3^- ions (although leguminous plants can supplement this with symbiotically fixed N_2 from the air), and that all the other elements are taken up by plant roots from the soil as ions and translocated throughout the plant — carried in the transpiration stream. This general outline remains today the basis for our present understanding of plant functions. We now know that there are 16 essential elements (C, H, O, S, N, P, K, Ca, Mg, B, Cl, Cu, Fe, Mn, Mo, Zn), and we have extended our knowledge about how these elements function in plants, at what levels they are required to maintain healthy, vigorous growth, and how they are absorbed and translocated.

Although there is much that we do know about plants and how they grow, there is still much that we do not understand, particularly about the role of some of the essential elements. Balance, the relationship of one element to another, and its forms in the plant, may be as important as the concentration of any one of the elements in optimizing the plant's nutritional status. There is still some uncertainty as to how elements are absorbed by plant roots and how they then move within the plant. Elemental form, whether individual ions or complexes, may be as important for movement and utilization as concentration. For example, chelated iron (Fe) forms are effective for control of Fe deficiency, although unchelated ionic Fe, either as the ferric (Fe^{3+}) or ferrous (Fe^{2+}) ions, is equally effective but at higher concentrations.

The biologically active portion of an element in the plant, frequently referred to as the *labile* form, may be that portion of the concentration that determines the character of plant growth. Examples of these labile forms would be the NO_3 form of N, the SO_4 form of S, and soluble Fe and Ca in plant tissue — forms of these elements that determine their *sufficiency* status. The use of tissue tests is partly based on this concept, measuring that portion of the element that is found in the plant sap and then relating that concentration to plant growth (see pages 324–325).

The science of plant nutrition is attracting considerable attention today as plant physiologists determine how plants utilize the essential elements. In addition, the characteristics of plants can now be genetically manipulated by adding and/or removing traits that alter the ability of the plant to withstand biological stress and improve product quality (Mohyuddin, 1985; Waterman, 1993–94; Baisden, 1994). With these many advances, all forms of growing, whether hydroponic or otherwise, are now becoming more productive. Much of this work is being done for growing plants in space in confined environments where the inputs must be carefully controlled due to limited resources, such as water, and control of the release of water vapor and other volatile compounds into the atmosphere around the plant.

Much of the future of hydroponics may lie with the development of plant cultivars and hybrids that will respond to precise control of the growing environment. The ability of plants to efficiently utilize water and the essential elements may make hydroponic and soilless growing methods superior to what is possible today. The genetic yield potential of cultivars in use today is uncertain, and whether that potential can be increased has not been established. A recent report by Moreno et al. (2003) suggests that among 18 tomato cultivars in their study, those that were identified as "least efficient in their uptake of nutrient elements, particularly N," produced highest fruit yields. Therefore, high efficiency in nutrient element utilization may be an undesirable trait — something that may seem counter to what one would expect. It should also be remembered that the adaptability of a cultivar or hybrid to respond to one set of environmental conditions may limit its use to that set of conditions. Therefore, there is still much that needs to be discovered on how plants respond to various sets of conditions and how best to adjust those conditions to achieve high plant performance and yield.

Note

[1]Process of photosynthesis: the conversion of solar energy into several forms of chemical energy.

Carbon dioxide ($6CO_2$) + water ($6H_2O$) in the presence of light and chlorophyll yields carbohydrate ($C_6H_{12}O_6$) + oxygen ($6O_2$)

The photosynthetic process occurs primarily in green leaves, since they have stomata, and not in the other green portions (petioles and stems) of the plant, which do not have stomata. A molecule of CO_2 from the air passes into an open stoma, and a H_2O molecule, which is taken up through the roots, is split and then combined with CO_2 to form carbohydrate, and in the process a molecule of O_2 is released. The rate of photosynthesis is affected by factors external to the plant, such as air temperature (high and low), air movement over the leaf surfaces, level of CO_2 in the air around the leaves, and light intensity and its wavelength composition. The number of stomata on leaves, and whether they are open or closed, will also determine the rate of photosynthesis. Turgid leaves in a continuous flow of air and with open stomata will have high rates of photosynthesis.

Chapter 3

Soil and Hydroponics

Scientifically speaking, plant growth in any rooting medium, including soil, is hydroponic, since the elements absorbed by plant roots must be in a water-based solution. The concentration and movement of the elements within this solution depend on the nature of the surrounding medium. For example, in soil, the soil solution and its elemental composition are the result of many interacting factors — an ever-changing, dynamic system of complex equilibrium chemistry (Lindsay, 1979; Tan, 1998; Peverill et al., 1999; Essington, 2004), in which the soil, soil microorganisms, and the plant root (Carson, 1974) each play unique and specific roles that alter the availability and eventual absorption by the plant root of the elements required for growth (Barber and Bouldin, 1984; Barber, 1995; Wignarajah, 1994). The complexity of the chemistry of the soil (nutrient) solution is significantly simplified when the support medium is an inert substance, such as sand, gravel, perlite, or rockwool, and becomes even simpler when the plant roots are suspended in a nutrient solution, as is the case in the standing aerated nutrient solution (see pages 123–126), nutrient film technique (NFT) (see page 127–141), and aeroponic (see pages 142–143) methods of hydroponic growing.

In soil, elemental uptake is affected by the movement of the elements within the soil solution and by the growth of plant roots; the various processes involved are discussed by Barber (1995) and Jones (1998a). The movement of elements along with soil water is called "mass flow"; it can carry elements to or away from plant roots by soil water movement. Within the soil solution itself, elements move from regions of high to low concentration by the physical process called "diffusion." Thus, as the ions of elements are absorbed by plant roots from the solution in immediate contact with the root surface, a concentration gradient is formed (a lower ion concentration exists in the soil solution next to the root, called the rhizosphere, as compared to the higher ion concentration away from the root), which provides a mechanism for resupply: ions flow (diffuse) from high to low areas of concentration. The plant also plays a role by root extension (growth) into the soil mass, bringing greater contact between root surfaces and the soil mass.

Much of the complexity of the root–soil phenomenon is reduced in hydroponic systems, where the plant roots are periodically bathed with a moving nutrient solution that contains the essential elements required by the plant. The flow (application) of the nutrient solution acts much like the mass flow behavior in soil systems. Therefore, the impact of diffusion and root extension on elemental availability and root uptake is reduced. It should be noted that in a soil–plant system, only a very small portion of the soil makes physical contact with plant roots, whereas in most hydroponic systems, plant roots are exposed to almost the full volume of nutrient solution. Such an extensive exposure of rooting surface to the nutrient solution has advantages, but it also poses problems that will be discussed in more detail later.

Nutrient element uptake by plants that are grown in a soilless organic medium, such as peat, pinebark, and coir, will act more like that occurring in soil where the principles of mass flow, diffusion, and root extension will significantly affect plant growth. Similarly, plants that are grown in an inorganic medium, such as vermiculite, zeolite, or expanded clay, substances that have a cation exchange capacity, will also act in a similar manner to plants grown in soil.

There are those who would consider soil growing as a system that is "out of control," while hydroponics is classed as a system "for control." This would seem at first glance to be a reasonable assessment, although not entirely true in practice. A soil system is indeed difficult to keep in control due to the complex inorganic–organic and biological nature of soil, as well as the interaction of plant roots with soil processes. Plants growing in soil are frequently competitors for the essential elements in the soil solution with other organisms (bacteria, fungi, etc.) present in the soil. These interactive processes and competition can be minimized in a hydroponic system. Therefore, the grower has the ability to regulate the composition of the nutrient solution and, in turn, control plant growth to a considerable degree. The challenge for the hydroponic grower is the control of the nutrient solution composition, a topic that will be dealt with in some detail in this book. It should also be remembered that in soil, the soil itself acts as a "buffer" that can be beneficial to plant growth, while in most hydroponic growing systems, no such buffer characteristic exists. Therefore, any error made in the composition and use of a nutrient solution can have far greater adverse impact on the plant than, say, an error made in the use of fertilizers or other amendments added to a soil. The source of the soil buffer capacity effect comes from the organic material in the soil plus the cation exchange phenomenon of both the organic and inorganic colloidal material in soil. Therefore, the use of any substance in a soilless mix that has both of these properties will also add some degree of buffer capacity to the rooting medium. An example would be the mixing of an inorganic rooting medium, such as perlite, with an organic medium, such as pinebark (see Chapter 10).

There have been those who have attempted to duplicate hydroponically what occurs in soil. The challenge is to maintain a constant level of nutrient element availability that is neither excessive or deficient. The unique characteristic of most soils is that the concentration of elements in the soil solution is defined by equilibrium phenomena. Therefore a "fertile soil" is one in which the soil solution is kept maintained in the constant state of optimum elemental composition and content. Asher and Edwards (1978a,b), for example, have been able to duplicate the soil solution hydroponically in their study of plant nutrition on low-fertility soils. One of the procedures they used was exposing the plant roots to a rapid flow of a low concentration–ion balanced nutrient solution; the deficient, just adequate, and toxic ranges for the essential elements are given in Table 3.1. A similar effect would be obtained if a plant is grown in an infinite volume of nutrient solution in which removal of elements from the nutrient solution by plant roots does not alter the composition of the nutrient solution. Such a system could be classed as an "ideal" hydroponic growing system. The only hydroponic system in use today that would come close to this ideal is aeroponics (see pages 142–143).

Those holding the organic view of plant growth and development have considerable difficulty in accepting hydroponics as a natural system of plant production. Their contention is that unless the elements essential for plants are derived from an organic and/or natural source, plant growth and development are deficient and, therefore, unnatural. Scientific proof that such is

Table 3.1 Comparisons of Limiting Concentrations for Nine Elements in Some Nutrient Solutions Commonly Used for Experimental Purposes

Element	*Deficient*	*Just Adequate*	*Toxic*	*Common Range in Nutrient Solutions*
	Concentration in Parts per Million (ppm)			
Nitrogen (N)				
As nitrate (NO_3)	0.14 to 10	3.0 to 70	20 to 200	49 to 210
As ammonium (NH_4)	0.007 to 5	0.03 to 25	0.4 to 100	0 to 154
Potassium (K)				
Ammonium present	0.4 to 6	10 to 39	—	59 to 300
Ammonium absent	0.04 to 4	1.1 to 5	—	
Calcium (Ca)	0.02 to 22	0.24 to 40	—	80 to 200
Magnesium (Mg)	0.05 to 6	0.2 to 9	—	24 to 60
Phosphorus (P)	0.003 to 4	0.007 to 2.6	0.03 to 4	15 to 192
Sulfur (S)	—	1.3	—	48 to 224
	Concentration in Parts per Billion (1/1000 ppm)			
Manganese (Mn)	0.55 to 71	0.55 to 2.310	16.5 to 3.850	110 to 550
Zinc (Zn)	0.65 to 3	3.25 to 16	195 to 390	0 to 146
Copper (Cu)	0.63	1.26	—	0 to 10

Source: Asher, C.J. and Edwards, D.G., l978, pp. 13–28 in A.R. Ferguson, B.L. Bialaski, and J.B. Ferguson (Eds.), Proceedings 8th International Colloquium, Plant Analysis and Fertilizer Problems. Information Series No. 134. New Zealand Department of Scientific and Industrial Research, Wellington, New Zealand.

the case is lacking, although many argue the natural point of view with considerable elegance, despite the lack of factual substantiation (Bezdicek, 1984). The possibility of growing organically using hydroponic procedures is discussed later.

Chapter 4

The Plant Root: Its Roles and Functions

Plant roots have two major functions:

- They physically anchor the plant to the growing medium.
- They are the avenue through which water and ions enter into the plant for redistribution to all parts of the plant.

Although the first role given above is important, it is the second role that deserves our attention in this discussion. The book edited by Carson (1974) provides detailed information on plant roots and their many important functions, and the book chapter by Wignarajah (1994) discusses the current concepts on nutrient element uptake.

Water Content and Uptake

Water is essential for all living organisms. It has unique physical (can exist in various forms, liquid, solid, and gaseous) and chemical (association with polar groups on membranes and proteins) properties, is a participant in photosynthesis (the rate of photosynthesis is affected by the water status of the plant, decreasing with increasing water stress), is a solvent, and is a catalyst for countless chemical reactions. The water molecule participates in a number of important biochemical reactions (Volkmar and Woodbury, 1995). However, only 5% of the water absorbed by plants is utilized for biological functions, while 95% is lost mainly by transpiration.

The shape of the plant is determined by its water content, for when the water content declines, wilting occurs and the plant begins to lose its shape and begins to droop. Wilting occurs initially in newly developing tissue that has not yet developed a firm cellular structure. There may be conditions where water uptake and movement within the plant are insufficient to keep the plant fully turgid, particularly when the atmospheric demand is high and/or when the rooting environment is such that it restricts the uptake of water through the roots (see below). In general, field-grown plants are less sensitive to water stress than are plants grown in controlled environments, which may partially explain why plants in the greenhouse are particularly sensitive to water stress that in turn significantly impacts growth rate and development.

Water is literally pulled up the conductive tissue (mainly in the xylem) by the loss of water from the leaves of the plant by a process called "transpiration," which takes place mainly through open stomata located on leaf surfaces as well as through lenticels and the cuticle (Srivastava and Kumar, 1995). To understand this process, visualize a continuous column of water from the root cells up to atmospherically exposed leaves; the rate of water movement is driven by a water potential gradient between the leaves and the surrounding air. Transpiration has two important effects, it reduces foliage temperature by evaporative cooling (as plant leaves absorb solar energy, most of the absorbed energy is converted into heat), and it is the main means for the translocation of elements from the rooting environment to the upper portions of the plant. Leaves exposed to direct solar radiation will rise in temperature if water movement up the plant is restricted. Leaf temperature affects rates of photosynthesis, respiration, and growth. The amount of water lost by transpiration will depend on the difference in vapor pressure between the leaf and ambient air. Leaf and air temperatures impact gas diffusional rates, hence rates of photosynthesis and leaf respiration (all decrease with increasing leaf temperature). The rate of transpiration increases significantly with increasing movement of air over the leaf surfaces at similar stomata aperture openings. In addition, water lost by transpiration is affected by a complex relationship between air temperature and relative humidity as well as the taxonomic classification and ontogenetic age of the plant organ. In C3 plants (see page 378), stomata are more sensitive to water stress and therefore are responsive to the CO_2 content of the surrounding atmosphere under optimum water conditions to a greater extent than C4 plants are (see page 379).

In order for water to enter the roots, the roots must be fully functional. Water absorption by plant roots declines with decreasing temperature, decreases with increasing ion content of the water surrounding the root, and decreases with decreasing O_2 content of the surrounding root mass environment (Table 4.1). In soil and soilless mixes, a greater root mass can contribute to increasing absorption capacity, while in a hydroponic growing system, root mass is less a contributing factor. The nutritional status of a plant can be a factor, as a healthy actively growing plant will supply the needed carbohydrates required to sustain the roots in an active respiratory condition. It is generally believed that most of the water absorption by plant roots occurs in younger tissue just behind the root tip. Water movement across the root cortex occurs primarily intercellularly, but can also occur extracellularly with increasing transpiration rate.

Table 4.1 Oxygen Content in Fresh Water Related to Water Temperature

Temperature		Oxygen Content, mg/L (ppm)
°F	°C	
32	0	14.6
41	5	12.8
50	10	11.3
59	15	10.1
68	20	9.1
77	25	8.2
86	30	7.5
95	35	6.9

Source: Nickols, M., 2002, *The Growing Edge* 13(5):30–35.

As water is pulled into the plant roots, those substances dissolved in the water will also be brought into the plant, although a highly selective system regulates which ions are carried in and which are kept out. Therefore, as the amount of water absorbed through plant roots increases, the amount of ions taken into the root will also increase, even though a regulation system exists. This partially explains why the elemental content of the plant can vary depending on the rate of water uptake. Therefore, atmospheric demand can affect the elemental content of the plant, which can be either beneficial or detrimental. In addition, many water-soluble compounds in the rooting medium can be brought into the plant and enter the xylem.

Ion Uptake

All essential mineral ions are accumulated by plant cells to a higher concentration than that present in their environment; the accumulation is selective. Jacoby (1995) poses the following questions:

- How is passage through the impermeable liquid layer accomplished?
- How is accumulation against the concentration gradient accomplished?
- How is metabolic energy coupled to such transport?
- What is the mechanism of selectivity?
- How is vectorial transport accomplished?

The concepts of ion absorption and movement up the plant are described by six processes:

1. Free space and osmotic volume
2. Metabolic transport
3. Transport proteins
4. Charge balance and stoichiometry
5. Transport proteins
6. Transport to the shoot

Depending on the specific ion, transport is by passive uniport through channels or by carrier-aided cotransport with protons (Jacoby, 1995).

The absorption of ions by the root is by both a passive and an active process. Passive root absorption means that an ion is carried into the root by the passage of water; that is, it is sort of "carried" along in the water taken into the plant. It is believed that the passive mode of transport explains the high concentrations of some ions, such as K^+, NO_3^-, and Cl^-, found in the leaves and stems of some plants. The controlling factors in passive absorption are the amount of water moving into the plant (which varies with atmospheric demand), the concentration of these ions in the water, and the size of the root system. Passive absorption is not the whole story however, as a process involving chemical selectivity occurs when an ion-bearing solution reaches the root surface.

The cell membranes of the root cells form an effective barrier to the passage of most ions into the root. Water may move into these cells, but the ions contained in the water will be left behind in the solution surrounding the root. Also, another phenomenon is at work: ions will only move physically from an area of high concentration to one of lower concentration. However, in the case of root cells, the concentration of most ions in the root is higher than that in the water surrounding the root. Therefore, ions should move from the root into the surrounding water, and indeed, this can and does happen. The question is, "how do ions move against this concentration gradient and enter the root?" The answer is by active absorption.

In a typical plant root, solutes can be found in three compartments. The outermost compartment, and the one where solutes have ready accessibility, is called apparent (AFS) or outer free space (OFS). This compartment contains two subcompartments, water free space (WFS), which dissolved substances (such as ions) can freely move into by diffusion, and Donnan free space (DFS), whose cell walls and membranes have a number of immobile negatively charged sites that can bind cations. The cation exchange capacity of plant cells is determined by the DFS. Ion movement across these cell walls and membranes requires both energy and a carrier system, and therefore the process is called "active absorption."

Active absorption works based on carriers and Michaells-Menten kinetics. These theories are based on the nature of cell membranes. Cell membranes function in several ways to control the flow of ions from outside to inside the cell. It is common to talk about "transporting" an ion across the cell membrane and, indeed, this may be what happens. An ion may be complexed with some substance (probably a protein) and then "carried" across (or through) the membrane into the cell against the concentration gradient. For the system to work, a carrier must be present and energy expended. As yet, no one has been able to determine the exact nature of the carrier or carriers, although they are thought to be proteins. However, the carrier concept helps to explain what is observed in the movement of ions into root cells. The other theory relates to the existence and function of ion or proton pumps rather than specific carriers. For both of these systems to work, energy is required, one linked to respiratory energy, and the other from adenosine triphosphate

(ATP), a high-energy intermediate associated with most energy-requiring processes. For a more detailed explanation on the mechanism of ion uptake by roots, refer to the article by Wignarajah (1995).

Although we do not know the entire explanation for active absorption, general agreement exists that some type of active system regulates the movement of ions into the plant root.

We know these three things about ion absorption by roots:

1. The plant is able to take up ions selectively even though the outside concentration and ratio of elements may be quite different than those in the plant.
2. Accumulation of ions by the root occurs across a considerable concentration gradient.
3. The absorption of ions by the root requires energy that is generated by cell metabolism.

A unique feature of the active system of ion absorption by plant roots is that it exhibits ion competition, antagonism, and synergism. The competitive effects restrict the absorption of some ions in favor of others. Examples of enhanced uptake relationships include:

- Potassium (K^+) uptake is favored over calcium (Ca^{2+}) and magnesium (Mg^{2+}) uptake.
- Chloride (Cl^-), sulfate (SO_4^{2-}), and phosphate ($H_2PO_4^-$) uptake is stimulated when nitrate (NO_3^-) uptake is strongly depressed.

The rate of absorption is also different for various ions. The monovalent ions (i.e., K^+, Cl^-, NO_3^-) are more readily absorbed by roots than the divalent (Ca^{2+}, Mg^{2+}, SO_4^{2-}) ions are.

The uptake of certain ions is also enhanced in active uptake. If the NO_3^- anion is the major N source in the surrounding rooting environment, then there tends to be a balancing effect marked by greater intake of the cations K^+, Ca^{2+}, and Mg^{2+}. If the NH_4^+ cation is the major source of N, then uptake of the cations K^+, Ca^{2+}, and Mg^{2+} is reduced. In addition, the presence of NH_4^+ enhances NO_3^- uptake. If Cl^- ions are present in sizable concentrations, NO_3^- uptake is reduced.

These effects of ion competition, antagonism, and synergism are of considerable importance to the hydroponic grower in order to avoid the hazard of creating elemental imbalances in the nutrient solution that will, in turn, affect plant growth and development. Therefore, the nutrient solution must be properly and carefully balanced initially and then kept in balance during its term of use. Imbalances arising from these ion effects will affect plant growth. Steiner (1980) has discussed in considerable detail his concepts of ion balance when constituting a nutrient solution. His concept is presented in Chapter 7.

Unfortunately, many current systems of nutrient solution management do not effectively deal with the problem of imbalance. This is true not only of systems in which the nutrient solution is managed on the basis of weekly dumping and reconstitution but also of constant-flow systems. Indeed, the concept of rapid, constant-flow, low-concentration nutrient solution management is made to look deceptively promising in minimizing the interacting effects of ions in the nutrient solution on absorption and plant nutrition (more about these problems in Chapter 7).

Finally, nonionic substances, mainly molecules dissolved in the soil water, can also be taken into the root by mass flow. Substances such as amino acids, simple proteins, carbohydrates, and urea can easily enter the plant and contribute to its growth and development.

Metabolic transport across root structures to the xylem regulates the amount of ions conveyed to the tops; interestingly, the amount is little affected by the velocity of xylem sap flow. Once in the xylem, ions and other soluble solutes move by mass flow, primarily to the leaf apoplast.

Physical Characteristics

Root architecture is determined by plant species and the physical environment surrounding the roots. Plant roots grow outward and downward, although most rooting containers are not so designed. Root architecture would suggest a pyramid-shaped container, narrow at the top and wide at the bottom (Figure 4.1). In soil, it has been observed that feeder roots grow up, not down. This is why plants, particularly trees, do poorly when the soil surface is compacted or physically disturbed. In soil, any root restriction can have a significant impact on plant growth and development due to the reduction in soil–root contact. Root pruning, whether done purposely (to bonsai plants) or as the result of natural phenomena (plow or clay pans), will also affect plant growth and development in soil. Therefore, in most hydroponic/soilless growing systems, roots may extend into a much greater volume of growing area or medium than would occur in soil.

Root size, measured in terms of length and extent of branching, as well as color are characteristics that are affected by the nature of the rooting

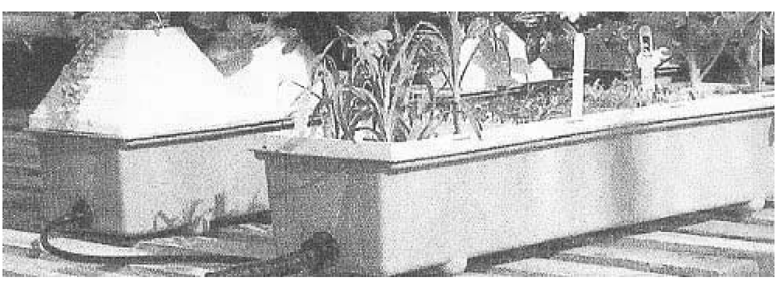

Figure 4.1 Pyramid-shaped container designed for optimum root development for hydroponic growing (a plant pot configuration designed by Dr. Robert Irvine). See Savage, A.J., 1995, *The Growing Edge* 6(3):40–47.

environment. Normally, vigorous plant growth is associated with long, white, and highly branched roots. It is uncertain whether vigorous top growth is a result of vigorous root growth or vice versa.

Tops tend to grow at the expense of roots, with root growth slowing during fruit set. Shoot:root ratios are frequently used to describe the relationship that exists between them, with ratios ranging from as low as 0.5 to a high of 15. Root growth is dependent on the supply of carbohydrates from the tops, and, in turn, the top is dependent on the root for water and essential elements. The loss or restriction of roots can significantly affect top growth. Therefore, it is believed that the goal should be to provide and maintain those conditions that promote good, healthy root development, neither excessive nor restrictive.

The physical characteristics of the root itself play a major role in elemental uptake. The rooting medium and the elements in the medium will determine to a considerable degree root appearance. For example, root hairs will be almost absent on roots exposed to a high concentration (100 mg/L, ppm) of NO_3^-. High P in the rooting medium will also reduce root hair development, whereas changing concentrations of the major cations, K^+, Ca^{2+}, and Mg^{2+}, will have little effect on root hair development. Root hairs markedly increase the surface available for ion absorption and also increase the surface contact between roots and the water film around particles in a soilless medium; therefore, their presence can have a marked effect on water and ion uptake. Normally, hydroponic-plant roots do not have root hairs.

The question that arises is, "what constitutes healthy functioning roots for the hydroponic/soilless growing system?" The size and extent of root development are not as critical as in soil. It has been demonstrated that one functioning root is sufficient to provide all the essential elements required by the plant, with size and extensiveness of the roots being primarily important for water uptake. Therefore, in most hydroponic systems, root growth and extension are probably far greater than needed, which may actually have a detrimental effect on plant growth and performance. It should be remembered that root growth and function require a continuous supply of carbohydrates, which are generated by photosynthesis. Therefore an ever-expanding and actively functioning root system will take carbohydrates away from vegetative expansion and fruit growth. Therefore, some degree of root growth control may be essential for high plant and fruit yields.

Aeration

Aeration is another important factor that influences root and plant growth. Oxygen (O_2) is essential for cell growth and function. If not available in the rooting medium, severe plant injury or death will occur. The energy required for root growth and ion absorption is derived by the process called "respiration," which requires O_2. Without adequate O_2 to support respiration, water and ion absorption cease and roots die.

Oxygen levels and pore space distribution in the rooting medium will also affect the development of root hairs. Aerobic conditions, with equal distributions of water- and air-occupied pore spaces, promote root growth, including root hairs.

If air exchange between the medium and surrounding atmosphere is impaired by overwatering, or the pore space is reduced by compaction, the O_2 supply is limited and root growth and function will be adversely affected. As a general rule, if the pore space of a solid medium, such as soil, sand, gravel, or an organic mix containing peat moss or pinebark, is equally occupied by water and air, sufficient O_2 will be present for normal root growth and function (Bruce et al., 1980).

In hydroponic systems where plant roots are growing in a standing solution or a flow of nutrient solution, the grower is faced with a "Catch-22" problem in periods of high temperature. The solubility of O_2 in water is quite low (at 75°F, about 0.004%) and decreases significantly with increasing temperature, as is illustrated in Figure 4.2. However, since plant respiration, and therefore O_2 demand, increase rapidly with increasing temperature, considerable attention to O_2 supply is required. Therefore, the nutrient solution must be kept well aerated by either bubbling air into the solution or by exposing as much of the surface of the solution as possible to air by agitation. One of the significant advantages of the aeroponic system (see pages 142–143) is that plant roots are essentially growing in air and therefore are adequately supplied with O_2 at all times. Root death, a common problem in most nutrient film technique (NFT) systems (see pages 127–141) and possibly other growing systems as well, is due in part to lack of adequate aeration within the root mass in the rooting channel.

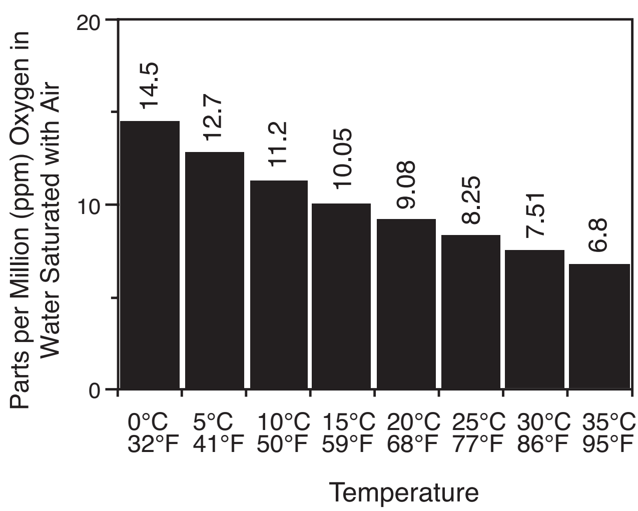

Figure 4.2 Dissolved oxygen (O_2) saturation limits for water at sea level pressure and temperature. ***Source:*** **Brooke, L.L., 1995a,** ***The Growing Edge*** **6(4):34–39, 70–71.**

Root Surface Chemistry

Many plant roots have the ability to alter the environment immediately around their roots. The most common alteration is a reduction in pH by the emission of hydrogen (H^+) ions. In addition, some plants have the ability to emit substances (such as siderophores) from their roots that enhance ion chelation and uptake. These phenomena have been most commonly observed in species that have the ability to obtain needed Fe under adverse conditions and are characteristic of so-called "iron (Fe)-efficient" plants (Rodriguez de Cianzio, 1991).

This ability of roots to alter their immediate environment may be hampered in hydroponic systems where the pH of the nutrient solution is being constantly adjusted upward or in those systems where the nutrient solution is not recycled. In such cases, care must be taken to ensure that the proper balance and supply of the essential elements are provided, since the plant roots may not be able to adjust the rooting environment to suit a particular need.

The impact of roots on a standing aerated nutrient solution system (see pages 123–127) may have an adverse effect on plant growth by either raising or lowering the solution pH, as well as by the introduction of complexing substances into the solution. Therefore, frequent monitoring of the nutrient solution and close observation of plant growth and development can alert the grower to the solution's changing status.

Temperature

Temperature is another important factor that influences root growth, as well as the absorption of water and essential element ions (Nielsen, 1974; Barber and Bouldin, 1984). The optimum root temperature will vary somewhat with plant species, but in general, root temperatures below 68°F (20°C) begin to bring about changes in root growth and behavior. Below optimum temperatures reduce growth and branching and lead to coarser-looking root systems. Absorption of both water and ions is also slowed as the permeability of cell membranes and root kinetics are reduced with decreasing temperature. Translocation in and out of the root is equally slowed at less than optimum root temperatures. When root temperatures are low, plants will wilt during high atmospheric demand periods, and elemental deficiencies will appear. Ion absorption of the elements P, Fe, and Mn seems to be more affected by low temperature than that of most of the other essential elements. It should also be noted that the viscosity of water decreases with decreasing temperature, which in turn affects water movement in and around the plant root.

The maximum root temperature that can be tolerated before significant reduction in root activity occurs is not clearly known. Roots seem to be able to tolerate short periods of high temperature. Roots are fully functional at 86°F (30°C) and probably can withstand temperatures up to 95°F (35°C). However, the current literature is not clear as to the exact limits of the optimum temperature range for best plant growth.

In order to avoid the hazards of either low or high temperatures, the roots and rooting medium should be kept at a temperature between 68 and 86°F (between 20 and 30°C). Reduced growth and other symptoms of poor nutrition will appear if root temperatures are kept at levels below or above this recommended temperature range

The relationship between temperature and the O_2 content of water is shown in Table 4.1.

Root Growth and Plant Performance

A large and extensive root system may not be the best for most hydroponic growing systems. Rather than the greatest size (mass), active efficiently functioning roots are what is needed, since the nutrient solution continuously bathes most of the root system, thereby requiring less surface for absorption to take place. One of the major problems with the NFT tomato hydroponic system (see page 127–141), for example, is the large root mass that develops in the rooting channel, which eventually restricts O_2 (Antkowiak, 1993) and nutrient solution penetration; the end result is a problem called "root death." Similar extensive root growth occurs with other types of growing systems, particularly with ebb-and-flow systems, where roots frequently grow into the piping that delivers and drains the growing bed of nutrient solution.

Similar extensive root growth is obtained with most hydroponic/soilless systems; roots frequently fill bags and blocks of media and sometimes grow through the openings in the outer walls of bags and media containers. The question is "does a large root mass translate into high plant performance?" The answer is probably no, if there is more root surface for absorption than needed. In addition, roots require a continuous supply of carbohydrates, which can be better used to expand top growth and contribute to fruit yield.

Unfortunately, the question as to root size has yet to be adequately addressed. It should also be remembered that roots require a continuous supply of O_2 to remain healthy and functioning. Roots will not grow in anaerobic conditions. Hydroponically speaking, a large, ever-expanding root system probably does not necessarily translate into greater top growth and yield and, in fact, may actually have some detrimental effect.

Chapter 5

The Essential Elements

Through the years, a set of terms has been developed to classify those elements essential for plant growth. This terminology can be confusing and misleading to those unfamiliar with it. Even the experienced can become rattled from time to time.

As with any body of knowledge, an accepted jargon develops that is understood well only by those actively engaged in the field. One of the commonly misused terms when referring to the essential metallic elements, such as Cu, Fe, and Zn, is mineral. The strict definition of mineral refers to a compound of elements and not a single element. Yet mineral nutrient is a commonly used term when referring to plant elemental nutrition. This phrase occasionally appears in conjunction with other words, such as plant mineral nutrition, mineral nutrition, or plant nutrition — all of which refer to the essential elements and their requirements for plants (Mengel and Kirkby, 1987; Glass, 1989; Wignarajah, 1994; Marchner, 1995; Rengel, 1998; Mengel et al., 2001).

Another commonly misused and misunderstood word is "nutrient," referring again to an essential element. It is becoming increasingly common to combine the words nutrient and element to mean an essential element. Therefore, elements such as N, P, and K are called "nutrient elements." Unfortunately, no one has suggested an appropriate terminology when talking about the essential elements; thus, the literature on plant nutrition contains a mixture of these terms. In this book, essential element and element are used in place of nutrient element and nutrient.

The early plant investigators developed a set of terms to classify the 16 elements identified as essential for plants, terms that have undergone changes in recent times. Initially, the major elements, so named because they are found in sizable quantities in plant tissues, include the elements C, H, N, O, P, and K. Unfortunately, three of the now-named essential major elements, Ca, Mg, and S, were initially named "secondary" elements. These so-called secondary elements should be classed as major elements, and they are referred to as such in this text.

Those elements found in smaller quantities, at first called "minor elements" or sometimes "trace elements," are the elements B, Cl, Cu, Fe, Mn, Mo, and Zn. More recently, these elements have been renamed "micronutrients," a term that better fits the comparative ratios between the major elements found in sizable concentrations and the micronutrients found at lower concentrations in plant tissues. Another term that has been used to designate some of the micronutrients is "heavy metals," which refers to those elements that have relatively high atomic weights. One definition is "those metals which have a density greater than 50 mg/cm^3," with elements such as Cd, Co, Cu, Fe, Pb, Mo, Ni, and Zn being considered as heavy metals (Ashworth, 1991; Pais and Jones, 1997).

Another category that has begun to make its way into the plant nutrition literature is the so-called "beneficial elements." Discussion of these elements will be deferred for consideration in Chapter 6.

The average concentration of the essential elements in plants is given in Table 5.1, using data by Epstein (1972). More recently, Ames and Johnson (1986) listed the major elements by their internal concentrations found in higher plants, as shown in Table 5.2.

Another recently naned category is the trace elements, which includes those elements found in plants at very low levels (<1 ppm) but not identified as either essential or beneficial. Some of these trace elements are found in the A-Z Micronutrient Solutions (see Table 7.14 in Chapter 7). Another set of

Table 5.1 Average Concentrations of Mineral Nutrients in Plant Dry Matter That Are Sufficient for Adequate Growth

Element	*Symbol*	*Dry Weight (μmol/g)*	*mg/kg (ppm)*	*%*	*Relative Number of Atoms*
Molybdenum	Mo	0.001	0.1	—	1
Copper	Cu	0.10	6	—	100
Zinc	Zn	0.30	20	—	300
Manganese	Mn	1.0	50	—	1000
Iron	Fe	2.0	100	—	2000
Boron	B	2.0	20	—	2000
Chlorine	Cl	3.0	100	—	3000
Sulfur	S	30	—	0.1	30,000
Phosphorus	P	60	—	0.2	60,000
Magnesium	M	80	—	0.2	80,000
Calcium	Ca	125	—	0.5	125,000
Potassium	K	250	—	1.0	250,000
Nitrogen	N	1000	—	1.5	1,000,000

Source: Epstein, E. 1972. *Mineral Nutrition of Plants: Principles and Perspectives,* John Wiley & Sons, New York.

Table 5.2 Internal Concentrations of Essential Elements in Higher Plants

	Concentration in Dry Tissue		
Element	*Symbol*	*ppm*	*%*
Major Elements			
Carbon	C	450,000	45
Oxygen	O	450,000	45
Hydrogen	H	60,000	6
Nitrogen	N	15,000	1.5
Potassium	K	10,000	1.0
Calcium	Ca	5,000	0.5
Magnesium	Mg	2,000	0.2
Phosphorus	P	2,000	0.2
Sulfur	S	1,000	0.1
Micronutrients			
Chlorine	Cl	100	0.01
Iron	Fe	100	0.01
Manganese	Mn	50	0.005
Boron	B	20	0.002
Zinc	Zn	20	0.002
Copper	Cu	6	0.0006
Molybdenum	Mo	0.1	0.00001

Source: Ames, M. and Johnson, W.S., 1986, in Proceedings of the 7th Annual Conference on Hydroponics: The Evolving Art, The Evolving Science, Hydroponic Society of America, Concord, CA.

elements under investigation is the rare earth elements, as their presence in plants seems to have stimulatory effects (Pais and Jones, 1997).

The word "available" has a specific connotation in plant nutrition parlance. It refers to that form of an element that can be absorbed by plant roots. Although its use has been more closely allied with soil growing, it has inappropriately appeared in the hydroponic literature. In order for an element to be taken into the plant, it must be in a soluble form in a water solution surrounding the roots. The available form for most elements in solution is as an ion. It should be pointed out, however, that some molecular forms of the elements can also be absorbed. For example, the molecule urea, $CO(NH_2)_2$ (a soluble form of N); the boric acid molecule, H_3BO_3; and some chelated complexes, such as FeDTPA, can be absorbed by the plant root. The elemental form will be discussed in more detail later.

The criteria for essentiality were established by two University of California plant physiologists in a paper published in 1939. Arnon and Stout (1939) described three requirements that an element had to meet in order to be considered essential for plants:

1. Omission of the element in question must result in abnormal growth, failure to complete the life cycle, or premature death of the plant.
2. The element must be specific and not replaceable by another.
3. The element must exert its effect directly on growth or metabolism and not by some indirect effect, such as by antagonizing another element present at a toxic level.

Some plant physiologists feel that the criteria established by Arnon and Stout may have inadvertently fixed the number of essential elements at the current 16 and that for the foreseeable future no additional elements will be found that meet these criteria for essentiality. The 16 essential elements, the discoverer of each element, the discoverer of essentiality, and the date of discovery are given in Table 5.3; the 16 essential elements, the form utilized by plants, and their function in plants are given in Table 5.4.

In the case of higher animals, 25 elements have been recognized as essential; of the 16 elements essential for plants, only B is not required by animals. The nine elements required by animals but not plants are As, Cr, Co, F, I, Ni, Se, Si, and V. A list of the elements essential for both plants and animals is given in Table 5.5.

Some plant physiologists feel that it is only a matter of time before the essentiality of Co, Ni, Si, and V will be demonstrated and those elements

Table 5.3 Discoverer of Element and Discoverer of Essentiality for the Essential Elements

Element	*Discoverer*	Year	*Discoverer of Essentiality*	*Year*
C	[a]	[a]	DeSaussure	1804
H	Cavendish	1766	DeSaussure	1804
O	Priestley	1774	DeSaussure	1804
N	Rutherford	1772	DeSaussure	1804
P	Brand	1772	Ville	1860
S	[a]	[a]	von Sachs, Knop	1865
K	Davy	1807	von Sachs, Knop	1860
Ca	Davy	1807	von Sachs, Knop	1860
Mg	Davy	1808	von Sachs, Knop	1860
Fe	[a]	[a]	von Sachs, Knop	1860
Mn	Scheele	1774	McHargue	1922
Cu	[a]	[a]	Sommer	1931
			Lipman and MacKinnon	1931
Zn	[a]	[a]	Sommer and Lipman	1926
Mo	Hzelm	1782	Arnon and Stout	1939
B	Gay Lussac and Thenard	1808	Sommer and Lipman	1926
Cl	Scheele	1774	Stout	1954

[a] Element known since ancient times.

Source: Glass, D.M., 1989, *Plant Nutrition: An Introduction to Current Concepts,* Jones and Bartlett Publishers, Boston.

Table 5.4 List of Essential Elements for Plants by Form Utilized and Biochemical Function

Essential Elements	*Form Utilized*	*Biochemical Function in Plants*
C, H, O, N, S	In the forms of CO_2, HCO_3^-, H_2O, O_2, NO_3^-, NH_4^+, N_2, SO_4^{2-}, SO_2; the ions from the soil solution, the gases from the atmosphere	Major constituents of organic material; essential elements of atomic groups involved in enzymatic processes; assimilation by oxidation–reduction reactions
P, B	In the form of phosphates, boric acid, or borate from the soil solution	Esterification with native alcohol groups plants; the phosphate esters are involved in energy transfer reactions
K, Mg, Ca, Mn, Cl	In the form of ions from the soil solution	Nonspecific functions establishing osmotic potentials; more specific reactions in which the ion brings about optimum conformation of an enzyme protein (enzyme activation); bridging of the reaction partners; balancing anions; controlling membrane permeability and electro-potentials
Fe, Cu, Zn, Mo	In the form of ions or chelates from the soil solution	Present predominantly in a chelated form incorporated in a prosthetic group; enable electron transport by valency charge

Source: Mengel, K. and Kirkby, E.A., 1987, *Principles of Plant Nutrition,* 4th ed., International Potash Institute, Worblaufen-Bern, Switzerland.

added to the current list of 16 essential plant elements; they would recommend that these elements be added to the rooting medium to ensure best plant growth. A more detailed discussion of these elements and others classified as beneficial elements is found in Chapter 6.

Explanation of Terms

Content in Plants

The major elements, C, H, O, N, P, K, Ca, Mg, and S, exist at percent (%) concentrations in the plant dry matter, while the micronutrients exist at concentrations of 0.01% or less in the dry matter. To avoid confusing decimals,

Table 5.5 Essential Elements for Plants and Animals

Life Form	*Major Elements*	*Micronutrients*
Plants and animals	Calcium (Ca) Carbon (C) Hydrogen (H) Magnesium (Mg) Nitrogen (N) Oxygen (O) Phosphorus (P) Potassium (K) Sulfur (S)	Chlorine (Cl) Copper (Cu) Iron (Fe) Manganese (Mn) Molybdenum (Mo) Zinc (Zn)
Plants only		Boron (B)
Animals only	Sodium (Na)	Arsenic (As) Chromium (Cr) Cobalt (Co) Fluorine (F) Iodine (I) Nickel (Ni)[a] Selenium (Se) Vanadium (V)

[a] Nickel has been suggested as being an essential micronutrient for plants (see Eskew et al., 1984; Brown et al., 1987).

micronutrient concentrations are expressed in micrograms per kilogram (mg/kg) or parts per million (ppm). Other terms are used to define elemental concentration, but % and mg/kg will be the terms used in this book. A comparison of commonly used concentration units is given in Table 5.6. Plant elemental content varies considerably with species, plant part, and stage of growth plus the effect of level of elemental availability. Elemental content data are mostly based on dry weight determinations, although some element determinations, such as N (as NO_3^- anion) and P (as $H_2PO_4^-$ and HPO_4^{2-} anions), can also be made using sap extracted from live tissue. An element may not be evenly distributed among various plant parts (roots, stems, petioles, and leaves), and uneven distributions may also exist within a leaf and among leaves at varying stages of development. Knowing the concentration of an element in a specific plant part of known stage of growth status, and even its distribution within the plant itself, provides valuable information for defining the nutritional status of the plant.

Function

The primary and secondary roles of all the essential elements required by plants are fairly well known (see Table 5.4). Some elements are constituents of plant compounds (such as N and S, which are constituents of proteins);

Table 5.6 A Comparison of Commonly Used Concentration Units for the Major Elements and Micronutrients in the Dry Matter of Plant Tissue

	Concentration Units			
Elements	*%*	*g/kg*	*cmol(p+)/kg*	*cmol/kg*
Major Elements				
Phosphorus (P)	0.32[a]	3.2	—	10
Potassium (K)	1.95	19.5	50	50
Calcium (Ca)	2.00	20.0	25	50
Magnesium (Mg)	0.48	4.8	10	20
Sulfur (S)	0.32	3.2	—	10
Micronutrients				
Boron (B)	20	20	1.85	
Chlorine (Cl)	100	100	2.82	
Iron (Fe)	111	111	1.98	
Manganese (Mn)	55	55	1.00	
Molybdenum (Mo)	1	1	0.01	
Zinc (Zn)	33	33	0.50	

[a] Concentration levels were selected for illustrative purposes only.

some serve as enzyme activators (K, Mg, Cu, Mo, Zn), have involvement in energy transfer reactions (P and Fe), are directly and/or indirectly related to photosynthesis (Mg, P, and Fe), or serve as osmotic balancers (K). Some elements have essentially one role or function, others multiple.

Deficiency Symptoms

In the literature can be found descriptions of visual deficiency symptoms as well as photographs showing these deficiency symptoms in plants at various stages of growth. It should be remembered that visual symptoms of deficiency may not appear similarly in all plants. In some instances, on-site visual symptoms may not be sufficiently distinct and therefore may be confusing to those unfamiliar with the techniques of diagnosis (see pages 319–325, 328–329). In order to confirm a suspected deficiency, it is well that more than one individual observe the symptoms and that a properly collected plant (leaf) tissue sample be submitted for elemental laboratory analysis and interpretation (see pages 319–329).

Excess Symptoms

Visual symptoms as a result of elemental excess are not well identifiable for many of the essential elements. Some have said that symptoms of excess are not much different than those of deficiency for some elements, particularly for several micronutrients. Some elements can accumulate to levels far exceeding their physiological requirement but will not be detrimental to the plant. However, it is also known that when an element exists in the plant at a concentration far beyond its physiological requirement, such high levels may be "toxic" to the plant, interfering with specific or general physiological functions. Toxicity can also take place on the root surface if an element is at a particularly high concentration in the rooting medium or nutrient solution bathing the roots. An excess of one element may result in an imbalance among one or more other elements, resulting in a "toxic effect" in terms of root function and plant growth. The combined influence of ions in solution will change the electrical conductivity (EC) of a solution surrounding the root, or a specific ionic balance may alter the pH of the surrounding solution. Therefore, the whole concept of excess can be confusing due to the varying factors associated with high concentrations of some elements in the rooting medium or plant itself. In this discussion, only those elements that have clearly defined excess symptoms and their resulting impact on the plant will be described.

Forms of Utilization

For all of the essential elements, the form or forms of the element utilized is specific, normally as a single ionic form, such as K^+, Ca^{2+}, Mg^{2+}, Cu^{2+}, Mn^{2+}, Zn^{2+}, Cl^-, and Mo_4^{2-}; or more than one ionic form, Fe^{2+} and Fe^{3+}; as two-element ions, NO_3^-, NH_4^+, and SO_4^{2-}, as multiple-element ions, HPO_4^{2-} and $H_2PO_4^-$; in two different ionic forms, NO_3^- anion and NH_4^+ cation; or as molecules, H_3BO_3, $CO(CH)_2$ (urea), and silicic acid (H_4SiO_4).

Effects on Roots and Elemental Uptake

The presence of an element in the rooting medium, its form and concentration, can have a significant impact on root growth and ion uptake.

Accumulation in the Rooting Medium

It is well known that with each application of a nutrient solution to a rooting medium, whether inorganic (sand, gravel, perlite, rockwool, etc.) or organic (pinebark, peat, coir, etc.), an accumulation of unabsorbed ions takes place. This can be observed by monitoring the EC of the solution exiting or in the rooting medium following a sequence of nutrient solution applications. When that EC measurement reaches a certain level, it is recommended that the rooting medium be leached with water to remove the accumulate. What is not as well known is that another type of accumulation occurs — the formation of precipitates consisting mainly of calcium phosphate and calcium sulfate. As those precipitates form, additional ions can be adsorbed on their surface or chemically combined with the forming precipitates. These precipitates do not contribute to the EC of the medium solution and are not easily leached from the rooting medium by water. The elements in the precipitates then begin to contribute to the elemental nutrition of the growing plant. Roots release acid into the rhizosphere surrounding the root, which dissolves a portion of these precipitates. With time, the accumulated precipitates begin to more strongly influence the plant element nutrition than that being applied by the nutrient solution for some elements. This partially explains why growers seem to lose control of the nutritional character of their crops over time.

Concentration in a Nutrient Solution

Numerous published nutrient solution formulations exist that define the desired concentrations of elements in solution based on crop species (tomato, cucumber, pepper, etc.) (see Chapter 11) and hydroponic/soilless method (see Chapters 5, 8, 9, and 10). In addition, a nutrient solution formulation may be altered based on

- Plant stage of growth (vegetative, fruiting, etc.)
- Changing environmental conditions (light intensity and duration temperature, etc.)
- Frequency of application (fixed time schedule or based on measured need, etc.)
- Changing the plant stress conditions (increase or decrease EC)
- Changing the pH of the rooting medium
- Need to alter the nutritional status of the plant to counter an insufficiency
- Need to alter the nutritional status of the plant due to changing environment

Nutrient Solution Reagents

For most of the essential elements, one or more reagents can be used to supply the element of interest; however, most of these reagents contain more than one of the essential elements. Therefore, the use of one reagent to supply a particular element will automatically add others. Reagents vary as to their "salinity index" (see Table 7.26) and ease of solubility (see Table 7.10); they may be best used in a chelated form (see page 379), may have varying water of hydration, and can be obtained by the use of nitrogen, phosphorus, and potassium (NPK) fertilizers. The question of purity of grade can affect what "impurities" might be added to the nutrient solution that can be either detrimental or beneficial to plants (see Chapter 6). A list of the commonly used reagents and their properties are given in Table 7.7 through Table 7.19.

The Major Elements

Nine of the 16 essential elements are classified as major elements: C, H, O, N, P, K, Ca, Mg, and S. Since the first three are obtained from CO_2 in the air and H_2O from the rooting medium and then combined by photosynthesis to form carbohydrates via the reaction carbon dioxide (CO_2) + water ($6H_2O$) → (in the presence of light and chlorophyll) carbohydrate ($C_6H_2O_6$) + oxygen

($6O_2$), they are not normally discussed in any detail as unique to hydroponic/soilless growing systems.

Carbon, H, and O represent about 90 to 95% of the dry weight of plants and are indeed the major constituents. The remaining six major elements, N, P, K, Ca, Mg, and S, are more important to the hydroponic/soilless culture grower since these elements must be present in the nutrient solution or added to a soilless medium in sufficient quantity and in the proper balance to meet the crop requirement. Most of the remaining 5 to 10% of the dry weight of plants is made up of these six elements.

Nitrogen (N)

Content in Plants

Nitrogen leaf content for plants sufficient in N will vary from a low of 2.00 to a high of 5.00% of the dry weight. The optimum leaf or plant sufficiency range will vary with plant species. In general, the N content in plants as a percentage of dry weight is highest during the early stages of growth and then decreases with age.

Function

Nitrogen is a major constituent of amino acids and proteins that play essential roles in plant growth and development. Nitrogen probably has a greater total influence on plant growth than most of the other essential elements, as within the range from deficiency to excess N level markedly affects plant growth as well as fruit yield and quality.

Deficiency Symptoms

Nitrogen deficiency appears as a lightening of the normal green color associated with a healthy plant appearance. Since N is a mobile element in the plant, the first symptoms of N deficiency appear on the older leaves, which become light green in color. As the deficiency intensifies, these leaves turn yellow and eventually die. Nitrogen deficiency will shift the morphogenetics of the plant, reducing growth, bringing an early onset of flowering and early completion of the life cycle. A plant subjected to N deficiency will partition more of its available resources to improving the physiological activity of the roots. Deficiency symptoms may develop quickly but can just as quickly be corrected by adding some form of available N to the growing medium at a concentration sufficient for normal plant growth and development to resume. Periods of inadequate N may have considerable effect on growth, appearance, and final yield; the deficiency effect is particularly severe on the plant if it occurs during critical stages of growth. Deficiency is best confirmed by means of a plant analysis for total N (see pages 319–324), by tissue tests for NO_3 (see pages 324–325), and more recently by the use of a chlorophyll meter measurement (Wood et al., 1993). Sulfur deficiency symptoms (see page 50) can mimic those of N deficiency, although S deficiency symptoms appear over the entire plant, while N deficiency symptoms initially appear on the older tissue, and then advance over the entire plant as the severity of the deficiency increases. Use of plant analysis will distinguish between the two elemental deficiencies (see pages 319–324).

Excess Symptoms

There is as much danger in N excess as deficiency, particularly for fruiting crops. Excess N produces lush plants with dark green foliage; such plants are susceptible to disease and insect attack and have greater sensitivity to changing environmental conditions. Excess N in fruiting crops not only impairs blossom set and fruit development but also reduces fruit quality. It is impossible to affect fruit quality by adjusting the supply of those elements related to fruit quality characteristics, mainly K and B, if the N content of the plant is in excess. Excess N frequently does more permanent damage to the plant than does N deficiency.

Forms of Utilization

In most soilless culture systems, proper control of N relates to both the concentration and the form of the element in the nutrient solution. Most nutrient solution formulas call for a balance between the two ionic forms of N, NO_3^-, and NH_4^+, which in turn provides some degree of pH control (see pages 102–105). If NO_3^- is the sole form of N in the nutrient solution, its uptake results in an increase in the medium pH; the reverse is true if NH_4^+ is the sole N source, although there are some exceptions depending on environmental conditions and plant species (Hershey, 1992). In general, in an acid environment, NO_3^- is more readily absorbed, while NH_4^+ is better absorbed at a higher pH. At a pH of 6.8, both ionic species are taken up equally. Maintaining a balance between the two forms in a nutrient solution can partially regulate the pH, although some have found that this means of pH control is not always effective.

Ammonium versus Nitrate

Experience has shown that the percentage of NH_4^+ ions in the nutrient solution should not exceed 50% of the total N concentration; the best ion ratio is 75% NO_3^- to 25% NH_4^+. If NH_4^+ is the major source of N in the nutrient solution, NH_4^+ toxicity can result. However, some NH_4^+ may be desirable, as experiments have shown that the presence of NH_4^+ in the nutrient solution stimulates the uptake of NO_3^-. It has been shown that as little as 5% of the total N in solution as NH_4^+ in a flowing nutrient solution system is sufficient. A higher percentage will be needed for aerated standing nutrient solution systems, in which up to 25% of the total N should be NH_4^+ in order to obtain the same stimulating effect on NO_3^- uptake. Variations of these suggested percentages may be required, depending on plant species, stage of plant growth, nutrient solution flow rate, and other factors.

If NH_4^+ ion is the major N source in the nutrient solution, its effect on tomato plant growth, for example, can be significant depending on the level of light intensity. At low light intensity, there is no significant effect, while at high light intensity plant growth is reduced by as much as one-third; the symptoms are leaf-roll, wilting, and interveinal chlorosis of the older leaves.

Another factor that needs to be considered when selecting the proper ion ratio of NH_4^+ to NO_3^- in the nutrient solution is plant species. Fruiting plants, such as tomato and pepper, are particularly sensitive to NH_4^+ nutrition. When NH_4^+ is present in the nutrient solution during flower and fruit initiation, fruit yields are lowered, and a physiological disorder in the fruits, called blossom-end-rot (BER), is very likely to occur. Therefore, NH_4^+ may be included in the nutrient solution during the early vegetative growth period but should then be excluded from flower initiation to the end of the growth cycle.

Ammonium Toxicity

Ammonium can be toxic to plants when it is the major source of N, resulting in slowed growth and development. Lesions will develop on the stem and leaves, and leaves will develop a cupping appearance. The vascular tissue may begin to deteriorate (NH_4^+ interferes with Ca function; Ca is required for maintaining cell wall integrity), causing the plant to wilt on high atmospheric demand days. Ammonium toxicity may eventually result in the death of the plant. If the stem of an affected plant is cut through just above the root line, a darkened ring of decayed vascular tissue is usually clearly visible. Some diseases produce the same symptoms; therefore, careful examination and testing may be needed to determine whether an organism present in the tissue is causing the decay or NH_4^+ toxicity is indeed the cause.

Effect on Roots and Elemental Uptake

It is known that the N concentration in the nutrient solution can influence the character of root growth. As the NO_3^- concentration increases, the number and length of root hairs decreases. Concentrations of the other major elements, P, K, Ca, and Mg, have no similar effect. Even a change in the NH_4^+ content of the nutrient solution has no effect on root hairs. However, roots exposed to high concentrations of NH_4^+ or in nutrient solutions where the major source of N is NH_4^+ will be coarse in appearance, with little branching or fine root structure. Root growth and its influence on plant growth are discussed in Chapter 4.

Concentration in a Nutrient Solution

Most formulas call for the total N concentration in the nutrient solution to range from 100 to 200 mg/L (ppm), and if NH_4^+ is included in the formulation, the ratio of NO_3^- to NH_4^+ ions should be about three or four to one.

Control of the Concentration

Instructions frequently call for the total N concentration in the nutrient solution to start at a low level (<100 mg/L, ppm), which is then increased as the growing crop matures. This is a common practice in the case of fruiting crops, when control of the N supply is set to minimize excessive vegetative growth and to promote fruit initiation and development. Since N is a key essential element affecting plant growth and fruit quality, careful control of its supply to the plant is extremely important. In soilless growing systems, success or failure hinges to a considerable degree on how well this element is managed. In general, the tendency is to supply too much N at all stages of plant growth and not to regulate N supply by monitoring plant N content by means of plant analyses (see pages 319–324).

Nutrient Solution Reagents

The common sources for NO_3-N are calcium nitrate, $Ca(NO_3)_2 \cdot 4H_2O$; potassium nitrate, KNO_3; and nitric acid, HNO_3; for both NH_4 and NO_3, ammonium nitrate, NH_4NO_3; and for NH_4 only, ammonium sulfate, $(NH_4)_2SO_4$; and ammonium mono- or dihydrogen phosphate, $(NH_4)_2HPO_4$ or $NH_4H_2PO_4$, respectively. Urea, $CO(NH_2)_2$, is not recommended as a N source in hydroponic formulations as its hydrolysis produces NH_4, which can be an undesirable cation in a nutrient solution. The urea molecule can be directly absorbed by plant roots, although its presence in the plant may or may not be desirable.

Phosphorus (P)

Content in Plants

The P content in plant leaves ranges from 0.20 to 0.50% of the dry matter. The P concentration in young plants is frequently quite high (0.50 to 1.00%), but it slowly declines with plant age. As with N, total P uptake increases up to the period of fruit set and then drops off sharply.

Function

Biochemically, P plays a key role in the plant's energy transfer system ("high energy" bond compounds, i.e., adenosine triphosphate [ATP], adenosine diphosphate [ADP], and phosphocreatine, which release energy for plant metabolic activity); thus, P deficiency slows growth considerably. Phosphorus is the main constituent of nucleic acid structures as well as a component of membrane phospholipids.

Deficiency Symptoms

The first symptom of P deficiency is slowed growth. As the deficiency intensifies, the older leaves develop a deep purple coloring. A similar discoloration can also be brought on by cool temperatures, either in the rooting media or surrounding atmosphere. Since P uptake by plants is somewhat temperature affected, a moderate P deficiency with accompanying symptoms may be induced by cool temperatures; the deficiency symptoms disappear when temperatures return to the optimum for active plant growth. Phosphorus deficiency can be easily detected by means of a plant analysis (see pages 319–324); deficiency occurs in most plants when the leaf concentration is less than 0.20% of the dry matter. A tissue test for P may also be used to confirm a suspected deficiency (see pages 324–325).

Excess Symptoms

Until recently, P excess has not been thought of as a common problem. However, recent studies have found that excess P can occur and will significantly affect plant growth. There is accumulating evidence that if the P content of the plant exceeds 1.00% of its dry weight, P toxicity will result (Jones 1998b). Phosphorus toxicity is most likely an indirect effect in as much as it affects the normal functions of other elements, mainly Fe, Mn, and Zn. The interference with Zn is the most likely to occur first. The likelihood of excess seems to be a problem more closely associated with soilless culture than growing in soil, although any form of container growing is subject to the hazard of P overfertilization. In some types of media culture, an initial application of P fertilizer may be sufficient to satisfy the crop requirement without the need for further additions. Phosphorus overfertilization occurs most frequently when the grower uses a general-purpose fertilizer containing P when the plants need only N and/or K.

Concentration in a Nutrient Solution

Most nutrient solution formulas call for a P concentration in solution between 30 and 50 mg/L (ppm), although there is increasing evidence that this should be reduced to 10 to 20 mg/L (ppm). In a continuously flowing nutrient solution, the P level can be significantly less (1 to 2 ppm) and still maintain plant sufficiency. The form of P in solution is either the mono- or dihydrogen phosphate (HPO_4^{2-} or $H_2PO_4^-$, respectively) anion; the particular dominant anion form is a function of the pH of the nutrient solution, the former being more prevalent at neutral pH, the latter at acidic levels. Plants take up P very efficiently; the P level in the plant can be 100- to 1000-fold that in the nutrient medium. Phosphorus can also accumulate on the root surface as a precipitate of either Al or Ca phosphate, which in turn can reduce the amount of P entering the root, leading to a possible P plant deficiency. This occurs under conditions that promote the formation of the precipitates — pH and concentration of the elements Al and Ca at the root surface.

Accumulation in the Rooting Medium

With each application of a nutrient solution containing P and the elements Ca and Mg to the rooting medium, whether inorganic (sand, gravel, perlite, rockwool, etc.) or organic (pinebark, coir, peat, etc.), a precipitation of P with Ca and Mg begins to occur, forming in the rooting medium at an ever-increasing accumulation. Because they are colloidal in physical form and in close contact with plant roots, a portion of these precipitates are dissolved by root acidification and the released P, Ca, Mg, and other elements trapped in the precipitates provide a major source of these elements for uptake and utilization. This partially explains why the effect of applied nutrient solution on the composition of the plant with time becomes less a reflection of the nutrient solution composition for most of the precipitated elements, both major and micronutrient, although the common recommended practice for control of the nutrient element content of the growing medium, determined by EC measurements (see page 106), is periodic water leaching. However, water leaching will not remove accumulated precipitates.

Nutrient Solution Reagents

Ammonium and K, as either the mono- or dihydrogen phosphates, $(NH_4)_2HPO_4$, $NH_4H_2PO_4$; K_2HPO_4, KH_2PO_4, respectively, are the common reagents used to supply P in nutrient solutions. More recently, phosphoric acid, H_3PO_4, has come into increasing use as a P source when the addition of either NH_4 or K is not desired and the acidic affect of this acid is desired.

Potassium (K)

Content in Plants

Potassium is the predominant inorganic element in the plant. Its content ranges from 1.25 to 3.00% of the dry matter; although there are plant species that have much higher K requirements up to 10.00% (e.g., bananas). Fruiting crops, such as tomato, cucumber, and pepper, have a higher K requirement than some other crops do. As with N and P, the K concentration in the plant is initially high (>5.00%) and then declines with age. Potassium can be easily taken up by plant roots and can accumulate in the plant at levels higher than physiologically required. Such high accumulations are referred to as "luxury consumption."

The uptake of K is substantial during vegetative growth and declines rapidly after fruiting. In most fruiting crops, such as tomato, as well as some flowering crops, the requirement for K is high, primarily influencing postharvest quality. Therefore, plants without adequate K during this critical stage of development will produce fruits or flowers of significantly reduced quality. Long-term postharvest quality of fruits and flowers can be also affected by K, requiring higher levels of plant K than that required for plant sufficiency. However, the quality of fruits and flowers due to insufficiencies of other elements, particularly high N, cannot be overcome by increasing the supply of K available for plant uptake. Since K is mobile in the plant, it can move rapidly from the older tissue to the younger, such as developing fruits and flowers. Therefore, a K deficiency can quickly result in visual symptoms in older plant tissue.

Function

Potassium is essential for maintaining the proper ion balance in the plant and is believed to be important for carbohydrate synthesis and movement. Potassium is essential for the activation of many enzymes, and the cation, K^+, is an important contributor to the osmotic potential of cells. It is the key element in the function of stomata guard cells, as K deficiency results in the closure of stomata, which in turn reduces transpiration and water uptake by the plant and reduces photosynthesis.

Deficiency Symptoms

Potassium-deficient plants have reduced turgor, wilt very easily, and plant growth is slowed. Potassium is very mobile in the plant; the K^+ ion is easily transported from the older to developing tissue, and therefore deficiency symptoms initially develop in the older leaves. As the severity of the deficiency increases, the lower leaves will develop a marginal chlorosis. Potassium deficiency symptoms have been described as a leaf scorch, where the leaf has the appearance of having been "burned" along its edges. For some crops, K deficiency will reduce stalk strength and the proliferation of roots.

Balance among Cations

A critical balance exists among the K^+, Ca^{2+}, and Mg^{2+} cations; when they are not in balance, plant stress occurs. When K is high in comparison to Ca or Mg, the first likely effect to occur is Mg deficiency. In some instances, the imbalance can induce a Ca deficiency. An imbalance among these three cations is usually the result of excessive K fertilization, as K is more readily absorbed and transported in the plant than is either Ca or Mg. This antagonism is greater between K and Mg than between K and Ca. Despite these differences, care must be taken to ensure that the proper balance between K and both Ca and Mg is maintained so that an induced deficiency of either of these two elements does not occur (Steiner, 1980). For best growth and fruit production for tomato, for example, the content of K and Ca in recently mature leaves should be about the same.

Excess Accumulation

Potassium is easily taken up by the plant and can accumulate in the plant at levels exceeding its metabolic requirements if readily available in the rooting medium. Uptake can also be influenced by the absorption of anions, particularly NO_3^-, as the K^+ ion is taken into the plant to assist in maintaining the proper cation/anion balance within the plant.

Concentration in a Nutrient Solution

Most hydroponic formulas call for the K concentration in the nutrient solution to be around 200 mg/L (ppm). The form of K in solution is the K^+ cation.

Nutrient Solution Reagents

The primary reagents for supplying K are potassium nitrate, KNO_3; and potassium sulfate, K_2SO_4; and under special conditions potassium chloride, KCl.

Calcium (Ca)

Content in Plants

Calcium content in plant leaves varies considerably, from 0.50 to 3.00% of the dry weight; the critical value depending on plant species. In some species, relatively little soluble or what may be referred to as "free Ca" is found in plant tissue, with most of the Ca existing as crystals of calcium oxalate or as precipitates of either calcium carbonate and/or phosphate. It has been suggested that the Ca requirement for plants is very low (about 0.08%), similar to that of a micronutrient, with higher concentrations required to detoxify the presence of other cations, particularly the heavy metals, such as Mn, Cu, and Zn (Wallace, 1971).

Calcium uptake is dependent on its concentration in the rooting medium and rates of transpiration as the Ca^{2+} ion is passively transported in the transpirational stream. Therefore, factors that affect the rate of transpiration will then affect Ca^{2+} transport to the aerial portions of the plant. Calcium uptake rate is less than that for K but remains fairly constant during the life of the plant. The rate of Ca uptake is also dependent on the counter-ions in solution; it is highest when the NO_3^- ion is present in the nutrient solution. With maturity, Ca movement becomes restricted, and the influx into leaves and developing fruit slows.

Function

Calcium is a major structural element of the middle lamella of cell wall; it maintains membrane integrity, which is probably its major, if not its only significant function in plants.

Deficiency Symptoms

Calcium deficiency primarily affects leaf appearance, changing the shape of the leaf and turning the tip brown or black. New emerging leaves will have a torn appearance as margins stick together, tearing the leaf along its margins as it expands. Some leaves may never fully expand to normal size and shape when Ca is deficient. Calcium also significantly affects root growth and development, and when deficient, roots turn brown, particularly the root tips. One of the major effects of Ca deficiency is blossom-end-rot (BER) of developing fruit, a physiological breakdown of the tissue at the blossom end due to insufficient Ca present required for normal cell development and metabolism.

Calcium deficiency or excess occurs in the plant when in the nutrient solution an imbalance with the K^+ and Mg^{2+} cations exists. In nutrient solution formulas with the NH_4^+ ion as the major source of N, this ion will act like K and become a part of the cation balance, and therefore, affect the uptake of Ca from the nutrient solution.

One of the results of NH_4^+ toxicity is the breakdown of the vascular tissue in the main stem of the plant that affects cell wall integrity, a Ca deficiency induced by a cation imbalance in the nutrient solution.

Excess Symptoms

Calcium excess is not a common occurrence, although a high Ca concentration in the plant may affect the relationship between the major cations K and Mg. Calcium excess may induce either a K or Mg deficiency, the latter most likely being Mg deficiency.

Accumulation in the Rooting Medium

With each application of a nutrient solution containing Ca and P to the rooting medium, whether inorganic (sand, gravel, perlite, rookwool, etc.) or organic (pinebark, coir, peat, etc.), a precipitation of Ca with P begins to occur, forming in the rooting medium an ever increasing accumulation. Being colloidal in physical form and in eminent contact with plant roots, a portion of this precipitate is dissolved by root acidification and the released Ca and P as well as other elements trapped in the precipitates provide a major source for these elements for uptake and utilization. This partially explains why the effect of applied nutrient solution on the composition of the plant with time becomes less a reflection of the nutrient solution composition for most of the precipitated elements, both major and micronutrient. although the common recommended practice for control of the nutrient element content of the growing medium, determined by EC measurements (see page 106), is periodic water leaching, leaching that will not remove accumulated precipitates.

Concentration in a Nutrient Solution

The concentration of Ca in most nutrient solution formulas is around 200 mg/L (ppm). Calcium exists in the nutrient solution as the divalent cation, Ca^{2+}. In stock solutions when the Ca concentration is high, depending on the presence of other ions in solution, Ca can precipitate as either calcium phosphate or calcium sulfate, and under high pH as calcium carbonate. By keeping precipitating elements (P and S) from the stock solution and keeping the solution acid (pH <6.5), precipitation is not likely to occur.

Nutrient Solution Reagents

The major reagent source is calcium nitrate [$Ca(NO_3)_2{\bullet}4H_2O$]. Calciuin sulfate ($CaSO_4$) can be used only as a supplementary source of Ca due to its low water solubility (2.98 grams per L). Also, calcium chloride ($CaCl_2$) may be used to a limited degree at rates designated to keep the Cl concentration less than 100 mg/L (ppm). Natural waters may contain a substantial quantity of Ca, as much as 100 mg/L (ppm), sufficient to meet or provide a substantial portion of the nutrient formula requirement. Therefore, when preparing a nutrient solution using such water (frequently referred to as hard water), the quantity of Ca contributed by the source water should be determined so that the proper Ca concentration in solution is not exceeded.

Magnesium (Mg)

Content in Plants

Magnesium content in plant leaves will range from 0.20 to 0.50%, although Mg content can be as high as 1.00% of the dry weight. The frequency of Mg deficiency in hydroponically-grown crops may equal that of N as the result of effects due to improper balance among the other major cations, Ca^{2+}, K^+, and NH_4^+. In addition, some plant species are more sensitive to Mg than others, that sensitivity varying with stage of growth and environmental conditions.

Function

Magnesium is a major constituent of the chlorophyll molecule (Figure 5.1), the substance in which photosynthesis takes place (see page 14). Magnesium is also an enzyme activator for a number of important energy transfer processes. Therefore, a deficiency will have serious impact on plant growth and development. Magnesium is related to a specific enzymatic function particularly associated with C3-type plants that when Mg is deficient, CO_2 fixation is reduced, and therefore the production of carbohydrates required for active plant growth declines. Magnesium uptake, like Ca, tends to remain fairly constant with time, but it differs from Ca in that Mg is more mobile in the plant. While Ca is mobile only in the zylem, Mg is mobile in both the zylem and phloem.

Deficiency Symptoms

Magnesium deficiency symptoms are quite distinct as an interveinal chlorosis that appears first on the older leaves. Once a Mg deficiency occurs, it is very difficult to correct, particularly if the deficiency occurs during the mid-point of the growing season. In those plant species that have a high Mg requirement, the deficiency may be triggered by various types of environmental and physiological stress. Deficiency can result from an imbalance between K^+ and Mg^{2+}, Ca^{2+} and Mg^{2+}, or NH_4^+ and Mg^{2+} cations. Of these cations, Mg^{2+} is the least competitive for root absorption. The Ca^{2+} and Mn^{2+} cations show a competitive effect on Mg^{2+} uptake and increased Ca^{2+} uptake ensures a concentration of divalent ion capacity sufficient to maintain cation/anion balance and proper functioning of physiological activity. When Mg is deficient, the increased uptake of Mn^{2+} prevents total failure of the biochemical processes of energy transfer, forestalling the collapse and death of plant cells.

The uptake of Mg shows a number of interactive effects, both synergistic and antagonistic. An interesting side effect of Mg deficiency is a possible increase in susceptibility to fungus disease infestation as well as the incidence of blossom-end-rot (BER) of fruit.

Excess Symptoms

Under normal conditions, Mg excess is not likely to occur. However, some investigators suggest that Mg concentrations in the nutrient solution, as well as the plant, should not exceed that of Ca in order to maintain the proper cation balance for best plant growth and development.

Accumulation in the Rooting Medium

With each application of a nutrient solution containing Mg and P to the rooting medium, whether inorganic (sand, gravel, perlite, rookwool, etc.) or organic (pinebark, coir, peat, etc.), a precipitation of Mg with P begins to occur, forming in the rooting medium an ever increasing accumulation. Being colloidal in physical form and in eminent contact with plant roots, a portion of this precipitate is dissolved by root acidification and the released Mg and P as well as other elements trapped in the precipitate provide a major source for these elements for uptake and utilization. This partially explains why the effect of applied nutrient solution on the composition of the plant with time becomes less a reflection of the nutrient solution composition for most of the precipitated elements, both major and micronutrient. although the common recommended practice for control of the nutrient element content of the growing medium, determined by EC measurements (see page 106), is periodic water leaching, leaching that will not remove accumulated precipitates.

Concentration in a Nutrient Solution

Most hydroponic formulas call for Mg to be at a concentration around 50 mg/L (ppm) in the nutrient solution, although that concentration may be too low to meet the requirement for some crops, such as tomato and cucumber. Magnesium is present in the nutrient solution as the divalent cation Mg^{2+}.

Nutrient Solution Reagents

The primary reagent source for Mg is magnesium sulfate ($MgSO_4 \cdot 7H_2O$). Natural waters may contain a substantial quantity of Mg, as much as 50 mg/L (ppm). Therefore, when preparing a nutrient solution, the quantity of Mg contributed by the water should be determined so that the Mg concentration in the nutrient solution does not exceed that recommended.

Sulfur (S)

Content in Plants

Sulfur plant leaf content ranges from 0.15 to 0.50% of the plant dry matter, although >1.00% levels are not unusual.

Function

Sulfur is a constituent of two amino acids, cystine and thiamine, which play essential roles in the plant. Plants in the Leguminosae and Cruciferae families have higher requirements for S than most others. They contain a number of S compounds which are easily recognized by their contribution to the odor and flavor of the eatable portion of the plant. Sulfur is absorbed by plant roots as the SO_4^{2-} anion.

Deficiency Symptoms

Sulfur deficiency symptoms are quite similar to those of N deficiency and therefore can confuse even those most expert in plant nutrition evaluation. In general, S deficiency symptoms appear as an overall loss of green color in the plant rather than a loss of primary color in the older leaves, which is the typical N deficiency symptom (see page 38). It may be necessary, and is probably best, to rely on a plant analysis to confirm a possible S and/or N deficiency problem, rather than relying on visual symptoms alone (see pages 319–324).

Some authorities feel that the relationship of S to N is far more important than S concentration alone. Therefore, the N/S ratio might be a better measure of S sufficiency in the plant than total S alone. Equally important may be the amount of SO_4^{2}-S present in the plant. Some plant physiologists have suggested the use of the ratio of SO_4^{2}-S to total S as the best indicator of sufficiency for this element. Therefore, the literature at the present time is confusing as to the best measure of S sufficiency in plants.

Accumulation in the Rooting Medium

With each application of a nutrient solution containing SO_4^{2-} and the element Ca to the rooting medium, whether inorganic (sand, gravel, perlite, rookwool, etc.) or organic (pinebark, coir, peat, etc.), a precipitation of SO_4^{2-} with Ca begins to occur, forming in the rooting medium at an ever increasing accumulation. Being colloidal in physical form and in eminent contact with plant roots, a portion of this precipitate is dissolved by root acidification and the released SO_4^{2-} and Ca s well as other elements trapped in the precipitate provide a major source for these elements for uptake and utilization. This partially explains why the effect of applied nutrient solution on the composition of the plant with time becomes less a reflection of nutrient solution composition for most of the precipitated elements, both major and micronutrient. although the common recommended practice for control of the nutrient element content of the growing medium, determined by EC measurements (see page 106), is periodic water leaching, leaching that will not remove accumulated precipitates.

Concentration in a Nutrient Solution

Most hydroponic formulas call for a S concentration around 50 mg/L (ppm). Sulfur exists in solution as the SO_4^{2-} anion. The concentration of the SO_4^{2-} anion in a nutrient solution formulation may be determined by what other reagents are in the formulation to supply either Mg as $MgSO_4{\bullet}7H_2O$, K as K_2SO_4, or NH_4 as $(NH_4)_2SO_4$.

Nutrient Solution Reagents

The sulfate salts of K, Mg, and NH_4 [K_2SO_4, $MgSO_4 \cdot 7H_2O$, $(NH_4)_2SO_4$, respectively] are frequently selected as one of the major sources for N, K, or Mg, which automatically adds S to the nutrient solution. There use in various formulations may add more S than needed for plant sufficiency. Little is known about S excess, including whether it can occur and in what form. Evidently plants can tolerate a high concentration of the SO_4^{2-} anion in a nutrient solution without harm to the plant.

The Micronutrients

Plants require considerably smaller concentrations of the micronutrients than the major elements to sustain sufficiency. However, the micronutrients are as critically essential as the major elements. The optimum concentrations for the micronutrients are typically in the range of 1/10,000th of the concentration range required for the major elements (see Tables 5.1 and 5.2). The micronutrients, as a group, are far more critical in terms of their control and management than some of the major elements, particularly in soilless culture systems. In the case of several of the micronutrients, the required range is quite narrow. Departure from this narrow range results in either deficiency or toxicity when below or above, respectively, the desired concentration range in the rooting media. Deficiency or toxicity symptoms are usually difficult to evaluate visually and therefore require an analysis of the plant for confirmation (see pages 319–324).

A deficiency of a micronutrient can usually be corrected easily and quickly, but when dealing with excesses or toxicities, correction can be difficult, if not impossible. If toxicity occurs, the grower may well have to start a new crop. Therefore, great care must be taken to ensure that an excess concentration of a micronutrient be introduced into the rooting media, either initially or during the growing season.

The availability of some of the micronutrients, particularly Fe, Mn, and Zn, can be significantly changed with a change in pH or with a change in the concentration of one of the major elements, such as P. Therefore, proper control of the pH and concentration of the major elements in a nutrient solution is equally critical.

There may be sufficient concentration of some of the micronutrients in the natural environment (i.e., in the water used to make a nutrient solution, the inorganic or organic rooting media, or from contact with piping, storage tanks, etc.) to preclude the requirement to supply a micronutrient by addition. Therefore, it is best to analyze a prepared nutrient solution after constituting it and after contact with its environment to determine its micronutrient content. In addition, careful monitoring of the rooting media and plants will ensure that the micronutrient requirement is being satisfied but not exceeded. Such testing and evaluation procedures are discussed in greater detail in Chapter 13.

Boron (B)

Content in Plants

The sufficiency range for B in leaf tissue is from 10 to 50 mg/kg (ppm) of the dry weight, with the critical values being closer to either the lower or upper concentration of the sufficiency range, depending on the plant species. Boron accumulates in the leaf margins at concentrations 5 to 10 times that in the whole leaf blade. Therefore, the percent of margin to leaf blade can significantly influence a B assay of a leaf tissue sample taken for analysis.

Function

Boron is important in carbohydrate synthesis and transport, pollen growth and development, and cellular activities (division, differentiation, maturation, respiration, growth, etc.).

Deficiency Symptoms

Plants deficient in B exhibit various visual symptoms; the first is slowed and stunting of new growth, followed by a general stunting of the whole plant, and when the deficiency is severe, the growing tip of the plant will die. The plant itself will be brittle (due to cell wall deterioration), as leaf petioles and stems will easily break from the main stem. Fruit development will be slow or non-existent, depending on the severity of the deficiency. Fruit quality will be impaired when B is inadequately supplied. When the deficiency is severe, the growing tip of both tops and roots will die.

Excess Symptoms

Because B accumulates in the leaf margins, an early symptom of excess B is discoloration and eventual death of the leaf margins. Normally, discoloration along the whole length of the leaf distinguishes B excess from Ca deficiency (see page 46), where just the leaf tip and margin at the tip turn brown and die. Boron toxicity can easily result from excess B in the nutrient solution or from B found in natural waters. The B level in the plant should be closely monitored by plant analysis and by care in making the nutrient solution and evaluating the quality of water used.

Concentration in a Nutrient Solution

Hydroponic formulas usually call for a B concentration of about 0.3 mg/L (ppm) in the nutrient solution; the borate (BO_3^{3-}) anion and molecular boric acid (H_3BO_3) are the forms found in solution and utilized by plants.

Nutrient Solution Reagents

Boric acid (H_3BO_3), Solubor ($Na_2B_4O_7 \cdot 4H_2O + Na_2B_{10}O_{16} \cdot 10H_2O$) and borax ($Na_2B_4O_7 \cdot 10H_2O$) are the primary reagent sources.

Chlorine (Cl)

Content in Plants

Leaf content of Cl ranges from low parts per million levels (20 mg/kg) in the dry matter to percent (0.15%) concentrations. Levels in excess of 1.00% would be excessive for most crops. The critical concentration range is thought to be between 70 to 100 mg/kg (ppm) in dry matter, but higher (1,000 mg/kg) for the small grains.

Function

Relatively little is known about Cl function, but plants tend to wilt easily when a deficiency exists, and some crop species, particularly small grains, become susceptible to various fungus diseases when Cl levels in the plant are low.

Deficiency/Excess

Since the Cl^- anion is ever-present in the environment, deficiencies are not likely to occur, except under special circumstances. There is far greater danger in excesses of Cl resulting from exposure of plants to salt-affected Cl-based environments. Symptoms of Cl toxicity include burning of the leaf tips or margins and premature yellowing and loss of leaves.

Concentration in a Nutrient Solution

Because Cl is a common contaminant in water and reagents used to prepare the nutrient solution, this element does not normally have to be added to a nutrient solution formulation. Care should be taken to avoid adding sizable quantities of Cl to the nutrient solution by using reagents such as potassium or calcium chloride (KCl or $CaCl_2$, respectively). If present in high concentration in the nutrient solution, the Cl^- anion will inhibit the uptake of other anions, particularly NO_3^-. Chlorine exists in the nutrient solution as the chloride (Cl^-) anion.

Copper (Cu)

Content in Plants

The sufficiency range for Cu in plant leaf tissue is between 2 and 10 mg/kg (ppm) in the dry matter, and for some plants the range between deficiency and toxicity is fairly narrow, with toxicity occurring when the Cu leaf tissue concentration is in excess of 15 mg/kg (ppm).

Function

Copper plays a role in electron transport in photosynthesis processes, is a constituent of a chloroplast protein, and is also known to be an enzyme activator.

Deficiency Symptoms

When deficient, plants are stunted and chlorosis develops on the older leaves. Plants moderately deficient in Cu may be dark green in color and slow growing. In fruiting crops, Cu deficiency affects the developing fruits; they are small and imperfectly formed. Death of the growing tip of the fruit may also occur with Cu deficiency.

Excess Symptoms

In hydroponic systems, Cu toxicity can result in significant root damage if the Cu content of the nutrient solution is too high [>0.1 mg/L (ppm)].

Concentration in a Nutrient Solution

The normal concentration range for Cu in nutrient solutions is from 0.001 to 0.01 mg/L (ppm). Copper exists in the nutrient solution as the cupric (Cu^{2+}) cation. It has been suggested by some that if the Cu concentration is raised to 4 mg/L in nutrient flow systems, some degree of root fungus control can be obtained. Additional research is needed to determine if such Cu levels will indeed control common root diseases and not damage or kill plant roots. Such Cu concentrations should not be used for other types of hydroponic growing systems. There is evidence that if a chelated form of Fe is present in the nutrient solution, Cu uptake and translation in the plant can be impaired (Rengel, 2002). However, there are not sufficient data to recommend an increase in the concentration of Cu in the nutrient solution to compensate for this effect.

Nutrient Solution Reagents

Copper sulfate, $CuSO_4 \cdot 5H_2O$, is the primary reagent source for Cu in nutrient solution formulas. However, there may be sufficient Cu contamination from contact with Cu-containing equipment (pipes, etc.) to supply all that is required.

Iron (Fe)

Content in Plants

The sufficiency range for Fe in leaf tissue for most plants is from 50 to 100 mg/kg (ppm) of the dry matter; the so-called critical concentration is 50 mg/kg (ppm). More than 75% of the Fe in plants is located in the chloroplast. Iron is stored in plants as a ferric phosphoprotein called phytoferritin. Iron accumulates in plants without any apparent deleterious effect; therefore, it is not unusual to find Fe concentrations in excess of many hundreds of mg/kg (ppm). Total Fe in the plant may be of little importance, somewhat similar to Ca in that the “soluble” or “labile” concentration determines sufficiency. Special tests have been developed to measure this form of Fe in plant tissue (Bar-Akiva et al., 1978; Bar-Akiva, 1984). Other extraction procedures have been proposed for determining the “active Fe” content in leaf tissue (Jones, 2001). Iron plant chemistry is complex, and the relationship between tissue content and function is not clearly understood.

Function

Iron plays a significant role in various energy transfer functions in the plant due to ease of valence change ($Fe^{2+} = Fe^{3+} + e^-$). Iron also has an important role in the photosynthesis process and in the formation of the chlorophyll molecule. It also has the tendency to form chelate complexes. Other exact roles are not clearly known.

Deficiency Symptoms

One of the symptoms of Fe deficiency is a loss of the plant’s green color due to the loss of chlorophyll, a green pigment compound. Although the appearance of Fe deficiency is not too dissimilar to that of Mg, an Fe deficiency symptom first appears in the younger plant tissue, whereas Mg deficiency symptoms first appear in the older tissue. Iron deficiency symptoms are not always clearly distinct and can be easily confused with other elemental deficiencies, as deficiencies of S, Mn, and Zn frequently produce leaf and plant symptoms that are not easily differentiated visually from those of Fe; therefore, the importance of confirming an Fe deficiency by means of a plant analysis or tissue test is underscored (see page 319–324).

Iron deficiency, once developed in the plant, is very difficult to correct. There is evidence that in some instances Fe deficiency may be genetically controlled, with specific individual plants incapable of normal Fe metabolism and therefore unresponsive to correction by foliar Fe application. Some plant species, as well as individuals within a species, can respond to Fe-deficient conditions as their roots release H^+ ions to acidify the area immediately surrounding the root and/or release Fe-complexing substances (i.e., siderophores). Plants that are able to modify their immediate root environment have been designated "Fe efficient" and those that cannot as "Fe-inefficient."

Although the use of Fe chelates has markedly improved the control of Fe deficiency, deficiency correction is still a major problem in many crops and growing situations. Iron deficiency may be easier to control hydroponically than in other systems of growing. Soilless culture systems that employ an organic rooting medium are particularly susceptible to Fe deficiency. This difficulty will be discussed in greater detail later.

In rapidly growing tomato plants, the author has observed Fe deficiency symptoms on new growth, with the symptoms slowly disappearing with maturity. Evidently, the movement of Fe into newly emerging leaf tissue is insufficient to prevent the visual symptom from appearing, but eventually, sufficient Fe reaches the developing tissue, and the deficiency symptom disappears.

Concentration in a Nutrient Solution

Normally, the Fe concentration must be maintained at about 2 to 3 mg/L (ppm) in the nutrient solution to prevent deficiency. Iron in solution exists as either the ferric (Fe^{3+}) or ferrous (Fe^{2+}) cation, depending on the characteristics of the nutrient solution. There may be sufficient Fe in a nutrient solution, depending on the water source and contact with Fe-based piping and other similar materials, to satisfy the plant requirement.

Most hydroponic formulas call for the use of a chelated form of Fe to ensure that its presence in the nutrient solution is maintained in an available form. Although iron ethylenediaminetetraacetic acid (FeEDTA) has been widely used as an Fe source, ethylenediaminetetraacetic acid (EDTA) is toxic to plants (Rengel, 2002), and therefore the diethylenetriaminepentaacetic acid (DTPA) chelate form is recommended, although its possible toxicity to plants has yet to be determined. Other forms of chelated Fe are iron hydroxyethylethylenediaminetriacetic acid (FeHEDTA) and iron ethylenediamine-di(o-hydroxyphenylacetiz)acid (FeEDDHA) as well as the double salt forms, sodium iron hydroxyethylethylenediaminetriacetic acid (NaFeHEEDTA), sodium iron ethylenediamine-di(o-hydroxyphenylacetic) acid (NaFeEDDHA), and sodium iron dethylenetriaminepentaacetate (NaFeDTPA). However, these forms of Fe chelates are seldom used in nutrient solution formulations. Iron easily complexes with many substances, which makes Fe concentration difficult to maintain in a nutrient solution or soilless medium. In addition, if the pH of the rooting medium is greater than 6.5, Fe availability decreases sharply. Since Fe is a common contaminant found nearly everywhere, it may be naturally present in sufficient concentration to prevent deficiency.

Forms of Utilization

Plants can use either the ionic form, although that taken in as ferric-Fe (Fe^{3+}), which must be reduced to the ferrous (Fe^{2+}) form. Ferric-Fe can form complexes and precipitates quite easily in the nutrient solution, thereby reducing its concentration and, therefore, availability to plants. It is evident that the chemistry of Fe in the nutrient solution and its uptake by plants are quite complex. In addition, utilization of Fe varies among plant species, as some have the ability to alter the character of the nutrient solution in the immediate vicinity of their roots, thereby influencing Fe availability. Such influences and their effect on plants are discussed in Chapter 4.

Nutrient Solution Reagents

Although FeEDTA is still listed in nutrient solution formulations, FeDTPA is the recommended chelated form since EDTA can be toxic to plants (Rengel, 2002). Other Fe sources are inorganic compounds, which are also suitable for use in nutrient solution formulations and were in common use before the chelated Fe forms were available. These Fe compounds are iron (ferrous) sulfate, $FeSO_4 \cdot 7H_2O$; iron (ferric) sulfate, $Fe_2(SO_4)_3$; iron (ferric) chloride, $FeCl_3 \cdot 6H_2O$; and iron ammonium sulfate, $FeSO_4(NH_4)_2SO_4 \cdot 6H_2O$. Two organic Fe compounds suitable for use in nutrient solution formulations are iron citrate and iron tartrate. As a general rule, it takes more Fe when in these inorganic/organic forms to provide the same level of "available Fe" as compared to the chelated forms. The author has had excellent results from just adding Fe filings to the rooting medium if it is sand, fine gravel, or perlite.

Manganese (Mn)

Content in Plants

The sufficiency range of Mn in plant leaf tissue is from 20 to 100 mg/kg (ppm) of the dry matter for most crops. Plant species sensitive to Mn deficiency are usually equally sensitive to Mn toxicity. Manganese tends to accumulate in leaf margins at a concentration two to five times that found in the leaf blade. Therefore, the ratio of leaf margin to leaf blade can influence an assay result.

Function

The function of Mn in the plant is not too different from that of Fe. Manganese is associated with the oxidation–reduction processes in the photosynthetic electron transport system and is a cofactor in the indolacetic acid IAA-oxidase enzyme system. Manganese can substitute for Mg in enzymatic reactions, and therefore its deficiency, which affects chloroplast activity, gives rise to similar visual symptom as Mg deficiency does, i.e., interveinal chlorosis, but it appears on younger tissue.

Deficiency Symptoms

Manganese deficiency symptoms first appear on the younger leaves as an interveinal chlorosis, not too dissimilar to symptoms of Mg deficiency, which first appear on the older leaves. In some instances, plants may be Mn deficient (moderate visual symptoms present) and yet plant growth will be little affected. However, when the deficiency is severe, significant reduction in plant growth occurs. Manganese deficiency can be easily corrected with a foliar application of Mn or by additions of a soluble form of Mn to the rooting medium.

Excess Symptoms

Initial Mn excess may produce toxicity symptoms not too dissimilar to deficiency symptoms. With time, toxicity symptoms are characterized by brown spots on the older leaves, sometimes seen as black specks on the stems or fruit, a symptom known as "measles." It is not unusual for typical Fe deficiency symptoms to appear when Mn is in excess. This similarity can result in improper diagnosis, which can only be resolved by means of a plant analysis (see pages 319–324). Phosphorus enhances the uptake of Mn and, when high in the rooting medium, can contribute to either correcting an insufficiency or creating a possible excess, which could lead to toxicity. Composted milled pinebark is high in Mn, which can be sufficient to supply the entire plant requirement.

Concentration in a Nutrient Solution

Hydroponic formulas call for a Mn concentration of 0.5 mg/L (ppm) in the nutrient solution. Since Mn can be easily taken up by plants, care should be exercised to prevent the application of excessive quantities of Mn in the nutrient solution. Manganese exists in the nutrient solution as the manganous (Mn^{2+}) cation, although other oxidation states can be present under varying conditions of O_2 supply. Composted pinebark if used as a rooting medium contains sufficient available Mn to satisfy the Mn requirement for most plants; therefore, inclusion of Mn in the nutrient solution formulation may not be necessary.

Nutrient Solution Reagents

The primary reagent source is manganese sulfate, $MnSO_4 \cdot 4H_2O$, although manganese chloride, $MnCl_2 \cdot 4H_2O$, can also be used as a suitable reagent.

Molybdenum (Mo)

Content in Plants

The plant's Mo requirement is very low; the critical level in plant tissue is less than 0.5 mg/kg (ppm) of the dry matter. The Mo concentration found in normally growing plants is usually between 0.5 and 1.0 mg/kg (ppm), but it may be considerably greater with no apparent toxic effect on the plant itself.

Function

Molybdenum is an essential component of two major enzymes involved in N metabolism. Nitrogen (N_2) fixation by symbiotic N-fixing bacteria requires Mo, and the reduction of the NO_3^- anion by the enzyme nitrate reductase requires Mo. Therefore, plants receiving all of their N by root absorption of the NH_4^+ cation either do not require Mo or have a reduced requirement for Mo.

Deficiency Symptoms

Molybdenum deficiency symptoms are unique in some ways, sometimes giving the appearance of N deficiency when insufficient. Plant growth and flower development are restricted. Cruciferae species are more sensitive to Mo deficiency than are other species. Whiptail of cauliflower is probably the most commonly known Mo deficiency.

Concentration in a Nutrient Solution

Hydroponic formulas call for 0.05 mg/L (ppm) Mo in the nutrient solution. Molybdenum exists in the nutrient solution as the molybdate anion, MoO_4^{2-}.

Nutrient Solution Reagents

Ammonium molybdate, $(NH_4)_6Mo_7O_{24}{\bullet}4H_2O$, is the primary reagent source.

Zinc (Zn)

Content in Plants

The sufficiency range of Zn in plant leaf tissue for most plants is from 20 to 50 mg/kg (ppm) of the dry matter. Zinc is unique in that the critical level in many plants is 15 mg/kg (ppm). At around 15 mg/kg (ppm), a difference of 1 to 2 mg/kg (ppm) can mean the difference between normal and abnormal growth. Precise measurement of the Zn concentration in the plant when doing a plant analysis determination is therefore critical (see pages 319–324).

Function

Zinc is an enzyme activator, involved in the same enzymatic functions as Mn and Mg. Only carbonic anhydrase has been found to be specifically activated by Zn. While Zn probably has additional roles, these other roles are not well understood. Considerable research has been done on the relationships between Zn and P and between Zn and Fe. The results suggest that excessive P concentrations (>1.00%) in the plant interfere with normal Zn function (Jones, 1996), while high Zn concentrations interfere with Fe usage, and possibly vice versa.

Deficiency Symptoms

Zinc deficiency symptoms appear as chlorosis in the interveinal areas of new leaves, producing a banding appearance on some plant leaves. In fruit and nut trees, rosetting occurs at the branch terminals with considerable dieback. Plant and leaf growth become stunted, and when the deficiency is severe, leaves die and fall off. Moderate Zn deficiency symptoms may be confused with symptoms caused by deficiencies of Mg, Fe, or Mn. Therefore, a plant analysis is required to determine which element is deficient (see pages 319–324).

Excess Symptoms

Many plant species are tolerant to fairly high levels of Zn in their tissues without untoward consequences. These species may contain Zn at concentrations in excess of several hundred parts per million without noticeable detrimental effect. However, for those species that are sensitive to both Fe and Zn, such high levels of Zn may induce Fe deficiency.

Concentration in a Nutrient Solution

Hydroponic formulas call for Zn at 0.05 mg/L (ppm) in the nutrient solution. Zinc exists in the nutrient solution as the divalent Zn^{2+} cation. There is evidence that if a chelated form of Fe is present in the nutrient solution, Zn uptake and translation in the plant can be impaired (Rengel, 2002). The author has observed increased instances of low Zn contents in tomato plants, which may reflect this chelate effect. One way to compensate for this is to increase the Zn concentration in the nutrient solution to 0.10 mg/L (ppm). I have also observed that if nonchelated source of Fe is used in the nutrient solution formulation, there is no apparent significant reduction in Zn content in plant tissue.

Nutrient Solution Reagents

Zinc sulfate, $ZnSO_4 \cdot 7H_2O$, is the primary reagent source.

Summary

The essential elements, their forms in solution (see Table 7.16), and common chemical sources for preparing nutrient solutions are listed in Tables 7.8, and 7.9 in Chapter 7. Much is known about how to properly prepare and utilize a nutrient solution formulation, but knowledge gaps still exist, including the answers to the following questions:

1. What effect does the ratio of the form of N, NO_3^- versus NH_4^+, have on the nutrition of the plant during various stages of plant growth, and how do interactions affect the uptake and utilization of other elements, both anions (PO_4^{3-}, SO_4^{2-}, Cl^-) and cations (K^+, Ca^{2+}, Mg^{2+})?
2. Is the lack of adequate control of the N concentration in the rooting medium and plant the primary cause for poor plant performance, resulting in reduced fruit yields and quality?
3. Is the Hoagland/Arnon recommended P level (30 mg/L) in their nutrient solution formulations (see Table 7.10) excessive, which can lead to P toxicities that impact plant growth, though they are not easily observed?
4. What impact does the use of chelated reagents for the micronutrients, particularly Fe, have on the uptake and utilization of the other micronutrients, Cu, Mn, and Zn, thereby creating potential deficiencies of these elements?
5. Is the ratio between two elements more important than the specific concentration of an element in solution or in the plant?

Chapter 6

The Beneficial Elements

The number of elements presently considered essential for the proper nutrition of higher plants stands at 16; the last element added to that list was Cl in 1954 (see Table 5.3 in Chapter 5). Some plant physiologists feel that the criteria for essentiality established by Arnon and Stout (1939, see page 31) could preclude the addition of other elements, as these 16 include most of the elements found in substantial quantities in plants. However, there may be other elements that have yet to be proven essential, as their requirements are at such low levels that it will take considerably sophisticated analytical skills to uncover them, or their ubiquitous presence will require special skills to remove them from the rooting medium in order to create a deficiency. This was the case for Cl, the last of the essential elements to be so defined. The question is "what elements are likely to be added to the list of essentiality and where is the best place to start?" To complicate matters, plant response to some elements is species related — not all plants respond equally to a particular element (Pallas and Jones, 1978).

It should be remembered that since the beginning of time, plants have been growing in soils that contain all known elements. Those elements found in the soil and in the soil solution in a soluble form or forms as an ion can be taken into the plant by root absorption. This means that plants will contain most if not all those elements found in soil. Markert (1994) defined what he called the "Reference Plant Composition" of plants, which included 26 elements that are not essential but are found in plants at easily detectable concentrations (Table 6.1). Some of these elements would be classed as "trace elements," since they are found in the plant's dry matter at low concentrations. This designation, however, can lead to some confusion, since the term "trace elements" was once used to identify what are defined today as the essential micronutrients. Some of these elements exist at fairly high concentrations in the plant depending on the level of their availability in soil. Kataba-Pendias (2000) has given the approximate concentration of 18 nonessential elements

Table 6.1 Trace Element Content of "Markert's Reference Plant"[a]

Trace Element	*mg/kg*	*Trace Element*	*mg/kg*
Antimony (Sb)	0.1	Iodine (I)	3.0
Arsenic (As)	0.1	Lead (Pb)	1.0
Barium (Ba)	40	Mercury (Hg)	0.1
Beryllium (Be)	0.001	Nickel (Hi)	1.5
Bismuth (Bi)	0.01	Selenium (Se)	0.02
Bromine (Br)	4.0	Silver (Ag)	0.2
Cadmium (Cd)	0.05	Strontium (Sr)	50
Cerium (Ce)	0.5	Thallium (Ti)	0.05
Cesium (Cs)	0.2	Tin (Sn)	0.2
Chromium (Cr)	1.5	Titanium (Ti)	5.0
Fluorine (F)	2.0	Tungsten (W)	0.2
Gallium (Ga)	0.1	Uranium (U)	0.01
Gold (Au)	0.001	Vanadium (V)	0.5

[a] No data from typical accumulator and/or rejector plants.

Source: Markert, B., 1994, in D.C. Adriano, Z.S. Chen, and S.S. Yang (Eds.), *Biochemistry of Trace Elements*, Science and Technology Letters, Northwood, New York.

found in plant leaf tissue, giving their range of sufficiency to toxicity to excess (Table 6.2). The question is "which of the elements listed in Tables 6.1 and 6.2, irrespective of their found concentration in plants, would contribute, positively or negatively, to plant growth?" A colleague and the author (Pallas and Jones, 1978) found that platinum (Pt) at very low levels [0.057 mg/L (ppm)] in a hydroponic nutrient solution stimulated plant growth for some plant species but higher levels [0.57 mg/L (ppm)] reduced growth for all species. The growth effects at the low level of Pt in solution varied considerably among nine plant species (no response, radish and turnip; positive response, snap bean, cauliflower, corn, peas, and tomato; negative response, broccoli and pepper). It is the "stimulatory effect" of an element that needs to be investigated for those elements available in soils and soilless media that could be added to a hydroponic nutrient solution in order to benefit plant growth.

It was recognized by the early researchers that a "complete" nutrient solution should include not only the essential elements known at that time but also those that may be beneficial. Therefore, the A to Z micronutrient solution was developed (see Table 7.14). Eight of the 20 elements included in the A-Z micronutrient solution are considered essential and/or beneficial for animals; these elements are:

Arsenic (As)	Iodine (I)
Cobalt (Co)	Nickel (Ni)
Chromium (Cr)	Selenium (Se)
Fluorine (F)	Vanadium (V)

Many feel that these eight elements recognized as essential/beneficial for animals but not currently for plants (see Table 5.5) are good candidates for

Table 6.2 Approximate Concentrations of Micronutrients and Trace Elements in Mature Leaf Tissue

Concentration (mg/kg dry weight)			
Micronutrient /Trace Element	*Deficient*	*Sufficient or Normal*	*Toxic or Excessive*
Antimony (Sb)	—	7 to 50	150
Arsenic (As)	—	1 to 1.7	5 to 20
Barium (Ba)	—	—	500
Beryllium (Be)	—	<1 to 7	10-50
Boron (B)	5 to 30	10 to 200	5 to 200
Cadmium (Cd)	—	0.05 to 0.2	5 to 30
Chromium (Cr)	—	0.1 to 0.5	5 to 30
Cobalt (Co)	—	0.02 to 1	15 to 50
Copper (Cu)	2 to 5	5 to 30	2 to 100
Fluorine (F)	—	5 to 30	50 to 500
Lead (Pb)	—	5 to 10	30 to 300
Lithium (Li)	—	3	5 to 50
Manganese (Mn)	15 to 25	20 to 300	300 to 500
Molybdenum (Mo)	0.1 to 0.3	0.211	0 to 50
Nickel (Ni)	—	0.1 to 5	10 to 100
Selenium (Se)	—	0.001 to 2	5 to 30
Silver (Ag)	—	0.5	5 to 10
Thallium (Tl)	—	—	20
Tin (Sn)	—	—	60
Titanium (Ti)	0.2 to 0.5	0.5 to 2.0	50 to 200
Vanadium (V)	—	0.2 to 1.5	5 to 10
Zinc (Zn)	10 to 20	27 to 150	100 to 400
Zirconium (Zr)	0.2 to 0.5	0.5 to 2.0	15

Source: Kabata-Pendias, 2000 *Trace Elements in Soils and Plants*, 3rd ed., CRC Press, Boca Raton, FL.

essentiality in plants. Those who may wish to explore the potential for discovery of additional elements that may prove essential for both animals and plants will find the books by Mertz (1981), and the articles by Asher (1991), and Pais (1992), interesting.

Four elements, Co, Ni, Si, and V, have been studied as to their potential essentiality for plants. Considerable research has been devoted to each of these elements, and some investigators feel that they are important elements for sustaining vigorous plant growth.

Cobalt (Co)

Cobalt is required indirectly by leguminous plants because this element is essential for the *Rhizobium* bacteria that live symbiotically in the roots, fixing atmospheric N_2 and providing the host plant much of its needed N. Without

Co, the *Rhizobium* bacteria are inactive and the legume plant then requires an inorganic source of N as ions (such as NO_3^- and/or NH_4^+) in the soil solution of a fertile soil. It is not clear whether the plant itself requires Co to carry out specific biochemical processes. The irony of the relationship between *Rhizobium* bacteria and leguminous plants is that in the absence of sufficient inorganic N in the soil, which requires the plant to depend wholly on N_2 fixed by the *Rhizobium* bacteria, the plant will appear to be deficient in N, cease to grow, and eventually die if Co is not present.

Silicon (Si)

Plants that are soil grown can contain substantial quantities of Si, equal in concentration (percent levels in the dry matter) to that of the major essential elements. Most of the Si absorbed (plants can readily absorb silicic acid, H_4SiO_4) is deposited in the plants as amorphoous silica, $SiO_2.nH_2O$, or as opals. Epstein (1994) has identified six roles of Si in plants, both physiological and morphological. Reviewing 151 past nutrient solution formulations, Hewitt (1966) found that only a few included the element Si. Epstein (1994) recommends that Si as sodium silicate (Na_2SiO_3) be included in a Hoagland nutrient solution formulation at 0.25 m*M*. Morgan (2000a) reported that hydroponic trials conducted in New Zealand resulted in yield improvements for lettuce and bean crops when the Si content in the nutrient solution was 140 ppm. Recent studies with greenhouse-grown tomato and cucumber have shown that without adequate Si, plants are less vigorous and unusually susceptible to fungus disease attack (Belanger et al., 1995). Best growth is obtained when the nutrient solution contains 100 mg/L (ppm) of silicic acid (H_4SiO_4). The common reagent forms of Si added to a nutrient solution are either Na or K silicate, which are soluble compounds, while silicic acid is only partially soluble.

Silicon has been found to be required to maintain stalk strength in rice and other small grains (Takahashi et al., 1990). In the absence of adequate Si, these grain plants will not grow upright. Their tendency to lodge results in significant grain loss in commercial production situations. The problem of lodging has been observed primarily in paddy rice, where soil conditions may affect Si availability and uptake.

There can be confusion about this element as frequently the element silicon (Si) is improperly referred to as silica which is an insoluble compound, SiO_2.

Nickel (Ni)

Nickel is considered an essential element for both legumes and small grains (i.e., barley), as Brown et al. (1987) have shown that its deficiency meets the requirements for essentiality established by Arnon and Stout (1939) (see page 31). Nickel is a component of the enzyme urease, and plants deficient in Ni have high accumulations of urea in their leaves. Nickel-deficient plants are slow growing, and for barley, viable grain is not produced. It is recommended that a nutrient solution contain a Ni concentration of at least 0.057 mg/L (ppm) in order to satisfy the plant requirement for this element, although its requirement for other than grain crops has not been established. Nickel is also related to seed viability; its deficiency in seed-bearing plants results in seeds that will not germinate.

Vanadium (V)

Vanadium seems to be capable of substituting for Mo in the N metabolism of plants, with no independent role clearly established for V. If Mo is at its sufficiency level [its requirement is extremely low (see Table 5.1 and Table 5.2)] in the plant, V presence and availability are of no consequence.

Element Substitution

There is considerable evidence that some nonessential elements can partially substitute for an essential element, such as Na for K, Rb for K, Sr for Ca, and V for Mo. These partial substitutions may be beneficial to plants in situations where an essential element is at a marginally sufficient concentration. For some plant species, this partial substitution may be highly beneficial to the plant. Despite considerable speculation, it is not known exactly how and why such substitutions take place, although similarity in elemental characteristics (atomic size and valance) may be the primary factors.

New Beneficial Elements

Morgan (2000a) has identified what she calls "new" beneficial elements, those other than Co, Si, Ni, and V:

Sodium (Na)	Rubidium (Rb)
Strontium (Sr)	Lithium (Li)
Aluminum (Al)	Selenium (Se)
Iodine (I)	Titanium (Ti)
Silver (Ag)	

Of these elements, only Na and Ag are not included in the A-Z micronutrient solution. The 12 elements identified by Morgan (2000a) as being beneficial and their roles in plants are given in Table 6.3.

Summary

Growing evidence indicates that some elements not currently recognized as essential for plants have beneficial effects. This increasing body of knowledge

Table 6.3 The "New" Beneficial Elements and Their Roles

Element	*Role*
Silicon (Si)	Available as silicic acid (H_4SiO_4) which is slightly soluble; moves in the plant in the transpiration stream in the xylem; important roles in growth, mineral nutrition, mechanical support, resistance to fungal diseases
Sodium (Na)	Can be a replacement for K in some plants, such as spinach and sugar beet; small quantities have increased tomato yields; an element that can be beneficial at low concentrations and detrimental at high concentrations
Cobalt (Co)	Accelerates pollen germination, elevates the protein content of legumes, contributes to the maximum occupation of the leaf surface by chloroplasts and pigments, essential for the symbiotic N_2 fixation by legumes
Vanadium (V)	Complements and enhances the functioning of Mo, V and Mo participate in the N_2 fixation process, contributes to the initial stages of seed germination
Lithium (Li)	Some plants can accumulate Li to high concentrations; may affect the transport of sugars from leaves to roots in sugar beets; increases chlorophyll content of potato and pepper plants
Rubidium (Rb)	May partially substitute for K, when P and NH_4-N are high concentration in the plant, may play a role in the sugar beet plant by enhancing yield and sugar content
Strontium (Sr)	May partially replace Ca when Ca requirement is high
Aluminum (Al)	May be beneficial to plants that accumulate Al; traces found in DNA and RNA
Selenium (Se)	Stimulates growth for high-Se accumulator plants; can replace S in S-amino acids in wheat
Iodine (I)	Stimulates growth of plants in I-deficient soils; stimulates the synthesis of cellulose and lignification of stem tissue; increases concentration of ascorbic acid; seems to increase the salt tolerance of plants by lowering Cl uptake
Titanium (Ti)	May play a role in photosynthesis and N_2 fixation; increases chlorophyll content of tomato leaves; increases yield, fruit ripening, and sugar content of fruit; may be essential for plants but not found so because Ti is almost impossible to remove from the environment
Silver (Ag)	Induces production of male flowers on female plants, blocks the production of ethylene; cut flower life can be enhanced by pretreatment with Ag compounds

Source: Morgan, L., 2000a *The Growing Edge* 11(3):40–51.

should be sufficient to alert growers that the use of pure reagents and purified water for making a nutrient solution may not be the best practice. The presence of small quantities of elemental impurities may be desirable. Whether consideration should be given to specifically include them in the nutrient solution formula, including the use of the A to Z micronutrient solution (see Table 7.14 in Chapter 7), is questionable since the effort to include the right amount and the added cost for the reagents to be included in the nutrient solution formulation may far exceed any derived benefit. There is also danger that a particular element, if in excess, can adversely affect plant growth. These situations present real problems for plant physiologists as well as growers when using a nutrient solution as the only source of supply for elements, whether essential or only considered beneficial. In a soil or soilless growing medium, whether inorganic or organic, many of the elements existing naturally in the environment will be found, precluding the necessity of adding them in a supplemental nutrient solution. Hewitt (1966) did an extensive study on what elements and concentrations thereof exist in sand, other growing media, water from various sources, and reagents used to make a nutrient solution. Although some of these data might not apply today, particularly for contaminant elements found in currently used reagents, Hewitt's findings do point out that elements exist in most of the items used in hydroponic equipment, including water and reagents.

Morgan (2000a) states, "We have a lot to discover about the role of many elements present in plants. Most trace elements may never be considered 'essential' but they may prove, or have been proven, to be highly beneficial certainly makes them worth consideration."

Much of the interest in the so-called beneficial elements may be academic as their presence in plants could be only consequential. It also may be that their presence in plants may have no observed effect on plant growth unless conditions exist that would make that element a limiting factor. There is also the danger that their presence in plants may be detrimental and that they therefore should be excluded from the rooting media and nutrient solution rather than included. Hayden (2003) warns of the use of some organic materials, such as sawdust, rice straw, and composted garbage, that can contain substances that can harm plants, including organic substances, such as pesticides and herbicides, as well as heavy metals. Heavy metals (As, Cd, Cr, Pb, Hg) can also be present in inorganic fertilizers at levels that can harm plants. The Association of American Plant Food Control Officials (AAP-FCO) has developed and published recommended standards for "risk-based acceptable concentrations" (RBCs) on their web site (http://www.aapfco.org).

Humic Acid

Humic compounds are defined as amorphous, colloidal polydispersed substances; they are yellow to brown-black in color. They are hydrophilic, acidic, and high in molecular weight, ranging from several hundreds to thousands of atomic units. They are complex substances whose physical and chemical properties reflect their source and method of extraction (Tan, 1998).

Humic acid and its potential role in plant nutrition have gained considerable interest in recent years. Generally, humic acid is extracted from soil organic matter or peat; it is a material with interesting physiochemical properties that have been found to enhance plant growth (Tan, 1993). The addition of humic acid to the nutrient solution has been proposed, but its benefits have yet to be thoroughly evaluated. It is believed that humic acid would chelate some elements in the nutrient solution, thereby providing some control in elemental uptake and utilization.

Humates have been studied for sometime regarding their influence on plant growth and the chemistry of the plant-rooting medium complex. Recently, Vasilenko (2002) suggested that the humates and humic and fulvic acids can have positive effects on plant growth.

The author added humic acid to a nutrient solution formulation in a greenhouse tomato experiment and found that no significant benefit was obtained, either in terms of increased plant growth or fruit yield. Initially, there was a slight negative response when fruiting tomato plants wilted when first receiving the humic acid-included nutrient solution. These results suggest that humic acid needs to be included from the very beginning, from the seedling stage through final harvest. In another experiment, I found that including humic acid in a nutrient solution for hydroponic lettuce production from the seedling stage to harvest gave no significant positive or negative response.

One of the major problems associated with the humates and their related substances is that the source (whether derived from soil or some type of organic material) and the method of extraction and purification can have significant effects on the composition and activity of the humate product obtained (Tan, 1998). Therefore, any response (positive or negative) from the use of a humate product could be due to its derivation and method of extraction and preparation.

It is the author's opinion that humic acid and related substances should not be included in a nutrient solution formulation. There is a danger of a greater negative than positive effect.

Chapter 7

The Nutrient Solution

Probably no aspect of hydroponic/soilless growing is as misunderstood as the constitution and use of nutrient solutions. Most texts simply provide the reader with a list of nutrient solution formulas, preferred reagent sources, and the necessary weights and measures. Although such information is essential to properly prepare the nutrient solution, a soundly based understanding of its management is as important, if not more so, for successful growing. The complex interrelationships between composition and use are not understood by many growers, and it is this aspect of nutrient solution management for which much of the literature unfortunately provides little or no help. In an article about a new growing machine for lettuce and herb production, called "The Omagagarden Machine," the developers of the machine stated that "the hardest part is getting the plant food right and knowing how much to feed" (Simon, 2004b). This same thought can be echoed by many who have struggled with the selection and use of the many nutrient solution formulations found in the hydroponic literature.

Poor yields, scraggly plants, high water and reagent costs, indeed most of the hallmarks of a less than fully successful growing operation can be directly linked to faulty formulations and the mismanagement of the nutrient solution. There are, unfortunately, no absolute pat prescriptions or recipes that can be given to growers by any hydroponic advisor. Growers will have to experiment with their own systems, observing, testing, and adjusting until the proper balance between composition and use is achieved for their particular situation and specific crop. Over a five-year period, a greenhouse hydroponic tomato grower began growing in perlite bags, then switched to perlite in buckets, and then finally to composted milled pinebark in buckets, changing the nutrient solution formulations several times with each system. However, none of these changes had any significant effect on fruit yield and quality, although one significant improvement occurred — there were fewer nutrient element insufficiencies when the milled composted pinebark was the rooting medium. Even today that grower is still questioning what should be the next change to bring about significant improvement in fruit yield.

Although much is not known about how best to formulate and manage a nutrient solution, there are many good clues as to what should or should not be done. This chapter is devoted to an explanation of these clues. Growers using these clues will have to develop a scheme of management that best fits their environmental growing system and crops. They will have to experiment with various techniques to obtain maximum utilization of the nutrient solution while achieving high crop yields of top quality.

The use of a particular nutrient solution formulation should be based on three factors:

1. Hydroponic growing technique
2. Frequency and rate of nutrient solution dosing of plant roots
3. Crop nutrient element requirements

All of these influencing and interacting factors will be discussed in this chapter and in Chapter 11.

The making of a nutrient solution requires a quantity, which can be considerable, of relatively "pure" water, which may be available or needs to be generated.

Water Quality

All hydroponic/soilless culture systems require sizable quantities of relatively pure water. The best domestic water supplies and/or water for agricultural use frequently contain substances and elements that can affect (positively or negatively) plant growth. Even rainwater collected from the greenhouse covering may contain both inorganic and organic substances that can affect plant growth. In many parts of the United States and indeed throughout the world, water quality can be a major problem for hydroponic/soilless culture use due to contamination by various inorganic and organic substances.

Therefore, a complete analysis of the water to be used for any type of hydroponic/soilless culture system is essential. The analysis should include inorganic and organic components if the water is being taken from a river, shallow well, or other surface source. When taken from sources other than these, an inorganic elemental assay will be sufficient to determine elemental composition and concentration.

Natural water supplies can contain sizable concentrations of some of the essential elements required by plants, particularly Ca and Mg. In areas where water is being taken from limestone-based aquifers, it is not unusual for concentrations of Ca and Mg to be as high as 100 and 30 mg/L (ppm), respectively. Some natural waters will contain sizable concentrations of Na and anions such as bicarbonate (HCO_3^-), carbonate (CO_2^{3-}), sulfate (SO_4^{2-}), and chloride (Cl^-). In some areas, B may be found in fairly high concentrations.

Sulfide (S^-), primarily as iron sulfide, which gives a "rotten egg" smell to water, is found in some natural waters.

Suggested composition characteristics of waters suitable for use hydroponically as well as for irrigation have been published. Verwer and Wellman (1980) established what the maximum mineral concentration would be for water used in rockwool culture, as shown in Table 7.1. Farnhand et al. (1985) have established criteria for irrigation water based on salinity, electric conducivity (EC), total dissolved solids (TDS), and ion content (Table 7.2). Waters et al. (1972) have set the suitability of water for irrigating pot plants; their data are given in Table 7.3. Smith (1999) elemental maximums for water for hydroponic use (Table 7.4). Ideal water-quality guidelines for plug culture and characteristics of high-quality irrigation water are given in Table 7.5 and Table 7.6.

Table 7.1 Maximum Mineral Concentrations for Irrigation Water Used in Rockwool Culture

Element/Ion	*Maximum Concentration (mg/L, ppm)*
Chloride (Cl)	50 to 100
Sodium (Na)	30 to 50
Carbonate (CO_3)	4.0
Boron (B)	0.7
Iron (Fe)	1.0
Manganese (Mn)	1.0
Zinc (Zn)	1.0

Source: Verwer, F.L. and Wellman, J.J.C., 1980, in Fifth International Congress on Soilless Culture, International Society for Soilless Culture, Wageningen, The Netherlands.

Table 7.2 Water Quality Guidelines for Irrigation

	Degree of Problem		
Characteristic	*None*	*Increasing*	*Severe*
EC, dS/m[a]	<0.75	0.75 to 3.0	>3.0
TDS, mg/L[b]	<480	480 to 1920	>1920
Sodium (Na) sodium absorption ratio (SAR) value	<3	3 to 9	>9
Chloride (Cl) mg/L	<70	70 to 345	>345
Boron (B), mg/L	1.0	1.0 to 2.0	2.0 to 10.0
Ammonium (NH_4) and nitrate (NO_3), mg/L	<5	5 to 30	>30
Bicarbonate (HCO_3) mg/L	<40	40 to 520	>520

[a] Electrical conductance.

[b] Total dissolved solids.

Source: Farnhand, D.S., Hasek, R.F., and Paul, J.L., 1985, Water Quality, Leaflet 2995. Division of Agriculture Science, University of California, Davis, CA.

Table 7.3 Suitability of Water for Irrigating Potted Plants

Water Classification	*Electric Conductance (mmho/cm)*	*Total Dissolved Solids (Salts), mg/L, ppm*	*Sodium (% of Total Solids)*	*Boron (mg/L, ppm)*
Excellent	<0.25	<175	<20	<0.33
Good	0.25 to 0.75	175 to 525	20 to 40	0.33 to 0.67
Permissible	0.75 to 2.0	525 to 1400	40 to 60	0.67 to 1.00
Doubtful	2.0 to 3.0	1400 to 2100	60 to 80	1.00 to 1.25
Unsuitable	>3.0	>210	>80	>1.25

Source: Waters, W.E., Geraldson, C.M., and Woltz, S.S., 1972, The Interpretation of Soluble Salt Tests and Soil Analysis by Different Procedures, AREC Mimeo Report GC-1972, Bradenton, FL.

Table 7.4 Common Compounds and Elements and the Maximum Levels Allowable in Water for General Hydroponic Use

Element	*Concentration, mg/L (ppm)*
Boron (B)	<1
Calcium (Ca)	<200
Carbonates (CO_3)	<60
Chloride (Cl)	<70
Magnesium (Mg)	<60
Sodium (Na)	<180
Zinc (Zn)	<1

Source: Smith, R., 1999, *The Growing Edge* 11(1):14–16.

Surface or pond water may contain disease organisms or algae, which can pose problems. Algae grows extraordinarily well in most hydroponic culture systems, plugging pipes and fouling valves. Filtering and/or other forms of pretreatment are required to ensure that the water used to prepare the nutrient solution is free from these undesirable organisms and suspended matter.

In most cases, some form of water treatment will be necessary to make and maintain suitable nutrient solutions. Depending on what an analysis of the water supply indicates, no special treatment or filtering may be required to remove suspended matter. However, the grower may at one end of the quality scale simply have to filter out debris using sand beds or fine-pore filters; at the other extreme, sophisticated systems dedicated to ion removal by means of ion exchange or reverse osmosis may be required (Anon., 1997a).

In hard-water areas, there may be sufficient Ca and Mg in the water to provide a portion or all of the plant requirements. In addition, the micronutrient element concentration could be sufficient to preclude the need to add this group of elements to the nutrient solution. These determinations should be made only on the basis of an elemental analysis of the water (see pages 314).

Table 7.5 Ideal Water Quality Guidelines for Plug Culture

Element/Constituent	*Optimum Range, mg/L (ppm)*
Boron (B)	<0.5[a]
Iron (Fe), Copper (Cu), Zinc (Zn), Manganese (Mn)	<1.0[a]
Calcium (Ca)	50 to 125[b]
Chloride (Cl)	<100
Fluoride (F)	<1.0
Magnesium (Mg)	5 to 25[b]
Phosphate (P)	<5
Sodium (Na)	<50
Bicarbonate alkalinity	<120[c]
Alkalinity as calcium carbonate	<100[c]
Total soluble salts	650 to 1050
pH	5.8 to 6.4[d]
Electrical conductivity (EC)	1.0 to 1.5 μS/cm or preferably less[e]

[a] Commercial water-soluble fertilizers usually contain adequate levels of micronutrients. If your water contains high levels (1 to 5 mg/L) of any of the micronutrients, consult a water specialist.

[b] Calcium and magnesium at these levels can be beneficial nutritionally. Use these values in determining which micronutrients to feed seedlings.

[c] Water analysis may report bicarbonate alkalinity or express the total alkalinity in terms of calcium carbonate.

[d] Water pH range at which alkalinity is low and manageable.

[e] Electrical conductivity (EC) is now measured in milli-Siemens (mS). Some reports may use the older expression of millimho (mmho/cm). They are the same. Labs that report "total soluble salts" or TSS derive this number from the EC. One μS/cm is equal to about 650 to 700 ppm total salts.

Source: Faulkner, S.P., 1998b, *The Growing Edge* 10(1):87–88.

Organic chemicals, such as pesticides and herbicides, many of which are water soluble, can significantly affect plant growth if present even in low concentrations. Water from shallow wells or from surface water sources in intensively cropped agricultural areas should be tested for the presence of these types of chemicals.

Treatment should be employed only if the chemical and/or physical composition of the water warrants. Obviously, financial and managerial planning must incorporate the costs of producing nutrient-pure water in a grower's specified environment. For example, it may be financially prudent to accept some crop loss from the use of impure water rather than attempting to recover the cost of water treatment. Treatment may be as simple and inexpensive a task as acidifying the water to remove bicarbonates (HCO_3) and carbonates (CO_3) or as expensive as complete ion removal by reverse osmosis.

Water samples should be submitted to a testing laboratory for a complete analysis before use, and the analysis should be repeated whenever a change in the water source is made. It is also advisable to have the initial nutrient

Table 7.6 Characteristics of High-Quality Irrigation Water

Characteristic	*Desired Level*	*Upper Limit*
Soluble salts (EC)	0.2 to 0.5 μS/cm	0.75 μS/cm for plugs; 1.5 μS/cm for general production
Soluble salts (total dissolved solids)	128 to 320 ppm	480 ppm for plugs; 960 ppm for general production
pH	5.4 to 6.8	7.0
Alkalinity ($CaCO_3$ equivalent)	40 to 65 ppm (0.8 to 1.3 meq/L)	150 ppm (3 meq/L)
Bicarbonates	40 to 65 ppm (0.70 to 1.1 meq/L)	122 ppm (2 meq/L)
Hardness ($CaCO_3$ equivalent)	<100 ppm (2 meq/L)	150 ppm (3 meq/L)
Sodium (Na)	<50 ppm (2 meq/L)	69 ppm (3 meq/L)
Chloride (Cl)	<71 ppm (2 meq/L)	108 ppm (3 meq/L)
SAR[a]	<4	8
Nitrogen	<5 ppm (0.36 meq/L)	10 ppm (0.72 meq/L)
Nitrate (NO_3)	<5 ppm (0.08 meq/L)	10 ppm (0.16 meq/L)
Ammonium (NH_4)	<5 ppm (0.28 meq/L)	10 ppm (0.56 meq/L)
Phosphorus (P)	<1 ppm (0.3 meq/L)	5 ppm (1.5 meq/L)
Phosphate (H_2PO_4)	<1 ppm (0.01 meq/L)	5 ppm (0.05 meq/L)
Potassium (K)	<10 ppm (0.26 meq/L)	20 ppm (0.52 meq/L)
Calcium (Ca)	<60 ppm (3 meq/L)	120 ppm (6 meq/L)
Sulfate (SO_4)	<30 ppm (0.63 meq/L)	45 ppm (0.94 meq/L)
Magnesium (Mg)	<5 ppm (0.42 meq/L)	24 ppm (2 meq/L)
Manganese (Mn)	<1 ppm	2 ppm
Iron (Fe)	<1 ppm	5 ppm
Boron (B)	<0.3 ppm	0.5 ppm
Copper (Cu)	<0.1 ppm	0.2 ppm
Zinc (Zn)	<2 ppm	5 ppm
Aluminum (Al)	<2 ppm	5 ppm
Fluoride (F)	<1 ppm	1 ppm

[a] SAR = sodium absorption ratio = $Na^+/(Ca^{2+} + Mg^{2+})^{1/2}/2$.

Source: Whipker, B.E., Dole, J.M., Cavins, T.J., Gobson, J.L., 2003, in D. Hamrick (Ed.), Ball Redbook: Crop Production, Vol. 2, 17th ed., Ball Publishing, Batavia, IL.

solution assayed to be sure that its composition is as intended before its use. Instrumental devices and analysis kits can be used when monitoring water and nutrient solutions (see Chapter 13).

pH

The pH of water can vary over a wide range, and in addition, can be difficult to accurately determine if the water contains few ions. For example, the pH of pure water is not an easily measurable determination, and if such water is exposed to air, its pH will vary depending on the amount of CO_2 adsorbed. The ratio of cations to anions, the type of ions, and their concentration in solution will determine a water's pH. For example, a saturated solution of $CaSO_4$ will be acidic because $CaSO_4$ is a salt between a strong acid and weak base. A solution of NaCl will be near neutral in pH because NaCl is a salt between a strong acid and strong base. Other comparisons can be made for other salts. Water with a mix of ions can have a wide pH range. In addition, the amount of dissolved CO_2 will play a role, less so in a water with a high ion content versus one without.

Water and Nutrient Solution Filtering

Any suspended material in the water source should be removed by filtering through a sand bed or similar filter system (Anon., 1997a). Suspended material may contain disease-carrying organisms, be a source for algae, or precipitate some elements in reagents when constituting the nutrient solution.

With continuous use in a closed recirculating system, the nutrient solution is altered with each passage through the root mass and/or rooting medium, not only chemically by removal of elements by plant root absorption but also through additions produced by the sloughing off of root material, and substances contained in or incident to the support medium. As a result, the nutrient solution with each return to its storage tank will be physically and chemically changed due to the change in elemental content plus presence of suspended precipitates, microorganisms, and organic debris.

For short-term use (less than 5 days), a change in physical or chemical composition of the nutrient solution may be of little consequence. However, if the nutrient solution is to be used for an extended period of time (greater than 5 days), the replacement of spent elements must be made to extend its use, and filtering to remove suspended particles is necessary.

Filtering the nutrient solution is not a common practice, nor is it recommended in most of the literature on hydroponics. The only exception would be water dispensed through a drip irrigation system, which must be free of suspended particles.

Unfortunately, sophisticated filtering systems are expensive and require close attention to keep them in proper operating condition. They also add to the cost of growing plants hydroponically. Therefore, what may be gained by filtering must be evaluated against its added cost. Also, as there is little research or practical information available to adequately evaluate cost versus improvement in plant performance, the grower must make the analysis in terms of operating conditions and conservative assumptions.

Size, type, and installation requirements for a filtering system will vary depending on water volume, frequency of use, and quantity of material accumulating in the nutrient solution. Cartridge-type filters are recommended, as back-flushing is not generally possible or practical with most hydroponic systems, and cartridges can be easily replaced. Filtering devices should be placed in the outflow pipe leading to the growing bed from the supply reservoir or container. The coarser filter should be placed first in line, followed by the finer filter.

The grower has a number of options in filtering the nutrient solution. Swimming pool–type filtering systems are capable of removing suspended particles of 50 μm and larger. Removal of particles below 50 μm requires the installation of a sophisticated filtering system, such as Millipore filters (Millipore Corporation, Ashby Road, Bedford, MA 01730). Such a system is capable of removing substances that are microscopic in size (less than 1 μm). Thus, such a system removes not only large contaminants but also a number of disease organisms from the nutrient solution.

To provide some degree of control over microorganisms (bacteria, etc.), in addition to the use of a Millipore filter, the nutrient solution can be passed under ultraviolet radiation (Buyanovsky et al., 1981; Evans, 1995). Ultraviolet (UV) sterilizers have proven to be effective in reducing microorganism counts when two 16-watt lamps are placed in the path of the nutrient solution flowing at 13.5 L (3 gallons) per minute, giving a total exposure of 573 joules per square meter per hour.

Weights and Measures

Two sets of weights and measures are used in much of the hydroponic/soilless literature, English weight units, ounce (oz), and pound (lb); volume measures, pint (pt), quart (qt), and gallon (gal); and distance measures, inch (in.), foot (ft), and yard (yd), and metric weight units, gram (g) and kilogram (kg); volume measures, cubic centimeter (cc), milliliter (mL), and liter (L), and distance measures, millimeter (mm), centimeter (cm), meter (m), and area measures, hectare (ha) and area (A). In general, British units are referred to as "non-SI" units, metric as "SI" units. A conversion table for converting non-SI to SI units and vice versa is found in Appendix D.

Conversion Values Useful for Completing Nutrient Solution Calculations

1.0 pound (lb)	= 454 grams (g)
2.2 pounds (lb)	= 1 kilogram (kg)
1.0 gram (g)	= 1000 milligrams (mg)
1.0 gallon (gal)	= 3.78 liters (L)
1.0 liter (L)	= 1000 milliliters (mL)
1.0 milligram/liter (mg/L)	= 1 part per million (ppm)
1.0 pound (lb)	= 16 ounces (oz)
1.0 gallon (gal) water	= 8.3 pounds (lb)
1.0 quart (qt)	= 0.95 liters (L)
1.0 gallon (gal)	= 128 ounces (oz)
1.0 gallon (gal)	= 3780 milliliters (mL)

This text reports units as given in the source and provides converted units when appropriate. Although a considerable effort has been made to standardize units and measures worldwide, the hydroponic/soilless literature still uses a mix of units.

Nutrient solution formulations are generally based on the making of concentrates that are diluted and mixed together to give the nutrient solution that is applied to plant roots. The concentrates may be designated as Part A, Part B, etc., or as "macro" (containing the major elements) and "micro" (containing the micronutrients). In some instances, the concentrates may contain a mix of both major elements and micronutrients. The most common dilution rate from concentrate to final "to be used" nutrient solution is 1:100, one part concentrate to 100 parts water. However, other dilution rates have been used.

Reagents

What constitutes a nutrient solution is based on the reagents used. The literature contains many nutrient solution formulations, but what can be confusing is when the formulator uses a reagent name but does not give its elemental formula. For example, potassium phosphate is not sufficient, as there are two forms of this reagent, monopotassium phosphate or potassium dihydrogen phosphate (KH_2PO_4) and dipotassium phosphate or potassium monohydrogen phosphate (K_2HPO_4). The K and P contents of KH_2PO_4 are 30% and 32%, respectively, and for K_2HPO_4, 22% and 18%, respectively.

The other confusing factor is "how many waters of hydration are there for the reagent specified?" In general, most of the reagents used to formulate a nutrient solution have specific waters of hydration and may not pose a problem in identification since they are the usual commercial form, but this is not always the case for all reagents. For example, the usual commercial form of calcium nitrate, $Ca(NO_3)_2 \bullet 4H_2O$, has four waters of hydration, but $Ca(NO_3)_2$ is also available although it is not a common form. The usual commercial form of Cu is copper sulfate, $CuSO_4 \bullet 5H_2O$, which has five waters of hydration, but copper sulfate, $CuSO_4$, without any waters of hydration is also available. The usual commercial form for Mn is $MnSO_4 \bullet 4H_2O$, which has four waters of hydration although there are three other forms available, with two, three, and five waters of hydration, respectively. The elemental composition of a reagent determines its formula weight and in turn will affect the weight of reagent used to make a nutrient solution. For example, the formula weight for $CuSO_4 \bullet 5H_2O$ is 249.71, while the formula weight for $CuSO_4$ is 159.63. Characteristics of commonly used reagents for formulating a nutrient solution are given in Tables 7.7, 7.8, and 7.9.

The other issue is grade, whether fertilizer, pharmaceutical grade (USP), or reagent; the differences among these grades mainly involve purity. Normally, fertilizer grade is sufficient for the making of a nutrient solution although less pure than either USP or reagent grade forms, which are higher priced than fertilizer grade. One precaution is that the percent of the element present in each grade may vary slightly and is usually lower in fertilizer grade materials, which also can contain low levels of related elements (for example K fertilizers may contain Na).

Table 7.7 Content of Plant Nutrients in Commonly Used Reagent-Grade Compounds

Reagent	*Chemical Formula*	*Content of Nutrient in Reagent-Grade Compound, %*
Ammonium nitrate	NH_4NO_3	N: 35.0
Ammonium sulfate	$(NH_4)_2SO_4$	N: 21.2; S: 24.2
Urea	$CO(NH_2)_2$	N: 46.6
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$	N: 11.9; Ca: 17.0
Magnesium nitrate	$Mg(NO_3)_2{\bullet}6H_2O$	N: 10.9; Mg: 9.5
Potassium nitrate	KNO_3	N: 13.8; K: 38.7
Sodium nitrate	$NaNO_3$	N: 16.5
Monoammonium phosphate	$NH_4H_2PO_4$	N: 12.2; P: 27.0
Diammonium phosphate	$(NH_4)_2HPO_4$	N: 21.2; P: 23.S
Monocalcium phosphate	$Ca(H_2PO_4)_2{\bullet}H_2O$	P: 24.6, Ca: l5.9
Dicalcium phosphate	$CaHPO_4$	P: 22.8; Ca: 29.5
Monopotassium phosphate	KH_2PO_4	P: 22.8; K: 28.7
Monosodium phosphate	$NaH_2PO_4{\bullet}H_2O$	P: 22.5
Potassium chloride	KCl	K: 52.4
Potassium sulfate	K_2SO_4	K: 44.9; S: 18.4
Sodium sulfate	Na_2SO_4	S: 22.6
Calcium sulfate (gypsum)	$CaSO_4{\bullet}2H_2O$	Ca: 23.3; S: 18.6
Calcium carbonate	$CaCO_3$	Ca: 40.0
Magnesium carbonate	$MgCO_3$	Mg: 28 8
Magnesium sulfate (Epsom salts)	$MgSO_4{\bullet}7H_2O$	Mg: 9.9; S: 13.0
Ferrous sulfate	$FeSO_4{\bullet}7H_2O$	Fe: 20.1; S: 11.5
Manganese sulfate	$MnSO_4{\bullet}H_2O$	Mn: 32.5; S: 19.0
Zinc sulfate	$ZnSO_4{\bullet}7H_2O$	Zn: 22.7; S: 11.2
Zinc oxide	ZnO	Zn: 80.3
Copper sulfate	$CuSO_4{\bullet}5H_2O$	Cu: 25.5; S: 12.8
Sodium borate (borax)	$Na_2B_4O_7{\bullet}10H_2O$	B: 11.3
Boric acid	H_3BO_3	B: 17.5
Sodium molybdate	Na_2MoO_4	Mo: 46.6

Nutrient Solution Formulations

In this book, the author has not made any changes in the format for the various nutrient solution formulas included in the text but has kept the format as presented by the formulator. Since no standard format exists, the volume of solution made, units (British or metric), and use instructions are as given by the formulation author. In some instances, the element content in a nutrient solution applied to a particular crop and/or specified hydroponic/soilless growing method is given, either with or without the formulation data. When formulation instructions are lacking, the user will have to make that determination.

While it is true that numerous formulations for preparing nutrient solutions have been published, their proper use relative to the growing system and

Table 7.8 Reagents, Formulas, Molecular Mass, Water Solubility, and Percent Element Composition of Commonly Used Reagents for Making Nutrient Solutions

Reagent	*Formula*	*Solubility in Cold Water (15°C g/L)*	*Molecular Mass*	*Percent of Elements*
Major Elements				
Ammonium chloride	NH_4Cl	35	53.5	N 26
Ammonium nitrate	NH_4NO_3	1183	80.0	N 35
Ammonium sulfate	$(NH_4)_2SO_4$	706	132.1	N 21.2; S 24.3
Calcium chloride	$CaCl_2$	350	219.1	Ca 18.3
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$	2660	236.1	Ca 17.0; N 11.9
Calcium sulfate	$CaSO_4$	2.41	172.2	Ca 23.3; S 18.6
Diammonium phosphate	$(NH_4)_2HPO_4$	575	132.0	N 21.2; P 23.5
Dipotassium phosphate	K_2HPO_4	1670	174.2	K 44.9; P 17.8
Magnesium nitrate	$Mg(NO_3)_2$	1250	256.4	Mg 9.5; N 10.9
Monoammonium phosphate	$NH_4H_2PO_4$	227	119.0	N 11.8; P 26
Phosphoric acid	H_3PO_4	5480	98	P 31
Potassium chloride	KCl	238	74.6	K 52.4
Potassium dihydrogen phosphate	KH_2PO_4	330	136.1	K 28.7; P 23.5
Potassium nitrate	KNO_3	133	101.1	K 38.7; N 13.8
Potassium sulfate	K_2SO_4	120	174.3	K 44.9; S 18.4
Sodium nitrate	$NaNO_3$	921	85.0	N 16.5
Urea	$CO(NH_2)_2$	1000	60.0	N 46.7
Micronutrients				
Ammonium molybddate	$(NH_4)_6Mo_7O_{24}{\bullet}4H_2O$	430	1236	Mo 53
Boric acid	H_3BO_3	63.5	61.8	B 17.5
Copper sulfate	$CuSO_4{\bullet}5H_2O$	316	249.7	Cu 25.4
Iron (ferrous) sulfate	$FeSO_4$	156	278.0	Fe 20.1; S 11.5
Manganese chloride	$MnCl_2{\bullet}4H_2O$	1510	197.9	Mn 27.7
Manganese sulfate	$MnSO_4{\bullet}5H_2O$	1240	241.0	Mn 22.8
Manganese sulfate	$MnSO_4{\bullet}H_2O$	985	169.0	Mn 32.4
Manganese sulfate	$MnSO_4{\bullet}4H_2O$	1053	223.0	Mn 24.6
Sodium borate (borax)	$Na_2B_4O_7{\bullet}10H_2O$	20.1	381.4	B 11.3
Sodium molybdate	$NaMoO_4$	443	205.9	Mo 46.6
Sodium molybdate	$NaMoO_4{\bullet}2H_2O$	562	241.9	Mo 39.6
Zinc sulfate	$ZnSO_4{\bullet}7H_2O$	965	287.5	Zn 22.7

needs for a specific plant species have been frequently overlooked. The basis for most hydroponic nutrient solution formulations comes from two formulas that appeared in the 1950 California Agricultural Experiment Station Circular

Table 7.9 Maximum Solubilities of Reagents Commonly Used for Making a Hydroponic Nutrient Solution in Cold and Hot Water

		Maximum Solubility (g/L)		*Maximum Molar Solubility (moles/L)*	
Reagent Formula	Molar Mass (g)	Cold Water	Hot Water	Cold Water	Hot Water
KH_2PO_4	136.1	330	835	2.4	6.1
K_2HPO_4	174.2	1670	Very soluble	9.6	Very soluble
K_2SO_4	174.3	120	240	0.68	1.4
KCl	74.6	347	567	4.7	7.6
KNO_3	101.1	133	2470	1.33	24.4
KOH	56.1	1070	1780	19.0	31.7
$KHCO_3$	101.0	224	600	2.2	5.9
$KCO_3 \bullet 2H_2O$	174.2	1470	3310	8.4	19.0
$CaCO_3$	100.0	0.014	0.018	0.00014	0.00018
$Ca(NO_3)_2 \bullet 4H_2O$	236.2	2660	6600	11.3	27.9
$CaCl_2 \bullet 2H_2O$	147.0	477	3260	6.6	22.2
$CaSO_4 \bullet 2H_2O$	172.2	2.41	2.22	0.014	0.013
$Ca(H_2PO_4) \bullet H_2O$	252.1	18	Decomposes	0.07	—
$Ca(OH)_2$	74.1	1.85	0.77	0.025	0.01
$MgSO_4 \bullet 7H_2O$	246.5	710	910	2.88	9.69
$Mg(NO_3)_2 \bullet 6H_2O$	256.4	3300	1250	12.9	4.86
$MgCl_2 \bullet 6H_2O$	203.3	1670	3670	8.2	18.1
$(NH_4)_2CO_3 \bullet H_2O$	114.1	1000	Decomposes	8.76	—
NH_4NO_3	80.0	1180	8710	14.75	108.9
$NH_4H_2PO_4$	115.0	227	1732	1.97	15.1
$(NH_4)_2SO_4$	132.1	706	1038	5.34	7.86
$NaH_2PO_4 \bullet H_2O$	138.0	599	427	4.34	3.09
$NaNO_3$	85.0	921	1800	10.8	21.2
NaCl	58.4	357	391	6.1	6.7
Na_2SO_4	142.0	Soluble	420	Soluble	2.95
H_3PO_4 (85%)	98.0	548	Very soluble	5.6	Very soluble

347 authored by Hoagland and Arnon (1950). This circular has been the most widely cited publication in all crop science literature. The scientific literature is full of hydroponic formulas that are identified as "modified Hoagland nutrient solutions" with little given that describes what was modified. What most do not know is that the Hoagland/Arnon nutrient solution formulations have use components, 4 gallons of nutrient solution per plant with replacement on a weekly basis. If any of these parameters is altered, i.e., volume of solution, number of plants, and frequency of replacement, plant performance can be significantly affected, a factor that is probably not fully understood or considered by those who recommend a particular nutrient solution formulation. The nutrient element contents for Hoagland/Arnon Nutrient Solution Numbers 1 and 2 are given in Table 7.10.

Table 7.10 Hoagland/Arnon's Nutrient Solutions Number 1 and Number 2, Their Formulations and Elemental Content

Stock Solution	*To Use: mL/L*
Solution No. 1	
1 *M* potassium dihydrogen phosphate (KH_2PO_4)	1.0
l *M* potassium nitrate (KNO_3)	5.0
1 *M* calcium nitrate [$Ca(NO_3)_2 \bullet 4H_2O$]	5.0
l *M* magnesium sulfate ($MgSO_4 \bullet 7H_2O$)	2.0
Solution No. 2	
1 *M* ammonium dihydrogen phosphate ($NH_4H_2PO_4$)	1.0
1 *M* potassium nitrate (KNO_3)	6.0
l *M* calcium nitrate [$Ca(NO_3)_2 \bullet 4H_2O$]	4.0
l *M* magnesium sulfate ($MgSO_4 \bullet 7H_2O$)	2.0
Micronutrient Stock Solution	
Boric acid (H_3BO_3)	2.86
Manganese chloride ($MnCl_2 \bullet 4H_2O$)	1.81
Zinc sulfate ($ZnSO_4 \bullet 5H_2O$)	0.22
Copper sulfate ($CuSO_4 \bullet 5H_2O$)	0.08
Molybdate acid ($H_2MoO_4 \bullet H_2O$)	0.02
To use: 1m|/L nutrient solution	
Iron	
For Solution No. 1: 0.5% iron ammonium citrate	To use: 1 mL/L nutrient solution
For Solution No. 2: 0.5% iron chelate	To use: 2 mL/L nutrient solution

Element Content of Hoagland/Arnon Nutrient Solutions (ppm)

Element	*Hoagland No. 1*	*Hoagland No. 2*
Nitrogen (NO_3)	242	220
Nitrogen (NH_4)	—	12.6
Phosphorus (P)	31	24
Potassium (K)	232	230
Calcium (Ca)	224	179
Magnesium (Mg)	49	49
Sulfur (S)	113	113
Boron (B)	0.45	0.45
Copper (Cu)	0.02	0.02
Iron (Fe)	—	7.0
Manganese (Mn)	0.50	0.05
Molybdenum (Mo)	0.0106	0.0106
Zinc (Zn)	0.48	0.48

Source: Hoagland, D.R. and Arnon, D.I., 1950, The Water Culture Method for Growing Plants Without Soil, Circular 347, California Agricultural Experiment Station, University of California, Berkeley, CA.

The usual management considerations relating to costs for reagents and water, as well as the energy needs and costs required to move the nutrient solution, must be integrated into the operational plan for whatever hydroponic/soilless growing system is used. One of the major financial decisions involves balancing replenishment schedules against input costs, losses, and environmental requirements due to single use and dumping (Johnson, 2002c). The factor that will have the greatest impact now and particularly in the future will be the availability and cost of water.

Elemental Concentrations in Nutrient Solutions

Although a nutrient solution formula may be modified to suit particular requirements for its use, the critical requirements for proper management are either overlooked or not fully understood. The hydroponic literature is marked by much comment on nutrient solution composition in terms of the concentration of the elements in solution but is nearly devoid of instructions as to how the nutrient solution is to be used in such simple management terms as the volume per plant and frequency of application. If the nutrient solution is recirculated, then the renewal and replenishment of specific elements prior to renewal should be specified.

When discussing questions regarding the use of a particular nutrient solution, Cooper (1988), developer of the nutrient film technique (NFT) (Cooper, 1979b), remarked that "there is very little information available on this subject." In an interesting experiment, he obtained maximum tomato plant growth when tomato plants were exposed to 60 L (13.3 gallons) of nutrient solution per plant per week. Thinking that growth was enhanced by the removal of root exudate due to the large volume of solution available to the plants, he studied the relationship between root container size and nutrient solution flow rate. He found that plant growth was affected principally by the size of the rooting container and the volume of nutrient solution flowing through the container, not by the removal of root exudates. Cooper concluded that more fundamental research was needed to determine the best volume of nutrient solution and flow characteristics for maximum plant growth. He also observed that "the tolerance of nutrient supply was found to be very great."

This observation seems to be in agreement with Steiner (1980), developer of the Steiner formulas (Table 7.11), who feels that plants have the ability "to select the ions in the mutual ratio favorable for their growth and development," if they are cultivated in an abundant nutrient solution flow. Available evidence suggests that an advantage of flowing nutrient solution systems arises from the larger volume of nutrient solution available to the plant, resulting in increased contact with the essential elements and reduction in the concentration of inhibiting substances.

Steiner (1961) has suggested that only a handful of nutrient solution formulas are useful; at best, only one formulation would be sufficient for most plants as long as the ion balance among the elements is maintained. Steiner feels that most plants will grow extremely well in one universal nutrient solution with the following percentage equivalent ratios of anions and cations:

NO_3^-	50 to 70% of the anions
$H_2PO_4^-$	3 to 20% of the anions
SO_4^{2-}	25 to 40% of the anions
K^+	30 to 40% of the cations
Ca^{2+}	35 to 55% of the cations
Mg^{2+}	15 to 30% of the cations

He also suggests that these ion concentration ratios may vary a bit as follows:

$$\begin{array}{ccccc} NO_3^- & : & H_2PO_4^- & : & SO_4^{2-} \\ 60 & : & 5 & : & 35 \\ K^+ & : & Ca^{2+} & : & Mg^{2+} \\ 35 & : & 45 & : & 20 \end{array}$$

Steiner's (1980) thesis depends upon the assumption that plants can adjust to ratios of cations and anions that are not typical of their normal uptake characteristics, but that plants will expend much less energy if the ions of the essential elements are in proper balance as given above. Steiner's thesis explains, in part, why many growers have successfully grown plants using Hoagland-type nutrient solution formulations, as plants are apparently able to adjust to the composition of the nutrient solution even when the ratios of ions are not within the range required for best growth. Steiner also suggests that the proper balance and utilization of ions in the nutrient solution are best achieved by using his Universal Nutrient Solution formulas (Steiner, 1984). In contrast to the Steiner concept, Schon (1992) has discussed the need to tailor the nutrient solution to meet the demands of the plant. Faulkner (1998a) gives instructions for the formulation of a modified Steiner solution as a complete nutrient solution, the composition of which is given in Table 7.12. Faulkner suggests that the Steiner nutrient solution is a "versatile 'complete' nutrient solution ideal for general hydroponic culture of a wide variety of greenhouse crops." A recipe for making 100 gallons (378 L) of Steiner nutrient solution is given in Table 7.13.

The Hoagland and Arnon (1950) formulations provide another example of an imperfectly understood and improperly used system. The source of information for both of their nutrient solution formulas was obtained from the determination of the average elemental content of a tomato plant. They calculated the elemental concentration required based on one plant growing in 4 gallons of nutrient solution, which was replaced weekly. Naturally, one might ask "how would these nutrient solution formulas work if tomato is not the crop, the ratio of plant to volume of nutrient solution is greater or less than one plant to 4 gallons, and the replenishment schedule is shorter or longer than one week?"

Table 7.11 Steiner's Universal Method for Preparing Nutrient Solutions

Concept: Steiner raises the question as to whether it is the relative concentration of elements among each other or the absolute amount that determines uptake. He suggests that there must be a minimum concentration below which uptake is no longer possible and above which luxury consumption occurs, leading to internal toxicity. However, within this range, there also must be relative relationships that determine uptake and, therefore, the composition of the nutrient solution must be in a particular balance to satisfy the plant requirement for essential elements.

Method: Steiner's aim was to determine how a particular nutrient solution could be prepared that satisfies given requirements as to:

1. Relative cation ratios
2. Relative anion ratios
3. Total ionic concentration
4. pH

Concerning himself with three major anions and three major cations, Steiner established the equivalent ratios in percent as follows:

NO_3^-	:	$H_2PO_4^-$	:	SO_4^{2-}
80		5		1
K^+	:	Ca^{2+}	:	Mg^{2+}
80		10		10

Using five different source reagents and aliquots to establish the desired ratio of ions and not to exceed a total of 30 mg ions per liter, Steiner's formula was:

Reagent	*Normality (N)*	*mL/10 L*
KH_2PO_4	1	8.22
$Ca(NO_3)_2 \bullet 4H_2O$	0	1.644
$MgSO_4 \bullet 7H_2O$	2	8.22
KNO_3	1	115.07
K_2SO_4	1	8.22

Preparing various nutrient solutions with the objective of maintaining the desired ratio of ions and pH, it became evident to Steiner that if the total ionic concentration was raised above 30 mg ions per liter and the pH above 6.5, only a very few combinations were possible in order to avoid problems due to precipitation.

Result: Steiner's study reveals the possibility of preparing nutrient solutions that have specific ratios of ions to each other as well as a set total ion concentration and pH. He sets forth an interesting approach to nutrient solution formula development that bears further study for the inclusion of the other essential elemental forms, such as NO_3-N and NH_4-N, and techniques for use.

Source: Steiner, A.A., 1980, in R.G. Hurd, P. Adams, D.M. Massey, and D. Price (Eds.), Symposium on Research on Recirculating Water Culture, *Acta Horticulture* No. 98, The Hague, The Netherlands.

Table 7.12 Base Steiner Formula Consisting of Two 4-L Stock Solutions

Reagent	*Formula*	*Grams (ounces)*[a]
Stock Solution, Part 1		
Calcium nitrate (15.5% N, 19% Ca)	$Ca(NO_3)_2 \bullet 4H_2O$	364.9 (12.9)
Stock Solution, Part 2		
Monopotassium phosphate (22.7% P, 28.5% K)	KH_2PO_4	83.1 (2.9)
Potassium nitrate (13.75% N, 38% K)	KNO_3	55.0 (1.9)
Potassium sulfate (43% K, 17.5% S)	K_2SO_4	177.2 (6.3)
Iron EDTA (13% Fe)		8.7 (up to 14.5 g when feeding high Mn)
Zinc EDTA (14% Zn)		5.0 (0.17)
Copper EDTA (14.5% Cu)		0.3 (up to 1.3 g during bright sunny weather in spring to minimize fruit cracking problems)
Manganese EDTA (12% Mn)		3.1 (for tomatoes, increase up to 6.3 g during cloudy weather in winter to minimize deficiency problems)
Sodium molybdate (39.6% Mo)		0.1 (0.0035)
Borax or sodium borate (11.3% B)		3.3 (and up to 6.7 g)
Stock Solution, Part 3		
Epsom salt or magnesium sulfate (9.7% Mg, 13% S)	$MgSO_4 \bullet 7H_2O$	193.1 (6.8)

[a] All are per 4 L of final volume in distilled water.

Elemental Composition of a Full-Strength Steiner Solution

Element	*Concentration at 100% Solution Strength, mg/L(ppm)*
Nitrogen (N)	170
Phosphorus (P)	50
Potassium (K)	320
Calcium (Ca)	183
Magnesium (Mg)	50
Sulfur (S)	148
Iron (Fe)	3 to 4[a]
Manganese (Mn)	1 to 2[a]
Boron (B)	1 to 2
Zinc (Zn)	0.2
Copper (Cu)	0.1 to 0.5[b]
Molybdenum (Mo)	0.1

[a]Increase Mn to 2 ppm and iron to 4 ppm during cloudy weather.

[b]Increase Cu to 0.5 ppm during bright, sunny weather in spring to minimize fruit cracking.

Source: Faulkner, S.P., 1998, *The Growing Edge* 9(4):43–49.

Table 7.13 Recipe for 100 Gallons of Steiner Nutrient Solution

Reagent	*Grams*[a]	*Ounces*[a]	*ppm of Element*
Potassium nitrate (KNO_3)	67	2.4	25 N, 65 K
Calcium nitrate [$Ca(NO_3)_2 \bullet 4H_2O$]	360	12.7	147 N, 180 Ca
Potassium magnesium sulfate	167	5.9	80 K, 48 Mg, 37 S
Potassium sulfate (K_2SO_4)	140	5.0	154 K, 63 S
Chelated Fe (Fe 330 330–10% Fe)	11.5	0.4	3 Fe
Phosphoric acid (H_3PO_4) (75%)	50 mL		48 P
Micronutrient Concentrate (see below)	200 mL	—	
Recipe for 16 L of micronutrient concentrate, which can be diluted to make 8000 gal			
Manganese sulfate ($MnSO_4 \bullet 4H_2O$)	55.0		0.5 Mn
Boric acid (H_3BO_3)	86.5		0.5 B
Zinc sulfate ($ZnSO_4 \bullet 7H_2O$)	16.8		0.2 Zn
Copper sulfate ($CuSO_4 \bullet 5H_2O$)	24.2		0.2 Cu
Molybdenum trioxide (MoO_3) (66% Mo)	4.6		0.1 Mo

[a] Grams and ounces per 100 gallons of water.

Source: Larsen, J.E., 1979, in Proceedings of the First Annual Conference on Hydroponics: The Soilless Alternative, Hydroponic Society of America, Brentwood, CA.

In the first comprehensive review of the hydroponic method, which covered more than a century, Hewitt (1966) gave the composition of over 100 nutrient solution formulas, showing their historical development beginning in 1860. In his book, Muckle (1993) lists 33 “General and Historical Formulas” covering the time period from 1933 to 1943 as well as formulas designed for use when growing carnations, lettuce, strawberry, and tomato. Resh (1995) lists 36 formulas gathered from the literature covering the time period from 1865 to 1990, Jones (1998) published 22 major element formulas plus three micronutrient formulations gathered from the literature beginning in the late l800s to more recent times (Table 7.14), and Yuste and Gostincar (1999) listed 34 unnamed formulas plus six named formulas (Hoagland; Turner and Herry; Ellis and Swaney; Mier-Schwart; Kiplin-Laurie; and Steiner), covering the time period from 1865 to 1960.

From these and other sources, it is interesting to note the ranges in elemental concentration in various nutrient solution formulas, ranges that are given in the books by Muckle (1993), Barry (1996), Jones (1997), and Yuste and Gostincar (1999), and in two articles published in *The Growing Edge* magazine (Table 7.15). Two possible explanations for why such ranges exist have to do with the method of hydroponic growing and the crop being grown. However, the ranges in element concentration seem unusually large, and perhaps difficult to justify. The major and micronutrient concentration ranges and ionic forms in a typical nutrient solution are given in Table 7.16.

Eighteen articles have been published in *The Growing Edge* related to nutrient solution formulation and use; details about these articles are given in Table 7.17. These articles contain a wide range of opinion on how nutrient solutions are to be formulated and used.

General Purpose/Use Formulations

Smith (1999) provides a nutrient formulation that he identifies as a "Basic Nutrient Formula for General Use" (Table 7.18). Bradley and Tabares (2000) have given a nutrient solution formation that has been used in "many developing nations and with more than 30 species of vegetables, ornamental plants, and medicinal herbs" (Table 7.19). More recently, Morgan (2002e) has given the ingredients for what she has identified as a "General Purpose Hydroponic Solution" (Table 7.20). Hershey (1990) also has given what he describes as the "composition of some common nutrient solutions" (Table 7.21). Lorenz and Maynard (1988) published four researchers' nutrient solution formulas, identifying their use only for commercial greenhouse vegetable production (Table 7.22).

Crop Requirement Adjustments of the Nutrient Solution

It is generally accepted that specific nutrient element crop requirements exist that would be reflected in the elemental composition of a nutrient solution to be applied to that crop. Examples of what would be recommended for elements and crops are given in Table 7.23 and Table 7.24. In addition, nutrient solution composition adjustments may be made as the crop advances through its life cycle. Nutrient solution formulations based on crop factors are discussed in greater detail in Chapter 8 through Chapter 11.

Nutrient Solution Control

In addition, the usual management considerations relating to costs for reagents and water, as well as the energy required to move the nutrient solution, must be integrated into the operation and plan of a hydroponic/soilless growing system. One of the major financial decisions involves balancing replenishment schedules against input costs and losses due to single use and dumping.

One set of terms used to describe two methods of nutrient solution management are "open" and "closed." An "open" system is one in which the nutrient solution is used only once in a one-way passage through the rooting vessel. In a "closed" system, the nutrient solution is reused by recirculation (Hurd et al., 1980). These two means of nutrient solution management pose different problems for the grower, which will be discussed in greater detail later.

Faulkner (1998b) identified five nutrient solution characteristics given by Dr. John Larson, Emeritus Professor of Horticulture of Texas A&M University

Table 7.14 List of Formulas for Constituting Nutrient Solutions from the Early Literature on Hydroponics

Name	*Reagents*		*g/L (mg/mL)*		
Knop's Solution[a]	KNO_3		0.2		
	$Ca(NO_3)_2$		0.8		
	KH_2PO_4		0.2		
	$MgSO_4 \cdot 7H_2O$		0.2		
	$FePO_4$		0.1		
		a	b	c	
Crone's Solution (1902, 1904)[a]	KNO_3	1.00	0.75	0.75	
	$Ca_3(PO_4)_2$	0.25	0.25	0.25	
	$CaSO_4 \cdot 2H_2O$	0.25	0.25	0.50	
	$Fe_3(PO_4)_2 \cdot 8H_2O$	0.25	0.25	0.25	
	$MgSO_4 \cdot 7H_2O$	0.25	0.25	0.50	
Hoagland and Snyder (1933)[a]	KNO_3		0.31		
	$Ca(NO_3)_2$		0.82		
	$MgSO_4 \cdot 7H_2O$		0.49		
	KH_2PO_4		0.136		
	Ferric tartrate, 1 mL/L of 0.5% solution				
	Micronutrients: A to Z solution				
Trelease and Trelease (1933)[a]	KNO_3	0.683			
	$(NH_4)_2SO_4$	0.0679			
	KH_2PO_4	0.3468			
	K_2HPO_4	0.01233			
	$CaCl_2$	0.4373			
	$MgSO_4 \cdot 7H_2O$	0.7478			
	$FeSO_4 \cdot 7H_2O$	0.00278			
		a	b	c	Modified Crone's
The original Rothamsted solutions[a]	KNO_3	1.0	1.0	1.0	1.0
	$MgSO_4 \cdot 7H_2O$	0.3	0.3	0.5	0.5
	KH_2PO_4	0.45	0.4	0.3	—
	K_2HPO_4	0.0675	0.133	0.27	—
	$CaSO_4 \cdot 2H_2O$	0.5	0.5	0.5	0.5
	$Ca_3(PO_4)_2$	—	—	—	0.25
	$Fe_3(PO_4)_2 \cdot 8H_2O$	—	—	—	0.25
	$FeCl_3$	0.04	0.04	0.04	—
	H_3BO_3	0.001	0.001	0.001	0.001
	$MnSO_4 \cdot 4H_2O$	0.001	0.001	0.001	0.001
Arnon (1938)[a]	KNO_3		0.656		
	$Ca(NO_3)_2$		0.656		
	$NH_4H_2PO_4$		0.115		
	$MgSO_4 \cdot 7H_2O$		0.49		

Table 7.14 List of Formulas for Constituting Nutrient Solutions from the Early Literature on Hydroponics (continued)

Name	*Reagents*	*g/L (mg/mL)*
	$FeSO_4 \cdot 7H_2O$	0.5%
	Tartaric acid, 0.4%	0.06 mL/1.3x weekly
	H_3BO_3	2.86 mg
	$MnCl_2 \cdot 4H_2O$	1.81 mg
	$CuSO_4 \cdot 5H_2O$	0.08 mg
	$ZnSO_4 \cdot 7H_2O$	0.22 mg
	$H_2MoO_4(MoO_3 + H_2O)$	0.09 mg
Arnon and Hoagland (1940)[a]	KNO_3	1.02
	$Ca(NO_3)_2$	0.492
	$NH_4H_2PO_4$	0.230
	$MgSO_4 \cdot 7H_2O$	0.49
	See Arnon's Micronutrient Formula	
Shive and Robbins (1942) 1[a]	$Ca(NO_3)_2$	0.938
	$(NH_4)_2SO_4$	0.0924
	KH_2PO_4	0.313
	$MgSO_4 \cdot 7H_2O$	0.567
	$FeSO_4 \cdot 7H_2O$	5.50 mg
	H_3BO_3	0.57 mg
	$MnSO_4 \cdot 4H_2O$	0.57 mg
	$ZnSO_4 \cdot 5H_2O$	0.57mg
Shive and Robbins (1942) 1[a]	$NaNO_3$	0.34
	$CaCl_2$	0.1665
	KH_2PO_4	0.214
	$MgSO_4 \cdot 7H_2O$	0.514
	Iron and micronutrients as in I	
Piper (1942) 1[a]	KNO_3	1.3
	KH_2PO_4	0.3
	NaCl	0.1
Basic Formula, Bengal, India[b]	$NaNO_3$	0.17
	$(NH_4)_2SO_4$	0.08
	$CaSO_4$	0.04
	$CaHPO_4$	0.10
	K_2SO_4	0.11
	$MgSO_4 \cdot 7H_2O$	0.07
Rivoira's Formula, Sassari, Sicily[b]	$(NH_4)_2HPO_4$	0.20
	$Ca(NO_3)_2$	0.50
	KNO_3	0.20
	$MgSO_4 \cdot 7H_2O$	0.10
	FeEDTA	5.13 mg
	$MnSO_4 \cdot H_2O$	0.73 mg
	$ZnSO_4 \cdot 5H_2O$	0.06 mg

Table 7.14 List of Formulas for Constituting Nutrient Solutions from the Early Literature on Hydroponics (continued)

Name	*Reagents*	*g/L (mg/mL)*
	$ZnSO_4 \cdot 5H_2O$	0.06 mg
	$CuSO_4 \cdot 5H_2O$	0.06 mg
	H_3BO_3	0.59 mg
Wroclaw Formula, Poland[b]	KNO_3	0.6
	$Ca(NO_3)_2$	0.7
	NH_4NO_3	0.1
	$CaHPO_4$	0.5
	$MgSO_4 \cdot 7H_2O$	0.25
	$Fe_2(SO_4)_3$	0.12
	H_3BO_3	0.60 mg
	$MnSO_4 \cdot H_2O$	0.60 mg
	$ZnSO_4 \cdot 5H_2O$	0.06 mg
	$CuSO_4 \cdot 5H2O$	0.30 mg
	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	0.06 mg
Volcani Institute, Israel[b]	KNO_3	0.45
	NH_4NO_3	0.35
	$MgSO_4 \cdot 5H_2O$	0.05
	H_3PO_4	100 mL
Penningsfield's North African Formula[b]	KNO_3	0.38
	$Ca(NO_3)_2$	0.21
	$NH_4H_2PO_4$	0.04
	KH_2PO_4	0.14
	$MgSO_4 \cdot 7H_2O$	0.19
	$Fe_2(SO_4)_3$	0.01
	$Na_2B_4O_7 \cdot 10H_2O$	2.5 mg
	$MnSO_4 \cdot H_2O$	2.5 mg
	$CuSO_4 \cdot 5H_2O$	2.5 mg
	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	0.75 mg
	$ZnSO_4 \cdot 5H_2O$	0.02 mg
USDA Formula[b] Maryland (See below for Micronutrient Formula)	KNO_3	0.52
	$(NH_4)_2SO_4$	0.088
	$CaSO_4$	0.22
	$MgSO_4 \cdot 7H_2O$	0.40
	$CaSO_4$	0.43
Ag. Extension Service[b] Florida (See below for Micronutrient Formula)	KNO_3	0.36
	$(NH_4)_2SO_4$	0.08
	$CaHPO_4$	0.17
	$MgSO_4 \cdot 7H_2O$	0.16
	$CaSO_4$	0.90

Table 7.14 List of Formulas for Constituting Nutrient Solutions from the Early Literature on Hydroponics (continued)

Name		*Reagents*	*g/L (mg/mL)*
Micronutrient Formula[b] for USDA and Ag. Extension Service		$Fe_2(SO_4)_3$	9.50 mg
		$MnSO_4 \cdot H_2O$	0.63 mg
		$CuSO_4 \cdot 5H_2O$	0.29 mg
		$Na_2B_4O_7 \cdot 10H_2O$	7.20 mg
		$ZnSO_4 \cdot 5H_2O$	0.29 mg
Micronutrients	A.	$Al_2(SO_4)_8$	0.055
		KI	0.027
		KBr	0.027
		TiO_2	0.055
		$SnCl_2 \cdot 2H_2O$	0.027
		LiCl	0.027
		$MnCl_2 \cdot 4H_2O$	0.38
		H_3BO_3	0.61
		$ZnSO_4 \cdot 5H_2O$	0.055
		$CuSO_4 \cdot 3H_2O$	0.055
		$NiSO_4 \cdot 6H_2O$	0.055
		$Co(NO_3)_2 \cdot 6H_2O$	0.055
	B.	As_2O_3	0.0055
		$BaCl_2$	0.027
		$CdCl_2$	0.0055
		$Bi(NO_3)_2$	0.0055
		Rb_2SO_4	0.0055
		K_2CrO_4	0.027
		KF	0.0035
		$PbCl_2$	0.0055
		$HgCl_2$	0.0055
		MoO_3	0.023
		H_2SeO_4	0.0055
		$SrSO_4$	0.027
		VCl_3	0.0055
Arnon's Micronutrient Formula[a]		H_3BO_3	0.48 mg/L
		$MnSO_4 \cdot H_2O$	0.25 mg/L
		$ZnSO_4 \cdot 5H_2O$	0.035 mg/L
		$CuSO_4 \cdot 3H_2O$	0.008 mg/L
		$MoO_3 \cdot 2H_2O$	0.1104 mg/L

Sources: [a] Hewitt, E.J. 1966. Sand and Water Culture Methods Used in the Study of Plant Nutrition, Technical Communication No. 22, Revised, Commonwealth Agricultural Bureaux, Maidstone, Kent, England.

[b] Douglas, J.S. 1976. *Advanced Guide to Hydroponics*, Drake Publishers, New York.

Table 7.15 Nutrient Element Concentration Range of Common Nutrient Solutions

	Range in Concentration, ppm				
Element	Barry (1996)[a]	Jones (1997)[b]	Yuste/ Costincar (1999)[e]	10[a] (5)[d]	11[a] (5)[e]
Nitrogen (N)	70 to 250	100 to 200	47 to 284 (NO_3-N) 14 to 33 (NH_4-N)	140 to 300	100 to 200
Phosphorus (P)	15 to 80	30 to 50	4 to 448	31 to 80	15 to 90
Potassium (K)	150 to 400	100 to 200	65 to 993	160 to 300	80 to 350
Calcium (Ca)	70 to 200	100 to 200	50 to 500	100 to 400	122 to 220
Magnesium (Mg)	15 to 80	30 to 70	22 to 484	24 to 75	26 to 96
Sulfur (S)	20 to 200		32 to 640	32 to 400	
Boron (B)	0.1 to 0.6	0.2 to 0.4	0.1 to 1.0	0.06 to 1.0	0.4 to 1.5
Copper (Cu)	0.05 to 0.3	0.01 to 0.1	0.005 to 0.15	0.02 to 0.75	0.07 to 0.1
Iron (Fe)	0.8 to 6.0	2 to 12	Trace to 20	0.75 to 5.0	4 to 10
Manganese (Mn)	0.5 to 2.0	0.5 to 2.0	0.1 to 1.67	0.1 to 2.0	0.5 to 1.0
Molybdenum (Mo)	0.05 to 0.15	0.05 to 0.20	0.001 to 2.5	0.001to0.04	0.05 to 0.06
Zinc (Zn)	0.1 to 0.5	0.05 to 0.10	0.05 to 0.59	0.04 to 0.7	0.5 to 2.5

[a] Barry, Carl, 1996, Nutrients: *The Handbook of Hydroponic Nutrient Solutions*, Casper Publications Pty Ltd., Narrabeen, NSW, Australia.

[b] Jones J. Benton, Jr. 1997, *Hydroponics: A Practical Guide for the Soilless Grower*, S Lucie Press, Boca Raton, FL.

[c] Yuste M.P. and Gostincar J. (Eds.), 1999, Handbook of Agriculture, Marcel Dekker, New York, NY.

[d] *Growing Edge*, 1999, 10(5):13

[e] *Growing Edge*, 2000, 11(5):25

Sources: Barry, Carl., 1996, Nutrients: *The Handbook of Hydroponic Nutrient Solutions*, Casper Publications Pty Ltd., Narrabeen, NSW, Australia; Jones, J. Benton, Jr., 1997, *Hydroponics: A Practical Guide for the Soilless Grower*, St. Lucie Press, Boca Raton, FL; Yuste and Gostincar (Eds.), 1999, Handbook of Agriculture, Marcel Dekker, New York, NY.

for "optimum production of disease-free greenhouse tomatoes, cucumbers, and other crops:"

- Using a properly balanced nutrient solution in the rooting zone
- Adjusting the pH to an optimum range favorable for plant use
- Having no ions present in toxic amounts or at levels that may interfere with other ions
- Holding the total salt concentration in the nutrient solution within 1500 to 4000 ppm
- Having a well-aerated rooting medium and maintaining the environmental temperature within the range of about 65 to 75°F (18 to 24°C)

Table 7.16 Major Element and Micronutrient Ionic Forms and Normal Concentration Range Found in Most Nutrient Solutions

Element	*Ionic Form*	*Concentration Range*[a], *mg/L, ppm*
Major Elements		
Nitrogen (N)	NO_3^-, NH_4^+[b]	100 to 200
Phosphorus (P)	HPO_4^{2-}, $H_2PO_4^-$[c]	30 to 15
Potassium (K)	K^+	100 to 200
Calcium (Ca)	Ca^{2+}	200 to 300
Magnesium (Mg)	Mg^{2+}	30 to 80
Sulfur (S)	SO_4^{2-}	70 to 150
Micronutrients		
Boron (B)	BO_3^{3-}[d]	0.30
Chlorine (Cl)	Cl^-	—
Copper (Cu)	Cu^{2+}	0.01 to 0.10
Iron (Fe)	Fe^{2+}, Fe^{3+}[e]	2–12
Manganese (Mn)	Mn^{2+}	0.5 to 2.0
Molybdenum (Mo)	MoO_4^-	0.05
Zinc (Zn)	Zn^{2+}	0.05 to 0.50

[a] Concentration range based on what is found in the current literature.

[b] Urea in a nutrient solution formulation can be directly taken up by plant roots.

[c] Ionic form depends on the pH of the nutrient solution.

[d] The molecule boric acid (H_3BO_3) can be absorbed by plant roots.

[e] Ionic form depends on the pH and O_2 level in the nutrient solution.

All systems of nutrient solution management, whether open or closed, must lend themselves to precise control of the nutrient solution composition so that the concentration of elements can be varied in response to both known physiologic stages of the developing plant and the grower's sense of the condition of the crop (Schon, 1992). When beginning, it is advisable to have the constituted nutrient solution assayed by means of a laboratory analysis. Such an analysis ensures that all of the elements in the nutrient solution are at concentrations specified in the formula.

It is very important in a closed recirculating hydroponic system to add water to the nutrient solution in order to maintain its original volume. In addition, some elements will have been removed along with the water; these elements can be included in the make-up water. The question is "how much of which elements should be added?" A common practice is to use an electrical conductivity (EC) measurement of the nutrient solution as a means of determining what level of replenishment is needed. Surprisingly, this technique works fairly well. Unfortunately, such a measurement does not determine what differential change in elemental concentration may have taken place in order to enable the grower to add back what was removed element by element.

Table 7.17 Articles Published in *The Growing Edge* Magazine between 1990 and 2002 Relating to Nutrient Solutions and Their Management

Volume (Number)			
Page	*Year*	*Title*	*Author*
1(1):53	1990	Nutrient Solution Management	Erikson
1(2):47	1990	The Chemical Dynamics of Hydroponic Nutrient Solutions	Brooke
4(2):50	1992–1993	The Role of Gases in Nutrient Solutions	Thomas
4(2):60	1992–1993	Hydroponic Solutions for Beginners	Parker
4(4):18	1993	Hydro-Organics — Organic Hydroponic Systems	Thomas
5(3):45	1994	Check your Nutrient IQ	Brooke
8(1):21	1996	Extending the Life of Your Nutrient Solution	Thomas
9(2):32	1997	Organic Fertilizers for Hydroponics	Morgan
9(4):25	1998	The pH Factor in Hydroponics	Morgan
9(4):43	1998	The Modified Steiner Solution — A Complete Nutrient Solution	Faulkner
9(5):25	1998	Electrical Conductivity in Hydroponics	Morgan
10(1):87	1998	Slow-Release Nutrient Amendment Mix	Faulkner
11(3):40	2000	Beneficial Elements for Hydroponics: A New Look at Plant Nutrition	Morgan
12(5):32	2001	Organic Hydroponics	Martins/Karam
13(1):60	2001	Creating Your Own Nutrient Solution	Musgrave
13(1):68	2001	Nutrient Solution Dosers: Automation for Recirculation	Christian
13(6):39	2002	Greenhouse Nutrient Management: Regulations and Treatment Options	Johnson
14(1):63	2002	Hydroponics and Humates: Ancient Acids for Modern Agriculture	Vasilenko

Such a determination requires a complete elemental analysis of the nutrient solution (Chapter 13).

The elements that are most likely to show the greatest change in the nutrient solution with use are N and K. A possible rule of thumb would be to dilute the initial nutrient solution formula for the major elements only and add that as the make-up water, making this solution about one-quarter to one-third the strength of the original nutrient solution. Some experimenting and testing will be necessary to determine what that proper strength should be to

Table 7.18 Basic Nutrient Formula for General Use

Reagent	*Formula*	*Grams*	*Ounces*
Bag A			
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$	2000	70.60
Bag B			
Potassium nitrate	KNO_3	2275	80.25
Magnesium sulfate	$MgSO_4{\bullet}7H_2O$	1757	62.00
Potassium phosphate	KH_2PO_4[a]	878	31.00
Iron chelate (EDTA)		132	4.65
Manganese sulfate	$MnSO_4$	24.5	0.864
Boric acid	H_3BO_3	6.0	0.200
Copper sulfate	$CuSO_4{\bullet}5H_2O$	2.0	0.070
Zinc sulfate	$ZnSO_4{\bullet}5H_2O$	1.5	0.053
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\bullet}4H_2O$	0.35	0.0125

To use: To 10 L (2.65 gal) of water, add 1 level teaspoon of Bag A, stir until dissolved, and then add 1 level teaspoon of Bag B and stir to dissolve.

[a]Assumed formula

Source: Smith, R., 1999, *The Growing Edge* 11(1):14–16.

Table 7.19 Basic Nutrient Formula for Popular Hydroponic Gardens

Reagent	*Formula*	
Nutrient A (Macro)		**g per 10 L**
Monoammonium phosphate	$NH_4H_2PO_4$	340
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$	2080
Potassium nitrate	KNO_3	1100
Nutrient B (Micro)		**g per 4 L**
Magnesium sulfate	$MgSO_4{\bullet}7H_2O$	492.00
Manganese sulfate	$MnSO_4{\bullet}4H_2O$	2.48
Boric acid	H_3BO_3	6.20
Copper sulfate	$CuSO_4{\bullet}5H_2O$	0.48
Zinc sulfate	$ZnSO_4{\bullet}7H_2O$	1.20
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\bullet}4H_2O$	0.02
Iron chelate (EDTA)		8.46

To use: Mix 5 mL of Nutrient A (Macro) and 2 mL of Nutrient B (Micro) in 1 L of water.

Source: Bradley, P. and Tabares, C.H.M., 2000, *Spreading Simplified Hydroponics: Home Hydroponic Gardens*, Global Hydroponics Network, Corvallis, OR.

Table 7.20 General Purpose Hydroponic Nutrient Solution Formulation

Reagent	*Formula*	*Quantity (g)*
Part A		
Calcium nitrate	$Ca(NO_3)_2 \bullet 4H_2O$	13,110
Potassium nitrate	KNO_3	2557
Iron chelate		500
Part B		
Potassium nitrate	KNO_3	2557
Monopotassium phosphate	KH_2PO_4	3567
Magnesium sulfate	$MgSO_4 \bullet 7H_2O$	6625
Manganese sulfate	$MnSO_4 \bullet 4H_2O$	121
Zinc sulfate	$ZnSO_4 \bullet 7H_2O$	11
Boric acid	H_3BO_3	39
Copper sulfate	$CuSO_4 \bullet 5H_2O$	3
Ammonium molybdate	$(NH_4)_6Mo_7O_{24} \bullet 4H_2O$	1.02

To prepare: Dissolve in two 26-gallon (100-L) stock solution tanks.

To use: Dilute 1:100 of both Part A and B, EC = 2.5, TDS = 1806.

Source: Morgan, L., 2002e, *The Growing Edge* 14(1):11.

Table 7.21 Composition of Some Common Nutrient Solution Formulations (mg/L)

Element	Hoagland	*Nutri-Sol*	*Miracle-Gro*
Nitrogen (total)	210	210	210
as nitrate (NO_3)	210	135	0
as ammonium (NH_4)	0	45	96
as urea	0	30	114
Phosphorus (P)	31	65	181
Potassium (K)	235	249	174
Calcium (Ca)	200	54	0
Magnesium (Mg)	48	9	0
Sulfur(S)	64	15	0
Iron (Fe)	5	2.3	1.4
Boron (B)	0.5	0.3	0
Manganese (Mn)	0.05	1.2	0.7
Zinc (Zn)	0.05	0.8	0.7
Copper (Cu)	0.02	0.8	0.7
Molybdenum (Mo)	0.01	0	0
Chlorine (Cl)	0.6	Trace	Trace

Source: Hershey, D.R., 1990, *The Science Teacher* 57:42–45.

Table 7.22 Nutrient Solution Elemental Concentrations in Solution for Commercial Greenhouse Vegetable Production

Reagent	*Johnson*	*Jensen*	*Larson*	*Cooper*
	Amount (g/100 gallons Water)			
Potassium nitrate	95	77	67	221
Monopotassium phosphate	54	103	—	99
Potassium magnesium sulfate	—	—	167	—
Potassium sulfate	—	—	130	—
Calcium nitrate	173	189	360	380
Magnesium sulfate	95	187	—	194
Phosphoric acid (75%)	—	—	40 mL	—
Chelated Iron (FeDTPA)	9	9.6	12	30
Boric acid	0.5	1.0	2.2	0.6
Copper sulfate	0.01	0.5	0.15	
Copper chloride	—	0.05	—	—
Manganese sulfate	0.3	0.9	1.5	2.3
Zinc sulfate	0.04	0.15	0.5	0.17
Molybdic acid	0.005	0.02	0.04	—
Ammonium molybdate	—	—	—	0.14
Major Elements	*Concentration in Solution, mg/L (ppm)*			
Nitrogen (N)	105	106	172	236
Phosphorus (P)	33	62	41	60
Potassium (K)	138	156	300	300
Calcium (Ca)	85	93	180	185
Magnesium (Mg)	25	48	48	50
Sulfur (S)	33	64	158	68
Micronutrients				
Boron (B)	0.23	0.46	1.0	0.3
Copper (Cu)	0.01	0.05	0.3	0.1
Iron (Fe)	2.3	3.8	3.0	12.0
Manganese (Mn)	0.26	0.81	1.3	2.0
Molybdenum (Mo)	0.007	0.03	0.07	0.2
Zinc (Zn)	0.024	0.09	0.3	0.1

Source: Lorenz, O.A. and Maynard, D.N., 1988, *Knott's Handbook for Vegetable Growers*, 3rd ed., John Wiley & Sons, New York, NY.

avoid creating an ion imbalance by adding back too much or too little. The micronutrients should never be included in the make-up nutrient solution; this minimizes the possible danger from excesses. Phosphorus is also an element that should possibly be excluded from the make-up solution. Recommendations for the composition of make-up water will be given later for particular hydroponic growing systems.

Table 7.23 Recommended Major Element Concentrations in Nutrient Solutions by Crop

	Major Elements, mg/L (ppm)				
Crop	*Nitrogen*	*Phosphorus*	*Potassium*	*Calcium*	*Magnesium*
Cucumber	230	40	315	175	42
Eggplant	175	30	235	150	28
Herbs	210	80	275	180	67
Lettuce	200	50	300	200	65
Melon	186	39	235	180	25
Pepper	175	39	235	150	28
Tomato	200	50	360	185	45

Source: Schon, M., 1992, in D. Schact (Ed.), Proceedings of the 13th Annual Conference on Hydroponics, Hydroponic Society of America, San Ramon, CA.

Table 7.24 Nutrient Solution Formulas for the Hydroponic Production of Tomato, Lettuce, and Rose

Reagent (Fertilizer Grade, g/100 L)	*Tomato*	*Lettuce*	*Rose*
Major Elements			
Calcium nitrate (15.5-0-0)	680	407	543
Magnesium sulfate	250	185	185
Potassium nitrate (13-0-44)	350	404	429
Potassium chloride (0-0-60)	170	—	—
Monopotassium phosphate (0-53-34)	200	136	204
Ammonium nitrate (33.5-0-0)	—	60	20
Micronutrients			
Iron chelate (10% Fe)	15.0	19.6	19.6
Manganese sulfate (28% Mn)	1.78	0.960	3.9
Boron (Solubor) (20.5% B)	2.43	0.970	1.1
Zinc sulfate (36% Zn)	0.280	0.552	0.448
Copper sulfate (25% Cu)	0.120	0.120	0.120
Sodium molybdate (39% Mo)	0.128	0.128	0.128

Source: van Zinderen Bakker, E.M., 1986, in Proceedings 7th Annual Conference on Hydroponics: The Evolving Art, the Evolving Science, Hydroponic Society of America, Concord, CA.

Another factor that must be considered is what elements were being left behind in the rooting medium; the amount will vary depending on the medium characteristics, the composition of the nutrient solution, and the frequency of recirculation. An important measurement that is recommended with some growing systems is to periodically take from an access port an aliquot of solution from the rooting medium, or of that flowing from it, and then determine its EC. At some designated EC reading, the rooting medium would then be leached with water to remove accumulated salts.

Anyone who has used gravel as a rooting medium, for example, may have noticed that with time a gray-white sludge (primarily precipitated calcium phosphate and calcium sulfate) begins to form, which may also entrap other elements, particularly the micronutrients. If one would run a hand through the gravel, the hand on removal will be coated with a light-gray colored sludge. The sludge can be a major source of elements for plant uptake irrespective of what is being added by means of the nutrient solution. This accumulation of sludge and its utilization by the plant can give rise to a gradual or sudden marked change in plant elemental content, which frequently is undesirable. Therefore, control of this type of accumulation needs to be part of the nutrient solution management program. The author recommends that a sample of the growing medium be collected and analyzed as one would a soil (Jones, 2001), and based on the assay results, the nutrient solution formulation should be modified. A grower, upon learning of a significant accumulation of some elements (mainly Ca, Mg, P, S, Fe, Mn, Cu, and Zn) in his gravel-sump growing system, altered his nutrient solution formulation, which consisted only of the elements K, N, and B in the nutrient solution being delivered to his tomato plants. This change resulted in significant savings in reagent costs and possibly avoided a potential nutrient element insufficiency from occurring.

pH

The "ideal pH" or "optimum pH range" for a nutrient solution stems mostly from data obtained from a combination of pH effects on nutrient element availabilities in soil (Figure 7.1) or soilless organic media (Figure 7.2) with those of the plant species itself. Argo and Fisher (2003) authored a comprehensive bulletin on "Understanding pH Management" which provides useful information on all aspects of pH measurement and pH effects on plants. Morgan (1998a) gives the optimum pH range for 22 crops that can be hydroponically grown; the desired range in pH among these 22 species was between 5.0 and 7.5. In general, the range in pH suggested for most hydroponic solutions and that in an inorganic growing medium is between 5.8 and 6.5. Most nutrient solutions, when initially constituted, will have a pH between 5.0 and 6.0. There have been very few experiments conducted that would specifically define the "ideal pH" or "optimum pH range" for a nutrient solution, no matter how the solution is to be employed. It should be remembered that the pH of a nutrient solution is dependent on such factors as temperature, content of inorganic and organic ions and substances, type of ions present, and CO_2 content. Diurnal fluctuations in pH occur as the result of the changing solubility of CO_2 in the nutrient solution; however, these changes are usually not of sufficient magnitude to warrant daily adjustment. At any one point in time, the pH of a nutrient solution will oscillate about a point that can vary by as much as a 0.5 pH unit. Those who would recommend continuously monitoring and altering the pH of a nutrient solution may find this recommendation both costly and of no real benefit to the growing crop.

If the nutrient solution needs pH adjustment, the adding of an acid or alkali, as the case requires, to either lower or raise the pH, respectively, can

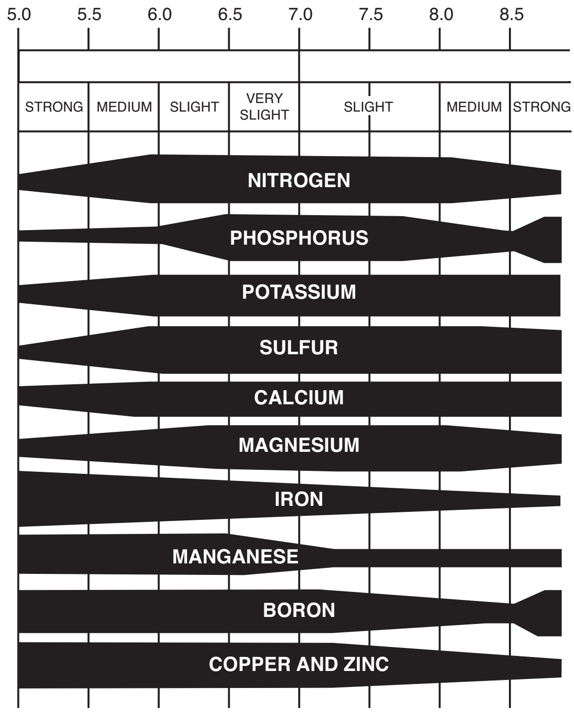

Figure 7.1 Effect of pH on the availability of the essential elements affecting root absorption in a mineral soil.

be made. A common procedure is to continuously monitor the pH of a nutrient solution when being dispensed and inject either acid or alkali as required into the flowing stream of nutrient solution. Solutions of either sodium or potassium hydroxide (NaOH and KOH, respectively) are suitable alkalis for raising the pH. Ammonium hydroxide (NH_4OH) can also be used; however, it is more difficult to handle safely, and the addition of the NH_4^+ ion to the nutrient solution may not be desirable. Nitric (HNO_3), sulfuric (H_2SO_4), and hydrochloric (HCl) acids can be used for lowering the pH. An advantage or disadvantage for the use of HNO_3 would be the addition of the NO_3^- anion. Phosphoric acid (H_3PO_4) can also be used, but its use would add P, which might not be desirable.

Therefore, those acids and alkalis that contain one or more of the essential elements are less desirable for use than those that do not contain such elements. Thus, NaOH is the preferred alkali, and either H_2SO_4 or HCl is the preferred acid even though they contain essential elements because their addition to the nutrient solution will have minimal effects. Commercially available pH control solutions for use in nutrient solutions are usually made from these reagents.

As stated earlier, nutrient solution pH and changes that can occur are influenced by many factors such as N source (NO_3^- versus NH_4^+), nutrient deficiency (e.g., P-deficient plants cause pH to decline), plant species, and plant growth stage. Ikeda and Osawa (1981) observed that 20 different

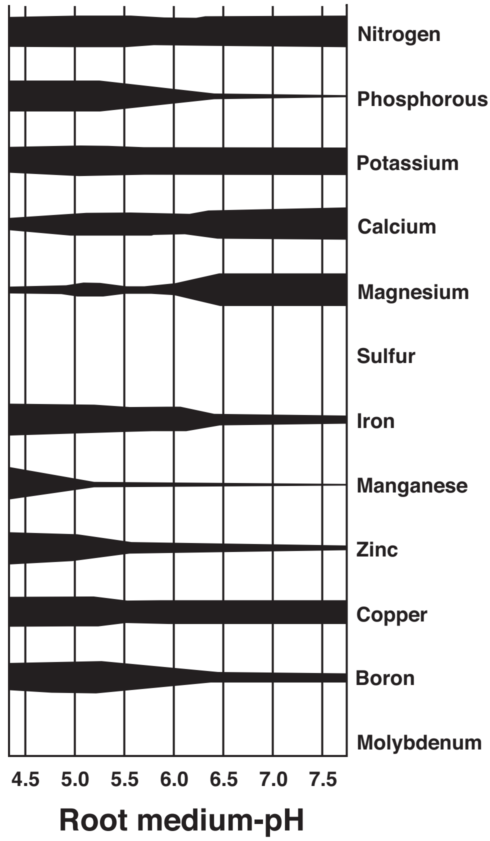

Figure 7.2 Effect of root medium pH on the availability of the essential elements affecting root absorption in an organic soilless mix. (*Source*: Agroand Fisher (2003)

vegetable species showed a similar N source preference for either NO_3^-- or NH_4^+-N when the pH of the nutrient solution was varied from 5.0 to 7.0. A considerable degree of pH control can be obtained by simply selecting a specific ratio of NO_3^- to NH_4^+ ions when the nutrient solution is initially prepared. If the ratio of NO_3^- to NH_4^+ is greater than 9 to l, the pH of the solution tends to increase with time, whereas at ratios of 8 to l or less, pH decreases with time, as illustrated in Figure 7.3. Hershey (1992) also studied the influence of the NO_3^- and NH_4^+ content of a nutrient solution on its pH as affected by plant growth (Table 7.25). Hershey also observed "that NH_4^+ tends to be much more acidifying in solution than NO_3^- in alkalinizing, therefore a relatively small percentage of the N as NH_4^+ is effective in stabilizing the nutrient solution pH."

Another means of control to minimize the pH and other effects is to use the chelated forms of the micronutrients whose forms and concentration levels have been identified by Wallace (1971, 1989).

Appropriate combinations of either mono- or dihydrogen phosphate salts (HPO_4^{2-} and $H_2PO_4^-$, respectively) of either Ca or K will also give some degree of pH control with time.

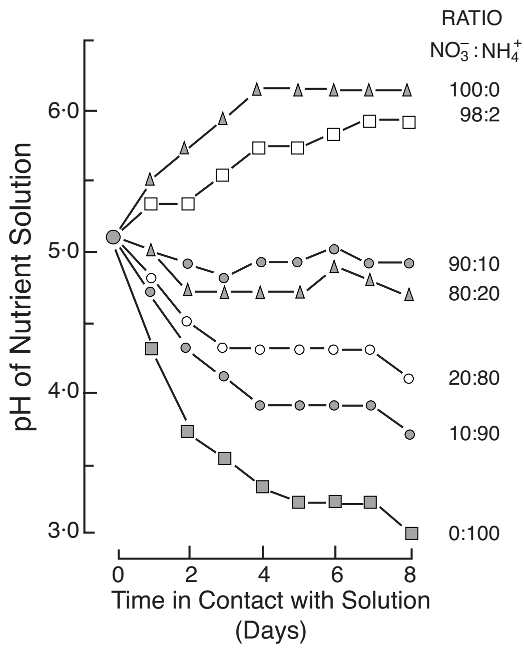

Figure 7.3 Effect of the ratio of nitrate- to ammonium-nitrogen on the rate and direction of pH changes in nutrient solutions in contact with the roots of wheat (*Triticum aestivium*) plants. (*Source*: Trelease, S.F. and Trelease, H.M., 1935, *Science* 78:438–439.)

Table 7.25 Situations in Which Plants Increase or Decrease Nutrient Solution pH

pH Change	*Solution*	*Species*
Increase	All N as NO_3^-	Most
Decrease	All N as NO_3^-	Some
Decrease	N as NH_4^+ or urea	Most
Decrease	All N as NO_3^-, no Fe	Fe-efficient
Decrease	All N as NO_3^-, no P	Some
Decrease	No N	Most
Decrease	No N	N_2 -fixing plants
Decrease	All N as NO_3^-	Shoot flushes, *Euonymus japonica*
Decrease	All N as NO_3^- Solution depleted	Most?
Decrease	All N as NO_3^-	Shoots in dark, *E. japonica*

Source: Hershey, D.R., 1992, *J. Biol. Educ.* 26(2):107–111.

As mentioned earlier (Chapter 4), some plants will effectively reduce the pH of the solution in the immediate vicinity of their roots. This acidification enhances their ability to absorb certain elements, probably the most important of which is Fe (Rodriguez de Cianzio, 1991). If the nutrient solution is constantly being adjusted upward to a neutral pH, it can interfere with the plant's natural ability to enhance its elemental ion-absorptive capability. Therefore, some have suggested that the pH of the nutrient solution should not be continuously adjusted but instead should be allowed to seek its own level naturally. This may be the desirable practice with those plant species sensitive to Fe when being grown hydroponically as well as other plant species that have a particular elemental sensitivity that is pH related.

pH control of the nutrient solution may be akin to nutrient solution filtering, discussed earlier. It may be that more has been made about pH control and its potential effect on plants than can be justified from actual experience. Therefore, the requirement for pH control becomes a management decision, balancing benefits gained versus costs to control. It is obvious that extremes exist that the pH of the nutrient solution should not be allowed to reach. What is needed to maintain the pH and prevent it from reaching those extremes may be academic, since those extremes are seldom reached with most nutrient solution formulas and their use.

Temperature

The temperature of the nutrient solution should never be less than the ambient air temperature, particularly in systems where plant roots are exposed to intermittent surges of a large volume of nutrient solution. On warm days, when the atmospheric demand on plants is high, root contact with nutrient solution below the ambient temperature can result in plant wilting, putting an undesirable stress on plants. Plant roots sitting in cool or cold nutrient solution cannot absorb sufficient water and elements to meet the demand of plant tops exposed to warm air and bright sunshine. Repeated exposure to cool nutrient solution results in plant growth and performance, below expected levels, evidenced by poor fruit set and quality and delayed maturity. In such circumstances, it may be necessary to warm the nutrient solution to avoid this stress. On the other hand, warming the nutrient solution above the ambient temperature is not recommended and may do harm to the crop.

Tindall et al. (1990) found that for greenhouse hydroponically grown tomato, when the ambient air temperature was 70°F (21°C), maximum nutrient element uptake occurred when the nutrient solution temperature was 80°F (26.7°C), while for maximum root and shoot growth, highest rate of shoot growth, and water uptake, the optimum root temperature was 77°F (25°C).

Electrical Conductivity (EC)

The EC of a nutrient solution as well as that in the growing medium can significantly affect plant growth. Most nutrient solution formulas have a fairly low [<3.0 dS/m (mmhos/cm)] EC when initially made. For example, the Hoagland/Arnon No. l nutrient solution given in Table 7.10 has an EC of 2.7 dS/m. The "salt effect" in a nutrient solution formulation can be minimized by selecting those compounds that have low salt indices (Table 7.26) when making the nutrient solution. It is with use and/or reuse that a soluble salt problem arises. This problem develops when substantial quantities of water are removed at a very rapid rate from the nutrient solution when in contact with plant roots, as happens on hot, low-humidity days. If the water loss is not replaced, the EC of the nutrient solution will rise. This becomes particularly acute if the nutrient solution is being recirculated and the water loss due to evapotranspiration is not immediately replaced.

An EC measurement of the nutrient solution can also be used to determine the nutrient element replenishment level required to reconstitute the solution before reuse. From previous determinations, the amount of replenishment solution required to be added to the nutrient solution would be based on that EC measurement. Although this system of nutrient solution management has worked reasonably well, it does not take into account individual losses of elements from the nutrient solution by root absorption or retained in the rooting media. Therefore, replenishment based on an EC measurement may not fully reconstitute the nutrient solution in terms of its elemental composition.

In rockwool and perlite bag culture, for example, measurement of the EC of an aliquot of the retained solution in the rockwool slab or perlite or the effluent from them can be used to determine when leaching would be required to remove accumulated salts.

The units of measurement for EC and related terms are as follows:

decisiemens per meter (dS/m)
millisiemens per centimeter (mS/cm)
microsiemens per centimeter (μS/cm)
(1 dS/m = 1 mS/cm = 1000 μS/cm = 1 mmho/cm)
(1 μS/cm = 0.001 dS/m)
EC (in dS/m) x 640 = TDS [in mg/L (ppm)]
(approximate measurement, depends on type of salt)
cf. (conductivity factor) of 10 = 1 dS/m

Oxygenation

The O_2 content of either a nutrient solution or the rooting medium will affect the rate of root activity and function, particularly the rate of water and nutrient element uptake. One of the major reasons that some NFT systems fail is due to the inability of the operating system to maintain sufficient O_2 in the ever-

Table 7.26 Relative Salt Index for Common Reagents Used for Preparing Nutrient Solutions

Reagent	*Formula*	*Relative Salt Index*
Ammonium nitrate	NH_4NO_3	104
Ammonium sulfate	$(NH_4)_2SO_4$	69
Calcium nitrate	$Ca(NO_3)_2•4H_2O$	52
Calcium sulfate	$CaSO_4•2H_2O$	8
Diammonium phosphate	$(NH_4)_2HPO_4$	29
Magnesium sulfate	$MgSO_4•7H_2O$	44
Monoammonium phosphate	$NH_4H_2PO_4$	34
Monocalcium phosphate	$CaHPO_4$	15
Monopotassium phosphate	KH_2PO_4	30
Potassium chloride	KC	116
Potassium nitrate	KNO_3	73
Potassium sulfate	K_2SO_4	46
Sodium nitrate	$NaNO_3$	100
Urea	$CO(NH_2)_2$	75

expanding root mass in the NFT trough. This is also why the length of the NFT trough can be a critical factor, as at the end of the run, little if any O_2 may remain in the passing nutrient solution. Attempts to oxygenate a nutrient solution prior to its introduction into the rooting medium have questionable value. Bubbling air or O_2 through a nutrient solution in an open environment will add some O_2 to the nutrient solution; the amount adsorbed depends on the temperature and composition of the nutrient solution. For example, even though a nutrient solution is saturated with O_2, its passage through a root mass or rooting medium can quickly strip all of the O_2 from it. Those plant roots in the initial contact position will benefit, those away will not.

The same NFT phenomenon will occur in vertical hydroponic/soilless culture growing systems (see page 148), as the nutrient solution being delivered at the top of the rooting medium column will be stripped of its O_2 content as it moves down through the medium column.

Methods and Timing of Nutrient Solution Delivery

The nutrient solution can be mixed at the application concentration desired for direct delivery to the rooting vessel, such as would be the case for ebb-and-flow, NFT, or aeroponics, as well as any system in which the nutrient solution is recovered after flowing through the rooting vessel for reuse. The other method is to make elemental concentrates and with the use of injectors (Figure 7.4-1 and 7.4-2), inject an appropriate aliquot of concentrate into a flowing water stream so that the final applied mix has the exact elemental composition specified in the nutrient solution formulations (Christian, 2001). This is the common method used for drip irrigation systems.

Figure 7.4–1 Dosatron dosers for dispensing stock nutrient solutions

The timing and techniques for delivering the nutrient solution to the roots of plants will play a role in determining its composition. For a nutrient solution application schedule based primarily on the demand of the crop for water, the grower may be applying a nutrient solution when the nutrient element demand by the plants is already satisfied — no additional nutrient elements at that specific time are needed. However, it is not the common practice to just apply nutrient-free water to the plants, although such a capability would be desirable. As discussed earlier, with increasing frequency of application of a nutrient solution, the concentration of the nutrient elements in solution should be lower (see Table 3.1). One could argue that on high-atmospheric-demand days when plants are rapidly transpiring, both water and nutrient element requirements would be near equal in terms of what is being supplied by the nutrient solution (assuming the nutrient solution formula is specifically made for these conditions, crop, etc.), while on less demanding days, the requirement for both is less but still equal. By not adjusting the nutrient solution composition, it is assumed that the proper balance is achieved

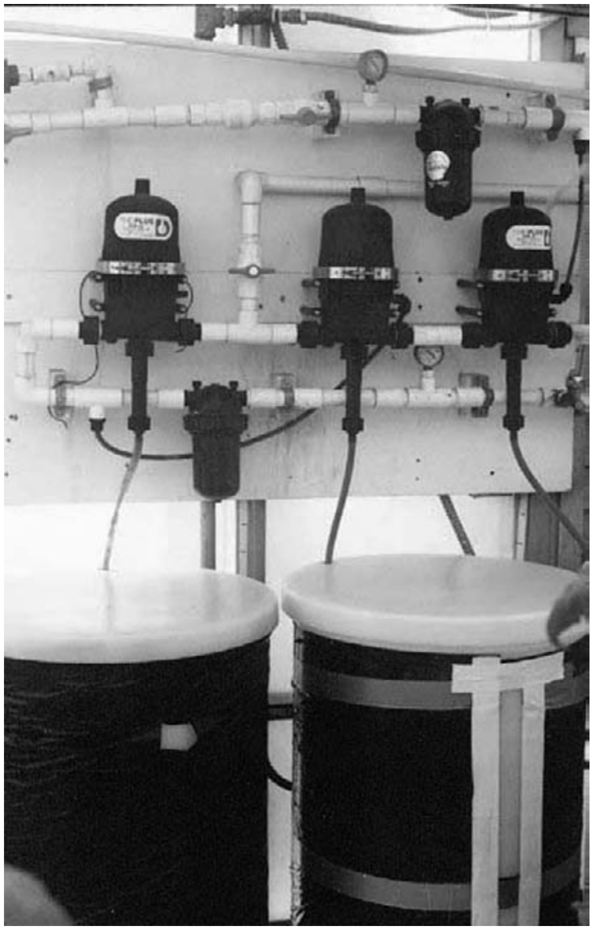

Figure 7.4–2 Dosers for dispensing stock nutrient solutions are shown in place over stock solution barrels. (Dosers are adjustable so that they can deliver a specific aliquot of stock nutrient solution into a flow of water for constituting a nutrient solution for delivery to plants. One doser is used for each stock nutrient solution.)

between water and nutrient element demand. Experience has shown that this concept is reasonably correct under most conditions. However, as the factors that relate to plant growth and development are better controlled, this assumed equal relationship between water demand and nutrient element need probably does not hold.

The size of the root mass is also a major factor that will affect water and nutrient element absorption (Barber and Bouldin, 1984). As the root surface increases, the influx of water and nutrient elements through the roots also increases. In hydroponic systems, one might ask "how large must the root mass be to ensure that the demand for water and nutrient elements is met?" Unfortunately, no one has adequately made such a determination. There is some evidence that suggests that the root mass is not as important as root activity and that a large root mass may actually be detrimental to best plant growth and development.

The most common method of nutrient solution delivery used today with bag, bucket (pot), and slab culture hydroponic systems is by means of drip irrigation, which provides an intermittent delivery of the nutrient solution at the base of the aerial portion of the plant, as shown in Figure 7.5.

Based on a predetermined schedule, nutrient solution flows from its reservoir out the end of the dripper; the frequency and rate of flow are usually based on stage of plant growth, atmospheric conditions, etc. When the dripper is on, the area around the point of delivery is saturated with nutrient solution; when off, the nutrient solution drains away, creating a changing root environment that may not be best for optimum plant growth and development. With the draining of nutrient solution away from the point of introduction, such is considered desirable since air is drawn into the rooting medium, bringing with it O_2. Usually, sufficient nutrient solution is applied so that the area immediately under the dripper is leached, pushing any unused accumulated nutrient elements deeper into the bag, bucket (pot), or slab. Normally, the bottom of the rooting vessel is open, which allows excess nutrient solution to flow out. Normally the access holes or cuts are slightly above the bottom of the growing vessel so that there is a shallow depth of accumulated nutrient solution that can be drawn on by the plant roots. Based on an analysis (usually a determination of EC) of a drawn solution sample from the medium or that exiting, water will be periodically applied through the dripper to leach the growing medium of any accumulated salts of retained unused nutrient elements.

In an ebb-and-flow hydroponic system, the nutrient solution is pumped from a reservoir into the growing medium, flooding it with solution for a short period, and then the nutrient solution is allowed to flow out of the rooting

Figure 7.5 Drip irrigation line (black tubing) placed at the base of a tomato plant growing in a rockwool cube set on a rockwool slab.

medium back into the reservoir (see page). This outflow of nutrient solution from the growing medium draws air into the rooting bed, providing a source of O_2. From the moist rooting medium, plants are able to obtain water and nutrient elements. Again, in such a system of nutrient solution delivery, the roots experience a changing environment, which may not be ideal for best plant growth and development, although plant performance is usually satisfactory with this hydroponic technique. In the rooting medium (coarse sand or gravel are the two common materials used for such systems), with time an accumulation of unspent nutrient elements occurs in the form of precipitates as the growing medium dries. The precipitate is primarily a mixture of calcium phosphate and calcium sulfate, which will also occlude other elements from the applied nutrient solution, i.e., the micronutrients. Since the precipitates are not removed from the rooting medium by water leaching, the medium will require intensive strong acid leaching for removal or the rooting medium will have to be replaced, as the accumulating precipitate will begin to significantly affect plant growth and development.

For standing aerated systems (see pages 123–127), roots are suspended in a continuously aerated nutrient solution. Depending on the volume of nutrient solution versus number of plants, the nutrient solution will significantly change, requiring periodic replenishing or replacement; a higher frequency of replenishment or replacement is needed with large numbers of plants and/or a small volume of nutrient solution. Failure to replenish or replace, when needed, will result in poor plant performance.

In NFT, the nutrient solution flows down a channel occupied by plant roots (see pages 127–141). As the distance from the point of introduction increases, the characteristics of the nutrient solution will significantly change; first the dissolved O_2 in the nutrient solution dissipates (Antkowiak, 1993), and a change in the elemental composition of the solution also occurs. Therefore, the length of flow is critical. As the root mass increases, the nutrient solution will tend to flow over or around the root mass rather than through it, which will significantly affect plant performance.

In vertical growing columns (see page 148), during the downward movement from the top of the column to the bottom, the nutrient solution will change considerably in elemental and O_2 content, as occurs in NFT systems. The length of the column and number of plants will determine the extent of change. Nutrient solution either applied on a timed schedule or based on atmospheric demand should be of sufficient volume to saturate the growing medium from top to bottom creating an outflow at the bottom of the column.

For the aeroponic system, the nutrient solution periodically bathes the roots with a fine mist of nutrient solution; the finer the mist, the better the plant performance (see pages 142–143). Oxygen deficiency is not a problem, but the frequency of misting must be sufficient to keep the roots supplied with sufficient water to meet the transpiration demand of the plant. Under high-atmospheric-demand conditions, a small reservoir of water or nutrient solution may be required at the base of the growing vessel so that the tips of the roots have access to this supply.

None of these commonly used nutrient solution delivery systems is without some undesirable aspect, although all are capable of delivering sufficient water and essential elements to sustain plant growth. The question is "which system will work best in terms of efficient use of water and nutrient elements, resulting in high plant performance?" The answer at this time is that none of them will, and the ideal delivery and utilization system has yet to be devised for commercial use.

Constancy

Maintaining the nutrient element status of the rooting medium at a constant level is not possible with the currently employed hydroponic/soilless growing systems. With each application of the nutrient solution to the rooting medium, the plant roots "see" a mix of nutrient elements from that remaining from previous nutrient solution applications and that being applied.

The benefits from maintaining a reasonable constancy of nutrient element concentration within the rooting medium were demonstrated in the following experiment. Snap beans were grown in pots in which perlite was the growing medium. The amount of water necessary to leach the entire perlite mass was determined as well as the retention volume. Each day prior to the hand application of an aliquot of nutrient solution, sufficient water was slowly applied to the perlite to replace what nutrient solution had been retained from the previous day's application. After allowing the water to drain from the perlite, an aliquot of nutrient solution was added based on that needed to replace the previously applied water. This routine was followed every day of the experiment. Plant growth and pod yield were considerably greater than that obtained in previous experiments either using the standing aerated nutrient solution method or in experiments where the nutrient solution was periodically dripped on the perlite as needed to provide sufficient water as well as the required nutrient elements.

The only current hydroponic method that comes reasonably close to maintaining a constancy of water and nutrient elements is aeroponics (see page 142–143). Unfortunately, aeroponics has not been widely adapted or used for a number of reasons. The work by the author on his GroSystem method comes close to maintaining consistency (see page 162–165).

Programmable Controllers

Numerous control systems are available for scheduling the dispensing of nutrient solutions. The controller may be a time clock, which is on a preset time schedule, and dispenses a certain volume of nutrient solution or it may be a complex system that is computer controlled, which dispenses nutrient solution based on a demand determination, such as measured accumulated radiation. In addition, the controller may command other functions, such as the mixing of pH adjuster solution into the flow of nutrient solution, or the addition of a certain reagent to alter the composition of the nutrient solution. Since this technology is continuing to change as new devices are made available, it would not be appropriate to describe a system that will soon be obsolete. The roles that these control devices have in crop management and greenhouse operations (Kano, 1995) are also discussed in Chapters 11 and 12.

Summary

There is no such thing as an "ideal" nutrient solution formulation; however, there may be one or two formulations that will work with most crops under a wide range of cropping and environmental conditions. The concept of balance among the cations and anions, as suggested by Steiner (1980, 1984), is worthy of further investigation. If a rapidly growing plant is placed into a standing aerated nutrient solution, that plant will quickly exhaust the nutrient solution of the K^+ and NO_3^- ions — primarily the monovalent cations and anions (and possibly B too), while most of the other elements in solution will change relatively little. This ease or lack of ease in uptake among the essential elements poses a challenge to the formulator to keep a nutrient solution in balance if its exposure to plant roots is lengthy. The ideal hydroponic growing system would be one in which the nutrient solution being supplied to the plant roots remains constant in its elemental composition. The NFT and aeroponic hydroponic growing methods approximate this condition of constancy. Asher and Edwards (1978a,b), in a series of interesting experiments, observed that if plants are grown in a rapidly moving nutrient solution of constant composition, the elemental concentration in the nutrient solution could be reduced significantly (see Table 3.1) while plant growth remained normal. In fact, they found that most elements, particularly P, became toxic to plants unless reduced to concentrations [<2.6 mg/L (ppm)] considerably less than that recommended in most nutrient solution formulas. What this indicates is that if plants can be grown in an infinite volume of nutrient solution so that plant uptake has no effect on the elemental concentration in solution, this would be the "ideal" hydroponic growing system.

It should be remembered that in medium-based hydroponic growing systems, and possibly to some extent in the NFT growing system, the plant is essentially drawing nutrient elements from three different nutrient element pools, that being currently supplied by applied nutrient solution, that which has remained in the rooting media solution as ions (this is what is determined by an EC measurement), and that which is accumulating as precipitates. All of these pools can play major roles in determining the elemental content of the plant. This is probably one of the major factors that contribute to nutrient element insufficiencies that will affect plant growth and fruit yield and quality. The objective of a nutrient element supply system should be to provide what is needed and no more or no less.

The quantity and balance approach developed by Geraldson (1963, 1982), although designed for soil-field-grown tomato, has potential application hydroponically. Such a system of approach has been found applicable to a soilless medium system for the production of a wide variety of greenhouse (Bruce et al., 1980) and garden vegetables (Jones, 1980). It is the basis for the *Aqua-Nutrient* growing system developed by GroSystems (see www.GroSystems.com). This system approaches the "ideal" since plant roots are essentially exposed to a constant supply of both water and the essential elements.

Some of the issues that arise with the current formulations and use of nutrient solutions are as follows:

1. In general, most nutrient solution formulations are not well balanced, particularly with regard to the major elements, N and K.
2. The total elemental concentration in most nutrient solutions is higher than can be justified in terms of meeting crop requirements. Most nutrient element insufficiencies in plants are due to ion imbalances in the applied nutrient solution rather than due to a deficiency of one or more elements.
3. The atmospheric demand should be a determinant of the total elemental concentration of a nutrient solution as well as a factor in determining the frequency of application (the higher the atmospheric demand, the lower the element ion concentration should be in the nutrient solution with increased frequency of application).
4. There is justification for designing the nutrient solution delivery system so that only water can be applied, particularly during periods when the plant atmospheric demand is high. Also being able to easily change the dilution ratio during the delivery of a nutrient solution would be a very useful factor.
5. The concentration of P in most nutrient solution formulations is about twice that needed and may be the primary cause for some plant nutrient insufficiencies among the micronutrients Cu, Fe, Mn, and particularly Zn.
6. The concentration of N in a nutrient solution may be the primary factor determining fruit yield and quality (the higher the N, the lower the fruit yield and poorer the fruit quality). In general, the N content of a nutrient solution should be at the lower end of the recommended formulation amount and should be adjusted based on atmospheric demand — the higher the demand, the lower the N concentration in the nutrient solution.
7. The ratio between K and Ca in a nutrient solution is probably a major factor determining fruit yield and quality. That nutrient solution elemental ratio for most crops should about 1 to 1.
8. The use of chelated micronutrients may be the primary cause for deficiencies of the micronutrients Cu and particularly Zn in plants.
9. Insufficient Zn in most nutrient solution formulations may be the primary cause for low Zn levels in the plant. It is recommended that the Zn amount be double that specified in most nutrient solution formulations. It should be remembered that high P in a nutrient solution will inhibit Zn uptake and distribution within the plant. The use of chelated Fe is also a contributor to lower Zn uptake and distribution within the plant.
10. The inclusion of NH_4-N in a nutrient solution formulation can enhance the uptake of NO_3-N, which can be either beneficial or detrimental. The amount of total N in a nutrient solution formulation can be reduced by 10 to 20% if 5% of the total N in the nutrient solution is NH_4.

11. The adjustment of the pH of a nutrient solution to a particular point is unjustified unless the pH is outside the desired range between 5.2 and 6.5. It should be remembered that the pH in the immediate area around plant roots is determined by the roots themselves.
12. The adjustment of a nutrient solution to a particular EC is probably not justified unless there is a compelling need to restrict water and nutrient element uptake.
13. The accumulation of elements as precipitates in the rooting medium, whether the medium is inorganic or organic, can have a significant effect on the plant's nutrition with time. Therefore, reducing the concentration of most elements is justified, particularly Ca, Mg, P, S, and Mn, in the nutrient solution being applied with time.
14. The requirement for leaching a rooting medium due to the accumulation of unused elements can be significantly reduced by carefully adjusting the nutrient solution formulation and frequency of application as well as having the ability to apply only water for meeting high atmospheric demand.
15. An EC measurement of the solution exiting the growing medium or that within is used to determine when the rooting medium requires water leaching. That requirement for leaching should be viewed as a warning signal that the quality of nutrient elements being applied at greater than that required by the crop. This leaching requirement can be significantly reduced if greater care is used in formulating and applying a nutrient solution — the ideal is that no water leaching is required. An elemental analysis of exiting or retained nutrient solution will indicate which elements are accumulating, providing guidance in reformulating the applied nutrient solution in order to minimize this accumulation.
16. The reuse of a rooting medium can pose a problem since that medium will start with a significant nutrient element charge from the accumulation of nutrient elements as precipitates that can not be removed by leaching.
17. In a closed nutrient solution system, the nutrient solution must be filtered and sterilized between applications.
18. A nutrient solution should be assayed for its elemental content when initially made to ensure that all the elements are within the specifications of the formulation. Errors in selecting and weighing ingredients and mixing when preparing stock solutions can be easily made, and the malfunctioning of dosers (see Figures 7.4-1 and 7.4-2) is not uncommon.

Chapter 8

Systems of Hydroponic/ Soilless Culture

A number of ways to grow plants by means of hydroponic/soilless culture exist. For the purposes of this book, the classification scheme offered by Dr. John Larsen of the Texas Agricultural Extension Service is followed. In his classification system, hydroponics is one distinct technique for plant growing where no root-supporting medium is used, whereas the other systems employ a rooting medium, either inorganic or organic. Larsen's classification system is given in Table 8.1; it has been modified to include several rooting media materials in common use today.

As indicated earlier, growing plants hydroponically is different for systems that employ a support or rooting medium compared to nonmedia systems. Management of the nutrient solution for these two classes of systems is quite different. It is important, however, to keep in mind not only the differences but also the similarities between these growing systems, as some of the management procedures can be successfully transferred, whereas others cannot.

Container Growing

All forms of hydroponic/soilless culture involve growing plants in some kind of a container — a bed, pot, bag, bucket, enclosed slab, or trough. The volume and dimensions of the rooting vessel are frequently chosen on the basis of convenience or availability. For example, in the past, the Number 10 food can was widely used because of its low cost and availability. More recently, so-called "gallon" and "2-gallon" (actual volumes are 3 and 6 quarts, respectively) containers have become popular. Today, growers are placing soilless medium in a free-standing plastic bag and using it as the growing container,

Table 8.1 Dr. John Larsen's Hydroponic/Soilless Culture Classification System

Hydroponics or Water Culture	*Media Culture*		
	Inorganic	*Organic*	*Mixtures*
1. Standing aerated	1. Gravel	1. Peat moss	1. Peat moss/vermiculite/perlite
2. Nutrient film technique	2. Sand	2. Pinebark	2. Pinebark/vermiculite/perlite
3. Aeroponics	3. Perlite	3. Sawdust	3. Peat moss/pinebark/perlite
	4. Rockwool	4. Coir	

or they are growing directly in the bag that is used to package and transport a soilless mix or perlite.

What should the volume and dimensions for the rooting vessel be, whether the vessel is a bag, slab, pot, bucket, trough, or bed, in order to provide adequate space for normal root growth and development? The answer to that question, as far as most hydroponic/soilless growing systems are concerned, has not been adequately determined. It is surprising how little good information is available on the importance of rooting volume required by plants and the relationship that exists between rooting habit, rooting medium, and container environment and volume. A brief discussion of roots and their effect on plant growth and development was presented in Chapter 4.

Despite the uncertainties about the relationship between rooting vessel size and plant performance, there are some guidelines that will assist the grower in determining the rooting volume needed for the crop and system being employed:

1. For all containers, the depth should be one-and-a-half to two times the diameter of the surface area covered by the plant canopy when the plant reaches its maximum size. For example, if the canopy covers (or will cover) a surface area 12 inches (30 cm) in diameter, the growing container should be 18 to 24 inches (46 to 61 cm) deep.
2. In bed culture systems, increased spacing between plants can, in part, substitute for a lesser depth. For example, plants with a canopy occupying a surface area 12 inches (30 cm) in diameter growing in a bed less than 12 inches (30 cm) deep should be spaced 18 inches (46 cm) from one plant center to another. This ratio of 2 to 3 can be applied to plants with smaller or larger canopies when growing in bed systems.

It is generally accepted that roots of neighboring plants inhibit each other's growth. Therefore, close contact and intermingling of roots between neighboring plants (the result of close spacing or shallow rooting depth) should be minimized by providing the proper area and depth required.

Some feel that the present lack of knowledge about root growth in varying environments restricts our knowledge of plant growth in general. The consequence for the hydroponic/soilless culture grower is that he or she must experiment with the growing system to determine the rooting volume required to obtain maximum plant performance. Beginning with the recommendations given above, plants can be spaced closer together until a significant change in plant growth and yield appears.

Needless to say, root volume requirement becomes academic when plants must be widely spaced to allow sufficient light to penetrate the plant canopy for those plants that are widely branched and/or grow tall. However, the trend today is grow in the minimum of medium to reduce cost.

Media Hydroponic/Soilless Culture

From 1930 to the late 1950s, gravel or sand was commonly used as the rooting medium in closed recirculating ebb-and-flow commercial soilless culture systems. For small home hydroponic units, gravel, lava rock, expanded clay, or Hadite are the materials selected for use as the rooting medium. For the commercial hydroponic systems of today, perlite and rockwool are the most commonly used inorganic rooting media materials.

A wide variety of various organic rooting media materials are used today, most of which are combinations of various materials, primarily mixtures containing peat moss and/or composted milled pinebark or peat moss and composted milled pinebark mixed with inorganic substances, such as vermiculite and perlite. The formulations in common use today are presented in detail in Chapter 10.

The use of a rooting medium, whether inorganic or organic, poses a set of challenges. Although the medium itself may be inert, such as gravel, sand, perlite, or rockwool, it harbors pore spaces that will hold nutrient solution, which may eventually be absorbed by plant roots; the elements move with the solution by mass flow or by diffusion within the solution and are also reached by root extension (growth) (see Chapter 3). Organic media, such as peat moss and composted milled pinebark, have similar pore spaces, as well as a cation/anion exchange capacity that can remove ions from the solution and hold them for later release into solution. In both types of media, a precipitate of elements can occur, essentially as a combination of calcium phosphate and calcium sulfate, which can also entrap other elements, mainly the micronutrients. Although this precipitate is essentially insoluble, portions can become soluble, which will then contribute to the essential element supply being delivered to the plant roots by repeated passage of the nutrient solution through the rooting medium.

Regulating Water and Nutrient Element Requirements

There are two basic systems of nutrient solution use:

- An "open" system in which the nutrient solution is passed through the rooting vessel and discarded
- A "closed" system in which the nutrient solution is passed through the rooting vessel and then collected for reuse

Both systems have advantages and disadvantages. The major disadvantage to the "open" system is its inefficiency due to the loss of water and unused essential elements, since the flow of the nutrient solution is greater than that required by the plants. For the "closed" system, the nutrient solution can be substantially changed when passed through the rooting vessel, requiring some adjustment in volume (replacement of lost water) and pH and replenishment of absorbed essential elements (Hurd et al., 1980). In addition, any disease or other organisms picked up by the nutrient solution in its passage through the rooting vessel will be recirculated into the entire system unless removed or inactivated by some form of nutrient solution treatment. The controls and requirements for a recirculating hydroponic system have been discussed by Wilcox (1991), Schon (1992), and Bugbee (1995).

The nutrient solution is expected to provide both water and the essential elements needed by the plant in its flow through the rooting vessel. It is easily and erroneously assumed that these two physiological requirements, the need for both water and essential elements, occur in tandem. On warm days when plants are transpiring rapidly, however, only water may be needed to meet the atmospheric demand, while the nutrient elements in the nutrient solution may not be required by the crop in other than their usual amounts. The consequence is that the need for water is out of phase with the feeding cycle. This juxtaposition of events poses a major problem, as it is not common to have a water-only system operating in parallel with the nutrient solution delivery system. Therefore, increasing the circulation of the nutrient solution to meet the demand for water may lead to an elemental imbalance and an undesirable accumulation of unwanted elements.

With automatic control (Bauerle et al., 1988; Berry, 1989; Bauerle, 1990; Edwards, 1994) and an "open" system, it is possible to modify the nutrient solution composition by adding water into the flowing stream of nutrient solution passing through the rooting vessel, thereby reducing the nutrient element concentration. With a "closed" system, a delivery–collection system would be required to pass water only through the rooting vessel. Such "engineering" aspects of hydroponic culture have recently been discussed by Giacomelli (1991).

Active and Passive Systems of Nutrient Solution Distribution

In all commercial and most other types of hydroponic/soilless culture systems, the movement of the nutrient solution requires either electrical power (active) or gravity (passive), or a combination of both. For some situations, less dependency on electrical power can be of considerable advantage. However, with the requirements for greater control over the composition, application requirements, etc. of the nutrient solution more widely recommended and applied in commercial systems (Bauerle et al., 1988; Berry, 1989; Bauerle, 1990; Schon, 1992), the need for uninterrupted electrical power is becoming essential.

In addition, computer programmed systems are replacing manual management operations. Sensors are being placed in the growing medium and nutrient solution storage tanks for regulating the flow and composition of the nutrient solution, respectively. Measurements such as light intensity and duration and the temperature of the plant environment are factors being used to regulate the flow and composition of the nutrient solution. Therefore, passive systems of nutrient solution flow are becoming obsolete.

Chapter 9

Systems of Hydroponic Culture

True hydroponics is the growing of plants in a nutrient solution without a rooting medium. Plant roots are either suspended in standing aerated nutrient solution or in a nutrient solution flowing through a root channel, or plant roots are sprayed periodically with a nutrient solution. This definition is quite different from the usually accepted concept of hydroponics, which has in the past included all forms of hydroponic/soilless growing. In the first section of this chapter, these three techniques of hydroponic growing will be discussed. In the second section, hydroponic systems using inorganic rooting media will be presented.

Mediumless Hydroponic Systems

Standing Aerated Nutrient Solution

This is the oldest hydroponic technique, dating back to those early researchers who, in the mid-1800s, used this method to determine which elements were essential for plants. Sachs in the 1840s and the other early investigators grew plants in aerated solutions and observed the effect on plant growth with the addition of various substances to the nutrient solution (Russell, 1950). This technique is still of use for various types of plant nutrition studies, although some researchers have turned to flowing and continuous replenishment nutrient solution procedures.

The requirements for the aerated standing nutrient solution technique are:

1. A suitable rooting vessel
2. A nutrient solution
3. An air tube and pump in order to bubble air continuously into the nutrient solution, as shown in Figure 9.1

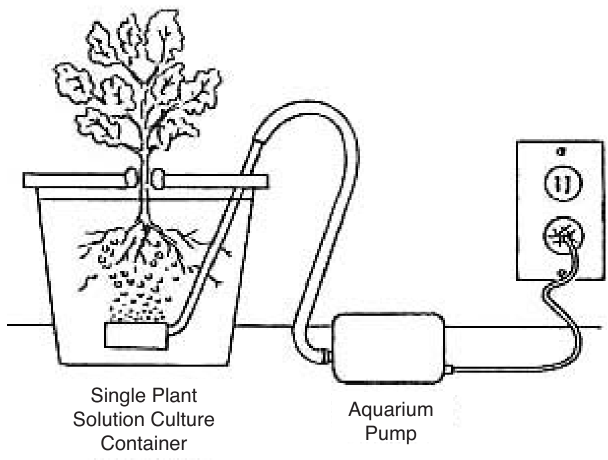

Figure 9.1 Standing aerated nutrient solution hydroponic growing system with the aquarium air pump attached to a line to a dispenser in the bottom of the growing vessel so that air can be bubbled into the nutrient solution.

The bubbling air serves to add O_2 to the nutrient solution as well as stirring it. The commonly used formula is Hoagland's (see Table 7.10) or some modification of it as has been designed by Berry (1985), whose nutrient solution formula is given in Table 9.1, with the plant nutrient solution volume ratio of 1 plant per 2 to 4 gallons (9 to 18 L) of nutrient solution.

The nutrient solution will require periodic replacement, usually every 5 to 10 days, the frequency based on the number of plants and their size as well as the volume of nutrient solution. Water loss from the nutrient solution will need to be replaced daily, using either nutrient-free water (pure water), or a diluted (1/10th strength) nutrient solution, although there is the danger that any further additions of nutrient elements could alter the initial balance among the elements and adversely affect the plants. It should also be remembered that with each day of use, the pH and composition of the initial nutrient solution will be altered by root activity and element uptake, changes that can have an effect on plant growth. The question becomes "should the pH and elemental content of the nutrient solution be restored daily to their original levels before replacement?" In most instances, adjustment other than water loss replacement is normally recommended.

Another aerated standing nutrient solution system has been described by Clark (1982); this technique has been used to study the elemental requirements of corn and sorghum. Several plants are grown in 1/2 gallon (2 L) of nutrient solution, with change schedules varying from 7 to 30 days depending on the stage of growth and plant species. The ratio of 8 to 1 of NO_3 to NH_4 in the nutrient solution is used to maintain some degree of constancy in pH. Clark's nutrient solution formula is given in Table 9.2. Although Clark's technique is primarily designed for corn and sorghum nutritional studies, his method of

Table 9.1 Stock Concentrates for Preparing a Nutrient Solution

		Concentration	
Reagent	*Formula*	*g/L*	*Ounces/5 Gallons*
Stock Concentrate #1			
Potassium nitrate	KNO_3	50.55	33.8
Potassium phosphate (mono)	KH_2PO_4	27.22	18.2
Magnesium sulfate	$MgSO_4 \bullet 7H_2O$	49.30	32.9
Micronutrient concentrate		100 mL	64 fl oz
Micronutrient Concentrate Formulation			
Boric acid	H_3BO_3	2.850	1.90
Manganese sulfate	$MnSO_4 \bullet H_2O$	1.538	1.03
Zinc sulfate	$ZnSO_4 \bullet 7H_2O$	0.219	0.15
Copper sulfate	$CuSO_4 \bullet 5H_2O$	0.078	0.05
Molybdic acid	$MoO_2 \bullet 2H_2O$	0.020	0.01
Stock Concentrate #2			
Calcium nitrate[a]	$Ca(NO_3)_2 \bullet 4H_2O$	118.0	78.8
Sequestrene 330 Fe[b]		5.0	3.3
To use: 1:200 dilution in water			

[a]Norsk Hydro Calcium Nitrate is used, with the formula 5 $Ca(NO_3)$: 2 NH_4NO_3 : 10 H_2O; add only 88.8 g/L or 59 oz./5 gallons.

[b]Mix the iron chelate thoroughly in a small amount of water before adding to the calcium nitrate.

Approximate concentration of elements in final solution (mg/L, ppm):

Major Elements: NO_3-N = 103, PO_4-P = 30, K = 140, Ca = 83, Mg = 24, SO_4-S = 32

Micronutrients: B = 0.25, Cu = 0.01, Fe = 2.5, Mn = 0.25, Mo = 0.005, Zn = 0.025

Source: Berry, W.L., 1985, in Proceedings of the 6th Annual Conference of Hydroponics, Hydroponic Society of America, Concord, CA.

nutrient solution management could be successfully applied to other plant species.

The aerated standing nutrient solution method of hydroponic growing has limited commercial application, although lettuce and herbs have been successfully grown on styrofoam sheets floating on an aerated nutrient solution (see pages 167 and 171). The plants are set in small holes in the styrofoam, with their roots growing into the nutrient solution. The sheets are lifted from the solution when the plants are ready to harvest. The commercial application for this technique of hydroponic growing is discussed in greater detail in Chapter 11.

Another reason why this system of growing hydroponically is not well suited for commercial application is that water and chemical use are quite

Table 9.2 Composition of Nutrient Solution for Standing Aerated Growing System

Solution Number	Stock Solution[a] Reagent	Stock Solution[a] Concentration (g/L)	Solution Used (mL/L)	Full-Strength Nutrient Solution (mg element/L) Cation	Full-Strength Nutrient Solution (mg element/L) Anion
1	$Ca(NO_3)_2 \bullet 4H_2O$	270.0	6.6	Ca = 302.4	NO_3-N = 211.4
	NH_4NO_3	33.8		NH_4-N = 39.0	NO_3-N = 39.0
2	KCl	18.6	7.2	K = 70.2	Cl = 63.7
	K_2SO_4	44.6		K = 142.2	SO_4-S = 58.3
	KNO_3	24.6		K = 68.5	NO_3-N = 24.5
3	$Mg(NO_3)_2 \bullet 6H_2O$	142.4	2.8	Mg = 37.8	NO_3-N = 43.6
4	KH_2PO_4	17.6	0.5	K = 2.5	P = 2.00
5[b]	$Fe(NO_3)_3 \bullet 9H_2O$	13.31	1.5	Fe = 2.76	NO_3-N = 2.1
	HEDTA	8.68		Na = 4.48	HEDTA = 13.0
6	$MnCl_2 \bullet H_2O$	2.34	1.5	Mn = 0.974	Cl = 1.3
	H_3BO_3	2.04			B= 0.536
	$ZnSO_4 \bullet 7H_2O$	0.88		Zn = 0.30	SO_4-S = 0.147
	$CuSO_4 \bullet 5H_2O$	0.20		Cu = 0.076	SO_4-S = 0.038
	$Na_2MoO_4 \bullet 2H_2O$	0.26		Na = 0.074	Mo = 0.155

Element	Final Composition mg/L (ppm)	Final Composition μM
Calcium (Ca)	302	7540
Potassium (K)	283	7240
Magnesium (Mg)	37.8	1550
Nitrate-nitrogen (NO_3-N)	321	22,900
Ammonium-nitrogen (NH_4-N)	39.0	2780
Chlorine (Cl)	65.0	1940
Phosphorus (P)	2.00	65
Iron (Fe)	2.76	49
Manganese (Mn)	0.974	18
Boron (B)	0.536	50
Zinc (Zn)	0.300	4.6
Copper (Cu)	0.076	1.2
Molybdenum (Mo)	0.155	1.6
Sodium (Na)	4.56	200
HEDTA	13.0	47

[a] In each solution, the respective reagents were dissolved together in the same volume. Some of the reagents in solutions 1 to 4 may be combined to make fewer stock solutions if desired, but calcium reagents should be kept separate from sulfate (SO_4) and phosphate (PO_4) reagents. Combinations of the salts noted are for convenience.

[b] This solution was prepared by (a) dissolving the HEDTA [N.2(hydroxyethyl)ethylene-diamine-triacetic acid] in 200 mL distilled water + 80 mL 1*N* NaOH; (b) adding solid $Fe(NO_3)_3 \bullet 9H_2O$ to the HEDTA solution and completely dissolving the iron salt; (c) adjusting the pH to 4.0 with small additions of 1*N* NaOH in step (c) too rapidly to allow iron to precipitate. The HEDTA was obtained from Aldrich Chemical Co., Milwaukee, WI (Catalog No. H2650-2).

Source: Clark, R.B., 1982, *J. Plant Nutr.,* 5(8):1003–1030.

high due to the requirement of frequent replacement. In addition, the composition of the nutrient solution is constantly changing, requiring monitoring and adjustment in order to maintain the pH and elemental ion balance and sufficiency concentration levels during the use period, which may range from 45 to 65 days. Temperature and root disease control are additional requirements if this method of growing is going to produce successful results.

Nutrient Film Technique (NFT)

A significant development in hydroponics occurred in the 1970s with the introduction of the nutrient film technique, frequently referred to as NFT (Cooper, 1976, 1979ab). Some have modified the name by using the word "flow" (Schippers, 1979) in place of "film," as the plant roots indeed grow in a flow of nutrient solution. When Allen Cooper first introduced his NFT system of hydroponic growing (1976), it was heralded as the hydroponic method of the future. It was, indeed, the first major change in hydroponic growing technique since the 1930s. At the "Hydroponics Worldwide: State of the Art in Soilless Crop Production" conference (Savage, 1985a), Cooper and his colleagues discussed their experiences with this method, which left those in attendance with the belief that the science of hydroponics had made a major step forward.

Experience has shown, however, that the NFT method does not solve the common problems inherent in most hydroponic growing systems. However, this did not deter its rapid acceptance and use in many parts of the world, particularly in Western Europe and England. NFT has been widely discussed and tested (Khudheir and Newton, 1983; Hurd, 1985; Cooper, 1985, 1988; Edwards, 1985; Gerber, 1986; Molyneux, 1988; Hochmuth, 1991b), but its future continues to be highly questionable unless better means of disease and nutrient solution control are found. A change in the design of the trough has been suggested by Cooper (1985), from the "U" shape to a "W" (called a divided gully system), in which the plant base sets on the top of the W center with the roots divided down each side of the W. A capillary mate is placed on the inverted "V" portion of the "W" to keep the roots moist with nutrient solution. There are a number of advantages to this redesign of the NFT single-gully system as initially proposed by Cooper (1976, 1979ab). A portion of the plant roots — that on the inverted "V"— is in air; a portion of the roots lies on a moist surface (capillary matting), which provides for better oxygenation of the rooting system; and the remaining root mass is now divided into two channels, which should minimize the problems associated with a large mass of roots in a single channel. It is now possible to use two different irrigation systems by flowing water or various types of nutrient solutions down either channel. Unfortunately, the NFT channel system has now been made more complicated in design, and it is uncertain whether this change would significantly improve plant performance. Cooper (1996) recently published a revision of his 1976 book on NFT in which he recognized some of the problems that can occur with this technique of hydroponic growing.

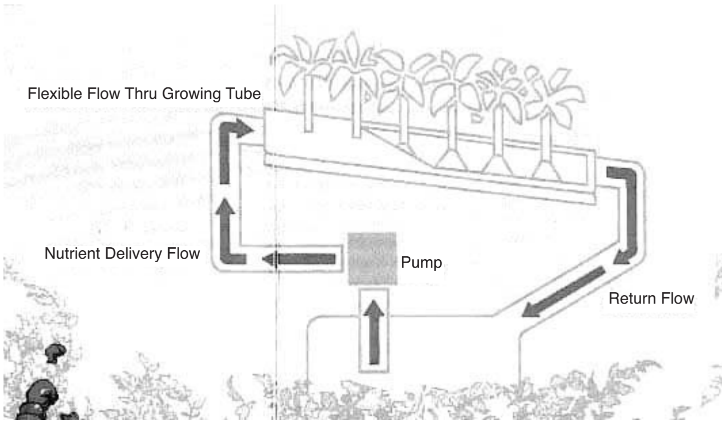

Figure 9.2 A typical arrangement for a closed NFT system in which nutrient solution is pumped from a storage tank into the sloping NFT trough and then by gravity the nutrient solution flows back into the storage tank.

Simply put, in the NFT system, plant roots are suspended in a trough, channel, or gully (trough will be the word used from this point on) through which a nutrient solution passes. The trough containing the plant roots is set on a slope (usually about 1%) so that the nutrient solution is introduced at the top of the trough can flow from the top to the lower end by gravity at a recommended flow rate of 1/4 gallon (1 L) per minute (Figure 9.2). As the root mat increases in size, the volume rate down the trough diminishes. As the nutrient solution flows down the trough, plants at the upper end of the trough reduce the O_2 and/or elemental content of the nutrient solution, a reduction that can be sufficient to significantly affect growth and development of plants at the lower end. Furthermore, as the root mat thickens and becomes denser, the flowing nutrient solution tends to move over the top and down the outer edge of the root mat, reducing its contact within the root mass. This interruption in flow results in poor mixing of the current flowing nutrient solution with water and elements left behind in the root mat from previous nutrient solution applications. One of the means for minimizing these effects is to make the trough no longer than 30 feet (9 m) in length. In addition, the trough can also be made wider, which can be more accommodating for root growth with longer-term crops.

One of the major advantages of NFT is the ease of establishment and the relative low cost of construction materials. The design of NFT troughs and materials suitable for making troughs is discussed by Morgan (1999c) and Smith (2004). A trough can be simply formed by folding a wide strip of polyethylene film into a pipe- or triangular-like shape (Figure 9.3). The polyethylene film may be either white or black but must be opaque to keep light out. If light enters the trough, algae growth becomes a serious problem. The polyethylene sheet is pulled around the plant stem and closed with pins or clips, forming a

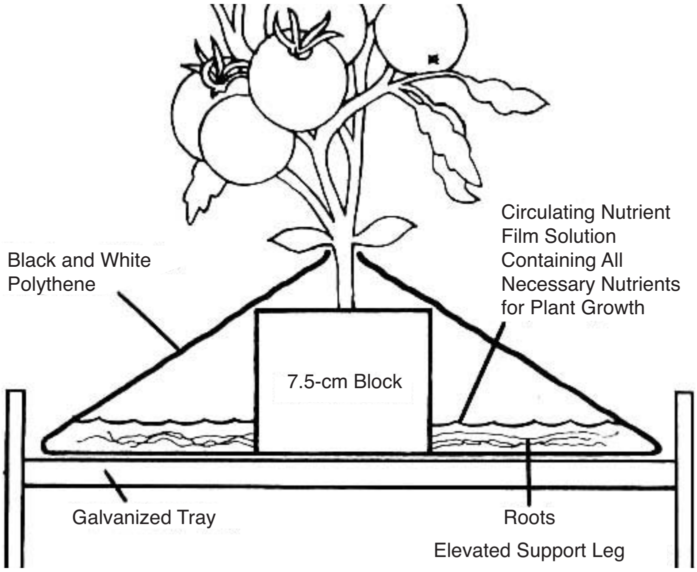

Figure 9.3 Cross-section of a NFT trough with a tomato plant rooted in a germination block with black/white polyethylene sheeting pulled up to and around the base stem of the plant to form a trough.

lightproof, pipe-like rooting trough. If the trough is formed from strips of polyethylene film, it can be discarded after each crop, thus only necessitating sterilization of the permanent piping and nutrient solution storage tank.

Most troughs in use today are made of various plastic materials, the requirements being opacity, structural strength, and ultraviolet (UV) resistance. The design of the trough (width, height, and form) is usually determined by the crop to be grown. Lack of structural strength can lead to unevenness in the trough bottom that allows nutrient solution to lie in depressions that can lead to anaerobic conditions.

The plants are set in the trough at the spacing recommended for that crop. Usually, plants are started in germination cubes made of fiberglass or similar material. The cube with its started plant is set directly in the trough. Experience has shown that the germination cube should not be made of materials that disintegrate with time. A durable germination cube helps keep the plant set in place in the NFT trough.

Normally NFT systems are closed systems, that is, the nutrient solution exiting the end of the trough is recovered for reuse. Bugbee (1995) discusses the requirements for the management of recirculating hydroponic growing systems. The addition of make-up water, the need for reconstituting the pH and nutrient element content, filtering, and sterilization are procedures that need to be established. An open system would mean that the nutrient solution exiting the trough is discarded, which is costly in terms of water and reagent use as well as posing a problem for proper disposal (Johnson, 2002c).

If the NFT system is operated as a closed system (i.e., the nutrient solution is recirculated a number of times before being discarded), Cooper (1979a) has recommended the use of a special nutrient solution, referred to as the topping-up solution, to be added to the starting solution to maintain its composition during use. The starting solution and the topping-up formulas for tomato and cucumber are given in Table 9.3. Schippers' (1979) NFT nutrient solution formulas for the starting and topping-up nutrient solutions are given in Table 9.4. Normally, the nutrient solution is monitored by periodic EC measurements, which determine the appropriate times to add make-up (or topping-up) nutrient solution to maintain the initial volume and when to dump and make a new batch of nutrient solution. The theoretical formula and elemental concentration level as suggested by Cooper (1979a) are given in Table 9.5.

Nutrient solution formulations suitable for NFT growing systems have been recommended based on crop and crop management conditions. Additional formulations for various NFT-grown crops are given in Chapter 11.

Molyneux (1988) has also given NFT nutrient solution formulas, one for soft-water and another for hard-water use, which are shown in Table 9.6. In addition, Molyneux (1988) has given the minimum, optimum, and maximum essential element concentrations in the NFT nutrient solution:

	Concentration (mg/L, ppm)		
Element	*Minimum*	*Optimum*	*Maximum*
Major Elements			
Nitrate-nitrogen (NO_3-N)	50	150 to 200	300
Phosphorus (P)	20	50	200
Potassium (K)	50	300 to 500	800
Calcium (Ca)	125	150 to 300	400
Magnesium (Mg)	25	50	100
Micronutrients			
Boron (B)	0.1	0.3 to 0.5	1.5
Copper (Cu)	0.05	0.1	1.0
Iron (Fe)	3.0	6.0	12.0
Manganese (Mn)	0.05	1.0	2.5
Molybdenum (Mo)	0.01	0.05	0.1
Zinc (Zn)	0.05	0.1	2.5

Other nutrient formulas have been proposed based on water source, whether soft (relatively free of ions such as Ca and Mg) or hard (containing Ca and Mg) and for various crops, such as tomato and cucumber. Such a set of formulas has been given by Papadopoulos (1991, 1994) as shown in Table 9.7 to Table 9.10.

Assuming a dilution ratio of 1:100 for Stock Solutions 1 and 2, the theoretical elemental concentrations in the circulating, diluted NFT solution are as follows:

	Concentration		Concentration
Element	*mg/L, ppm*	*Element*	*mg/L, ppm*
Major Elements		**Micronutrients**	
Nitrogen (N)[a]	214	Iron (Fe)	4.5
Phosphorus (P)	68	Manganese (Mn)	0.4
Potassium (K)	434	Boron (B)	0.2
Calcium (Ca)[b]	128	Copper (Cu)	0.09
Magnesium (Mg)	59	Zinc (Zn)	0.09
		Molybdenum (Mo)	0.09

[a] Additional N is supplied by the nitric acid (HNO_3) of Stock Solution 3; however, the amount is small because the amount of acid needed to control the pH of soft water is far less than that required for hard water.

[b] The Ca content of the water supply has not been taken into account.

Elements	*Concentration, mg/L (ppm)*
Major Elements	
Nitrogen (N)[a]	192
Phosphorus (P)[b]	—
Potassium (K)	490
Calcium (Ca)[c]	85
Magnesium (Mg)	59
Micronutrients	
Boron (B)	0.4
Copper (Cu)	0.2
Iron (Fe)	4.5
Manganese (Mn)	1.0
Molybdenum (Mo)	0.5
Zinc (Zn)	0.09

[a] Additional N is supplied by the nitric acid (HNO_3) of Stock Solution 3.

[b] Some P is supplied by the phosphoric acid (H_3PO_4) in Stock Solution 3.

[c] The Ca content of the water supply has not been taken into account.

Table 9.3 Reagents and Their Amounts to Prepare Nutrient Solutions[a]

Reagent	Formula	g/1000 L	Dilution mL/L	Concentration ppm
	Composition of Stock Starting Solution			
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$	787	1.25	117 N, 168 Ca
Potassium nitrate	KNO_3	169	3.9	254 K, 91 N
Magnesium sulfate	$MgSO_4{\bullet}7H2O$	329	1.5	49 Mg
Potassium phosphate	KH_2PO_4	91	3.0	62 P, 78 K
Chelated iron	FeNaEDTA	12.3	3.0	5.6 Fe
Manganese sulfate	$MnSO_4{\bullet}4H_2O$	3.0	3.0	2.2 Mn
Boric acid	H_3BO_3	1.23	1.5	0.32 B
Copper sulfate	$CuSO_4{\bullet}5H_2O$	0.17	1.5	0.065 Cu
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\bullet}4H_2O$	0.06	1.5	0.007 Mo
Phosphoric acid	H_3PO_4	—	0.044	23 P
	Composition of Topping-Up Stock Solution			
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$	787	0.5[b]	47 N, 67 Ca
			1.0[c]	93 N, 113 Ca
Potassium nitrate	KNO_3	169	2.13	147 K, 51 N
Magnesium sulfate	$MgSO_4{\bullet}7H_2O$	329	1.0	32 Mg
Chelated iron	FeNaEDTA	24.5	0.4[b]	1.5 Fe
			0.8[c]	3.0 Fe
Manganese sulfate	$MnSO_4{\bullet}4H_2O$	7.42	0.3[b]	0.55 Mn
			0.6[c]	1.1 Mn
Boric acid	H_3BO_3	6.17	0.3	0.32 B
Copper sulfate	$CuSO_4{\bullet}5H_2O$	1.7	0.15	0.065 Cu
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\bullet}4H_2O$	0.06	1.5	0.007 Mo

[a] Starting and Topping-up Stock Solutions and diluted elemental concentrations in the diluted solution for use in a NFT system for growing of tomato and cucumber

[b] For tomatoes.

[c] For cucumbers.

Source: Cooper. 1979b.

Table 9.4 Starting and Topping-Up Nutrient Solution Formulations for Use in a NFT System

		Starting Solution		*Topping-up Solution*	
Reagent	*Formula*	*Weight (g/ 1000 L)*	*Conc. (mg/L)*[a]	*Weight (g/ 1000 L)*	*Conc. (mg/L)*[a]
Calcium nitrate	$Ca(NO_3)_2 \cdot 4H_2O$	988.0	117 N 254 K	395.5 168 Ca	47 N 67 Ca
Potassium nitrate	KNO_3	658.1	91 N 49 Mg	367.5	142 K 51 N
Magnesium sulfate	$MgSO_4 \cdot 7H_2O$	496.6	62 P	324.3	32 Mg
Potassium phosphate	KH_2PO_4	272.0	8 K	—	
Chelated iron	FeNaEDTA	78.88	12 Fe	32.87	5 Fe
Manganese sulfate	$MnSO_4 \cdot H_2O$	6.154	2 Mn	1.539	0.5 Mn
Boric acid	H_3BO_3	1.714	0.3 B	1.714	0.3 B
Copper sulfate	$CuSO_4 \cdot 5H_2O$	0.275	0.07 Cu	0.275	0.07 Cu
Ammonium molybdate	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	0.092	0.05 Mo	0.092	0.05 Mo
Zinc sulfate	$ZnSO_4 \cdot 7H_2O$	0.308	0.07 Zn	0.308	0.07 Zn

[a] mg/L equivalent to parts per million (ppm).

Source: Schippers, P.A., 1979, The Nutrient Flow Technique, V.C. Mimeo 212. Department of Vegetable Crops, Cornell University, Ithaca, NY.

Table 9.5 Nutrient Solution Formulas to Give the Theoretically Ideal Concentration of Essential Elements

Reagent	*Formula*	*Amount (g/1000 L)*
Potassium dihydrogen phosphate	KH_2PO_4	263
Potassium nitrate	KNO_3	583
Calcium nitrate	$Ca(NO_3)_2 \cdot 4H_2O$	1003
Magnesium sulfate	$MgSO_4 \cdot 7H_2O$	513
EDTA iron	$[(CH_2\text{-}N(CH_2.COOH)_2]_2FeNa$	79
Manganous sulfate	$MnSO_4 \cdot H_2O$	6.1
Boric acid	H_3BO_3	1.7
Copper sulfate	$CuSO_4 \cdot 5H_2O$	0.39
Ammonium molybdate	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	0.37
Zinc sulfate	$ZnSO_4 \cdot 7H_2O$	0.33

This formula gives the following essential element concentrations in solution:

Element	*Concentration, mg/L (ppm)*
Major Elements	
Nitrogen (N)	200
Phosphorus (P)	60
Potassium (K)	300
Calcium (Ca)	170
Magnesium (Mg)	60
Micronutrients	
Boron (B)	0.3
Copper (Cu)	0.1
Iron (Fe)	12.0
Manganese (Mn)	2.0
Molybdenum (Mo)	0.2
Zinc (Zn)	0.1

Source: Cooper, A., 1979, *Commercial Applications of NFT,* Grower Books, London.

Table 9.6 NFT Nutrient Solution Formulas for Both Soft and Hard Water Use

Reagent	*Formula*	*Soft Water*	*Hard Water*
		Amount (kg/12.5 L)	
Stock Solution A			
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$	2.42	1.20
Ammonium nitrate	NH_4NO_3	—	60.0
Stock Solution B			
Potassium nitrate	KNO_3	1.53	2.59
Potassium dihydrogen phosphate	KH_2PO_4	0.55	—
Magnesium sulfate	$MgSO_4{\bullet}7H_2O$	1.27	1.27
		Amount (g/12.5 l)	
EDTA iron		75	75
Manganese sulfate	$MnSO_4$	10	10
Boric acid	H_3BO_3	6	6
Copper sulfate	$CuSO_4{\bullet}5H_2O$	2	2
Zinc sulfate	$ZnSO_4{\bullet}7H_2O$	1	1
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\bullet}4H_2$	0.25	0.25

Note: Equal portions of Stock Solution A and B are mixed to make the nutrient solution. Phosphoric acid (H_3PO_4) is used for pH adjustment to give a pH range of 6.0 to 6.5.

Source: Molyneux, C.J., 1988, *A Practical Guide to NFT*, T. Snap & Co. Ltd., Preston, Lancashire, England.

Table 9.7 Fertilizer (Reagent) Formulations Made in Soft Water for Use with NFT Growing System

Stock Solution 1 (1000 L Total Volume)		*Stock Solution 2[a] (1000 L Total Volume)*		*Stock Solution 3 (1000 L Total Volume)*	
Reagent	*Amount*	*Reagent*	*Amount*	*Reagent*	*Amount*
Calcium nitrate	75 kg	Potassium nitrate	90 kg	Nitric acid (67%)	7.9 l
Monopotassium phosphate	30 kg				
Magnesium sulfate	60 kg				
Iron chelate (15% Fe)	3.0 kg				
Manganese sulfate	0.4 kg				
Boric acid	0.24 kg				
Copper sulfate	80 g				
Zinc sulfate	40 g				
Ammonium molybdate	10 g				

To use: Dilution ratio 1:100.

[a] It may be necessary to slightly acidify Stock Solution 2 with a small amount of nitric acid (HNO_3) (20 mL) to prevent salt precipitation, e.g., magnesium phosphate.

Source: Papadopoulos, A.P., 1991, Growing Greenhouse Tomatoes in Soil and in Soilless Media, Agricultural Canada Publication 1865/E, Communications Branch, Agricultural Canada, Ottawa, Canada.

Table 9.8 Fertilizer (Reagent) Formulations Made in Hard Water for Use with NFT[a]

Stock Solution 1 (1000 L Total Volume)		*Stock Solution 2 (1000 L Total Volume)*		*Stock Solution 3 (1000 L Total Volume)*	
Reagent	*Amount*	*Reagent*	*Amount*	*Reagent*	*Amount*
Calcium nitrate	50 kg	Potassium nitrate	80 kg	Nitric acid (67%)	54 mL
Potassium sulfate	40 kg	Phosphoric acid (85%)	24 mL		
		Magnesium sulfate	60 kg		
		Ammonium nitrate	0.6 kg		
		Iron chelate (15% iron)	3.0 kg		
		Manganese sulfate	0.4 kg		
		Boric acid	0.2 kg		
		Copper sulfate	80 g		
		Zinc sulfate	40 g		
		Ammonium molybdate	10 g		

[a] No phosphatic fertilizer has been included other than the phosphoric acid (H_3PO_4) in Stock Solution 3. Where the water is not particularly hard and the acid requirement is correspondingly low, include 1.5 kg of monopotassium phosphate (KH_2PO_4) in Stock Solution 2 while decreasing the amount of potassium sulfate (K_2SO_4) from 4.0 to 3.0 kg.

To use: Dilution ratio 1:100.

Source: Papadopoulos, A.P., 1991, Growing Greenhouse Tomatoes in Soil and in Soilless Media, Agricultural Canada Publication 1865/E, Communications Branch, Agricultural Canada, Ottawa, Canada.

Table 9.9 Recommended Nutrient Solutions for Tomato in NFT Growing System

Stock Solution 1 (1000 L Total Volume)		*Stock Solution 2 (1000 L Total Volume)*	
Reagent	*Amount*	*Reagent*	*Amount*
Calcium nitrate	99.0 kg	Magnesium sulfate	49.7 kg
Potassium nitrate	65.8 kg	Monopotassium phosphate	27.2 kg
		Iron chelate (13% iron)	3.0 kg
		Manganese sulfate	0.5 kg
		Boric acid	180 g
		Copper sulfate	30 g
		Zinc sulfate	35 g
		Ammonium molybdate	8 g

Prepare the final solution by adding equal volumes of both stock solutions in water until a recommended final solution electrical conductivity (EC) of 2200 mS/cm is achieved; adjust the pH to 6.2 by adding phosphoric (low-light conditions) or nitric (high-light conditions) acid. Ideally, stock solutions are mixed and pH is adjusted automatically by EC and pH controllers. When starting a new crop, begin with an EC of 1500 mS/cm and gradually increase to 2200 mS/cm over a week. A background EC of 300 to 600 mS/cm from the water supply is assumed.

To use: Dilution ratio 1:100.

Source: Papadopoulos, A.P., 1991, Growing Greenhouse Tomatoes in Soil and in Soilless Media, Agricultural Canada Publication 1865/E, Communications Branch, Agricultural Canada, Ottawa, Canada.

Table 9.10 Recommended Elemental Solutions for Cucumber in NFT Growing System

Stock Solution A (1000 L Total Volume)		*Stock Solution B (1000 L Total Volume)*	
Reagent	*Amount*	*Reagent*	*Amount*
Calcium nitrate	44.4 kg	Monopotassium phosphate	22.0 kg
Potassium nitrate	62.7 kg	Magnesium sulfate	50.0 kg
Ammonium nitrate	5.0 kg	Iron chelate (13% iron)[a]	1.0 kg
		Manganese sulfate (25% Mn)[a]	250.0g
		Boric acid (14% B)[a]	90.0 g
		Copper sulfate (25% Cu)[a]	30.0 g
		Zinc sulfate (23% Zn)[a]	5.0 g
		Ammonium molybdate (57% Mo)[a]	8.0 g

[a] Alternatively, include 2.0 kg of Plant Product Chelated Micronutrient mix, which provides the following micronutrient concentrations (mg/L, ppm): 1.4 Fe, 0.4 Mn, 0.08 Zn, 0.26 B, 0.02 Cu, and 0.012 Mo.

Prepare the final solution by adding equal volumes of both stock solutions in water until a recommended final solution EC of 2200 mS/cm is achieved; adjust the pH to 6.2 by adding phosphoric (low-light conditions) or nitric (high-light conditions) acid. Ideally, stock solutions are mixed and pH is adjusted automatically by EC and pH controllers.

When starting a new crop, begin with an EC of 1500 mS/cm and gradually increase to 2200 mS/cm over 1 week. A background EC of 300 to 600 mS/cm from the water supply is assumed.

The final dilution formula should give a NFT solution with the following elemental composition:

Element	*Concentration, mg/L (ppm)*
Major Elements	
Nitrate (NO_3)	156
Ammonium (NH_4)	12
Phosphorus (P)	59
Potassium (K)	302
Calcium (Ca)	84
Magnesium (Mg)	50
Micronutrients[a]	
Iron (Fe)	1.3
Manganese (Mn)	0.62
Boron (B)	0.12
Copper (Cu)	0.07
Molybdenum (Mo)	0.08
Zinc (Zn)	0.03

[a]Alternatively, include 2.0 kg of Plant Product Chelated Micronutrient mix, which provides the following micronutrient concentrations (mg/L, ppm): 1.4 Fe, 0.4 Mn, 0.08 Zn, 0.26 B, 0.02 Cu, and 0.012 Mo.

Source: Papadopoulos, A.P., 1994, Growing Greenhouse Seedless Cucumbers in Soil and in Soilless Media, Agricultural Canada Publication 1902/E, Communications Branch, Agricultural and Agri-Food Canada, Ottawa, Canada.

Table 9.11 Target Nutrient Solution Elemental Levels for Growing in a NFT System for Tomato

Element	*Minimum*[a] *(pH 5.5,* EC 1800 mS)	*Optimum* *(pH 6.0,* EC 2000-2500 mS)	*Maximum* *(pH 6.5,* EC 3500 mS)
	mg/L (ppm)		
Major Elements			
Nitrogen-nitrate ($N\text{-}NO_3$)	50	150 to 200	300
Nitrogen-ammonium ($N\text{-}NH_4$)	5	10 to 15	20
Phosphorus (P)	20	50	200
Potassium (K)	100	300 to 500	800
Calcium (Ca)	125	150 to 300	400
Magnesium (Mg)	25	50	100
Sulfur (S)	—	50 to 200	
Micronutrients			
Boron (B)	0.1	0.3 to 5	1.5
Copper (Cu)	0.05	0.1	1.0
Iron (Fe)	1.5	6.0	12.0
Manganese (Mn)	0.5	1.0	2.5
Molybdenum (Mo)	0.01	0.05	0.1
Zinc (Zn)	0.05	0.5	2.5
Others			
Sodium (Na)	[b]	[b]	250
Chloride (Cl)	[b]	[b]	400

[a] Concentrations listed as minimal should be regarded as the approximate lower limit of a preferred range; in general, these minimum values are above those at which symptoms of deficiency develop.

[b] As little as possible.

Source: Papadopoulos, A.P., 1991, Growing Greenhouse Tomatoes in Soil and in Soilless Media, Agricultural Canada Publication 1865/E, Communications Branch, Agricultural Canada, Ottawa, Canada.

In addition to the nutrient solution formulas given in Table 9.7 through Table 9.10, Papadopoulos (1991) has also described what the target elemental concentrations should be for tomato in a NFT system; those target values are in Table 9.11. A similar list of concentrations for tomato in a NFT system has been given by Ames and Johnson (1986), as shown in Table 9.12. Hochmuth (2001) gives instructions for the preparation of four nutrient solution formulations based on the use of both individual reagents and fertilizer materials (4-18-38; 3-15-27; 5-11-26; 7-17-37) for use in growing tomatoes hydroponically in NFT. The concentration of the essential elements in the nutrient solution is adjusted for the stage of tomato plant growth, as shown in Table 9.13.

The influence of stage of tomato plant growth is also a factor in determining what the elemental concentration ranges should be, as has been suggested by Hochmuth (2001) for the NFT technique for tomato; those ranges are

Table 9.12 Nutrient Solution Elemental Concentrations for Growing in a NFT System for Tomato

Element and Form	*Concentration, mg/L (ppm)*
Major Elements	
Nitrogen (N)	
Nitrate (NO_3)	150 to 200
Ammonium (NH_4)	0 to 20
Potassium (K)	300 to 500
Phosphorus (P)	50
Calcium (Ca)	150 to 300
Magnesium (Mg)	50
Micronutrients	
Boron (B)	0.3 to 0.5
Copper (Cu)	0.1
Iron (Fe)	3.0
Manganese (Mn)	1.0
Molybdenum (Mo)	0.05
Zinc (Zn)	0.1

Source: Ames, M. and Johnson, W.S., 1986, in Proceedings 7th Annual Conference on Hydroponics: The Evolving Art, The Evolving Science. Hydroponic Society of America, Concord, CA.

shown in Table 9.13. As the stage of growth advances, the N, K, and Mg concentrations increase, while the other elements remain at constant concentration.

The timing to flow the nutrient solution down the NFT trough varies. One practice is to intermittently flow the nutrient solution down the trough on an "on-off" cycle or by a "half-on, half-off" circulation period; a more sophisticated system is based on timing recirculation on the accumulation of incoming radiation. For example, when 0.3 mJ/m^2 of light energy has accumulated, the nutrient solution is flowed down the trough for 30 minutes; the time and length are also affected by the crop and its stage of growth. Such systems are coming into wider use because they have proven to be successful in producing better and higher yielding tomato and cucumber crops.

The NFT principle has also been applied to smaller growing units for home garden use. For example, one such application for vegetable growing places sand-filled styrofoam cups in access holes in PVC pipes. The nutrient solution circulates through the pipe on a timed schedule. This system has the unique feature of easy removal of plants by lifting the styrofoam cup from its access hole. A typical arrangement for this home garden NFT system is shown in Figure 9.4.

Disease control can be difficult because a disease organism entering a NFT system will be quickly carried from one plant to another in the trough and

Table 9.13 Final Delivered Nutrient Solution Concentrations (mg/L, ppm) for Hydroponic (Perlite, Rockwool, and NFT) Tomato in Florida Greenhouses

	Stage of Growth[a]				
Element	1	2	3	4	5
Major Elements			**mg/L (ppm)**		
Nitrogen (N)	70	80	100	120	150
Phosphorus (P)	50	50	50	50	50
Potassium (K)	120	120	150	150	200
Calcium (Ca)	150	150	150	150	150
Magnesium (Mg)	50	50	50	60	60
Micronutrients					
Boron (B)	0.7	0.7	0.7	0.7	0.7
Copper (Cu)	0.2	0.2	0.2	0.2	0.2
Iron (Fe)	2.8	2.8	2.8	2.8	2.8
Manganese (Mn)	0.8	0.8	0.8	0.8	0.8
Molybdenum (Mo)	0.05	0.05	0.05	0.05	0.05
Zinc (Zn)	0.3	0.3	0.3	0.3	0.3

[a] Stage of growth: Stage 1 = transplant to first cluster; Stage 2 = first cluster to second cluster; Stage 3 = second cluster to third cluster; Stage 4 = third cluster to fifth cluster; Stage 5 = fifth cluster to termination.

Source: Hochmuth, G., 2001, Nutrient Solution Formulation for Hydroponic (Perlite, Rockwool, and NFT) Tomatoes in Florida, Nutrient Solutions, North Florida Research and Education Center, Suwannee Valley, Live Oak, FL.

from one trough to another if the nutrient solution is recirculated and not sterilized. Therefore, the same precautions are required as for any closed recirculating nutrient solution growing system. In warm climatic areas, the fungus *Pythium* is the major organism affecting plants grown in NFT systems. *Pythium* does not seem to be a serious problem when the temperature of the nutrient solution is maintained at less than 70°F (25°C).

Root death is another problem in NFT installations and may be the result of a lack of O_2 in the root mass (Antkowiak, 1993). Recently, it has been suggested that concern is greater than justified, inasmuch as root death is a natural physiological phenomenon brought on by competition within the plant for carbohydrates. During periods of high demand for carbohydrates (primarily at fruiting or during times of stress), some roots will die, but when stress is relieved, plant tissue regains an adequate carbohydrate supply and new roots will appear. As long as most of the roots in the mat are alive, some suggest that little attention should be paid to root death. This phenomenon probably occurs in all systems of growing; it is clearly visible in NFT but not as easily seen when roots are growing in an inorganic or organic medium.

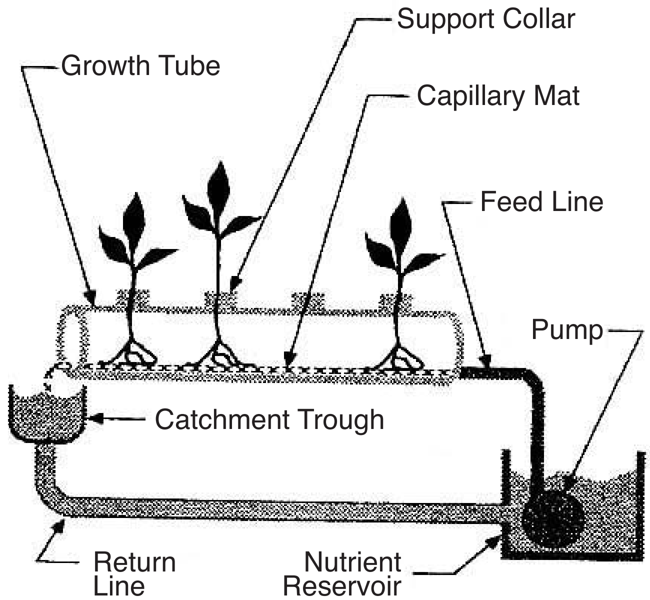

Figure 9.4 Typical arrangement for a home garden closed NFT system from which nutrient solution is pumped from a reservoir into a sloping growth tube with the nutrient solution flowing down the tube and back into the nutrient reservoir (*Source*: Van Patten, G.P., 1992, *The Growing Edge* 3(3): 24–33, 48–51).

Aeroponics

Another promising hydroponic technique for the future was thought to be aeroponics, which is the distribution of water and essential elements by means of an aerosol mist bathing the plant roots (Nickols, 2002). One of the significant advantages of this technique compared to flowing the nutrient solution past the plant roots is aeration, as the roots are essentially growing in air. The technique was designed to achieve substantial economies in the use of both water and essential elements. The critical aspects of the technique are the character of the aerosol, frequency of root exposure, and composition of the nutrient solution. Adi Limited (1982) described an aeroponic system that it said had proven to be highly successful. The system is computer controlled and requires a special fogging device, troughs, and an array of sensing devices. Although yields of crops obtained with this growing system have been reported to be considerably above those obtained with conventional hydroponic systems, the initial cost for the Adi system plus operating costs are very high, bringing into question its commercial viability (Soffer, 1985), although its value in plant propagation is considerable (Soffer, 1988).

Several methods have employed a spray of the nutrient solution rather than a fine mist; droplet size and frequency of exposure of the roots to the nutrient solution are the critical factors. Continuous exposure of the roots to a fine mist gives better results than intermittent spraying or misting. In most aeroponic systems, a small reservoir of water is allowed to remain in the bottom of the rooting vessel so that a portion of the roots has access to a continuous supply of water. The composition of the nutrient solution would be adjusted based on the time and frequency of exposure of the roots to the nutrient solution.

Medium Hydroponic Systems

In the culture systems described in this section, plants are grown in some type of inorganic rooting medium (Straver, 1996a,b; Morgan, 2003f), with the nutrient solution applied by flooding or drip irrigation. Some of the physical and chemical properties of commonly used inorganic substrates are given in Table 9.14.

Ebb-and-Flow Nutrient Solution Systems

This type of hydroponic growing system had been in wide use for many years, although it is not commonly used commercially today other than for hobby/home-type growing units. This system has also been called "flood and drain." The growing system consists of a watertight rooting bed, rooting bed containing an inert rooting medium, such as gravel, coarse sand, or volcanic rock, a nutrient solution sump (equal in volume to the growing bed(s)), an electrical pump for moving the nutrient solution from the sump to the growing bed(s), and a piping system to accommodate the delivery of the nutrient solution from the sump to the growing bed(s) and its return. Such a commercially designed system is shown in Figure 9.5. In order to have gravity return flow of nutrient solution from the growing bed(s) to the sump, the sump must be below the growing bed(s). Since this is a "closed" system, the nutrient solution is recirculated until no longer usable, when it is dumped and replaced with freshly made solution. Prior to each use, the nutrient solution should be tested for pH, EC, and possibly elemental content and then adjusted accordingly. The nutrient solution may also require filtering and sterilization after each circulation through the rooting bed. All of these procedures are discussed in Chapter 7.

This hydroponic growing system was that used by the U.S. Army in World War II to supply troops operating in the Pacific with fresh tomatoes and lettuce (Eastwood, 1947). Following WWII, this system of hydroponic growing was put into use by growers in several southern states in the United States and elsewhere (Eastwood, 1947), in outdoor hydroponic gardens growing primarily tomatoes. The author has advised growers using this method of growing in both greenhouse and outdoor settings.

The disadvantages for this system are susceptibility to root diseases, inefficient use of water and nutrient reagents, and the requirement for the periodic replacement of the rooting medium, which is usually gravel. An ebb-and-flow system designed for greenhouse tomato production was marketed in the 1960s and 70s. The sump held 2000 gallons of nutrient solution that needed daily

Table 9.14 Characteristics of Inorganic Hydroponic Substrates

Substrate	*Characteristics*
Rockwool and stonewool	Clean, nontoxic (can cause skin irritation), sterile, lightweight when dry, reusable, high water holding-capacity (80%), good aeration (17% air-holding), no cation exchange or buffering capacity, provides ideal root environment for seed germination and long-term plant growth
Vermiculite	Porous, spongelike, sterile material, lightweight, high water absorption capacity (five times its own weight), easily becomes waterlogged, relatively high cation exchange capacity
Perlite	Siliceous, sterile, spongelike, very light, free-draining, no cation exchange or buffer capacity, good germination medium when mixed with vermiculite, dust can cause respiratory irritation
Pea gravel and metal chip	Particle size ranges from 5 to 15 mm in diameter, free draining, low water-holding capacity, high weight density, which may be an advantage or disadvantage, may require thorough water leaching and sterilization before use
Sand	Small rock grains of varying grain size (ideal size: 0.6 to 2.5 mm in diameter) and mineral composition, may be contaminated with clay and silt particles, which must be removed prior to hydroponic use, low water-holding capacity, high weight density, frequently added to an organic soilless mix to add weight and improve drainage
Expanded clay	Sterile, inert, range in pebble size of 1 to 18 mm, free draining, physical structure can allow for accumulation of water and nutrient elements, reusable if sterilized, commonly used in pot hydroponic systems
Pumice	Siliceous material of volcanic origin, inert, has higher water-holding capacity than sand, high air-filled porosity
Scoria	Porous, volcanic rock, fine grades used in germination mixes, lighter and tends to hold more water than sand
Polyurethane grow slabs	New material, which has a 75 to 80% air space and 15% water holding capacity

Source: Morgan, L., 2003f, *The Growing Edge* 15(2):54–66.

volume water adjustment as well as possible adjustments in pH and nutrient element make-up (based on an EC measurement). The nutrient solution required complete replacement about every 2 to 3 weeks — a considerably inefficient use of valuable water and reagents. With time, plant roots began to grow into the pipes that delivered and returned the nutrient solution to and from the growing bed(s) and sump, thereby restricting the flow. One diseased plant introduced into the system would result in a total loss of the entire crop. Cleanup frequently meant the removal and replacement of the gravel rooting medium. Another problem with this system was that because they were in the ground, the sump and enclosed nutrient solution would have

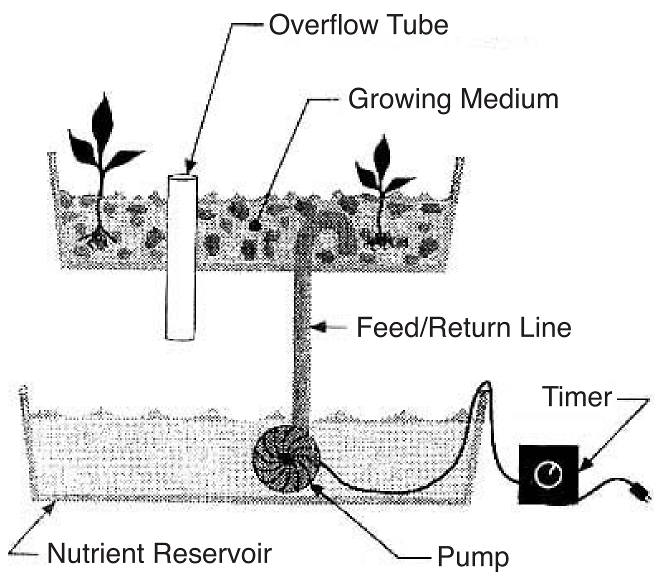

Figure 9.5 Flood-and-drain (ebb-and-flow) hydroponic growing system. Periodically, nutrient solution is pumped from the nutrient reservoir into the growing medium, flooding the medium with nutrient solution which is then allowed to drain back into the nutrient reservoir. (*Source*: Van Patten, G.P., 1992, *The Growing Edge* 3(3): 24–33, 48–51).

a temperature equal to that of the surrounding soil, meaning that during most of the season, the nutrient solution would be colder than the ambient air temperature, an undesirable trait that would harm plants when the nutrient solution was dispensed into the growing medium.

For the homeowner and hobbyist, the ebb-and-flow system of growing is relatively easy to construct and operate on a small scale and gives reasonably good plant performance with a moderate level of care.

The timing schedule for flooding the growing bed(s) will depend on the atmospheric demand and stage of growth for the crop, as well as the water-holding capacity of the growing medium. Normally, the composition of the nutrient solution is similar to the basic Hoagland solution (see Table 7.10 in Chapter 7) or some modification of it, depending on the crop and stage of growth (see Chapter 7).

Commercially, this system of hydroponic growing has proven to be difficult to manage and is very inefficient in its use of water and essential elements, important reasons for its lack of use today.

Drip/Pass-Through Inorganic Medium Systems

There are two such growing systems, one using perlite or similar inorganic rooting medium (Morgan, 2003f) in bags, pots, or buckets, and the other using rockwool slabs.

Inorganic Rooting Medium in Bags or Pots/Buckets

This system of hydroponic growing is in wide use today for commercial production in which the plant(s) is grown in a bag, pot, or bucket of inorganic medium, with perlite as the most common rooting medium (Gerhart and Gerhart, 1992; Morgan, 2003f). In one system, the bag used for shipping the perlite is laid on its side, small holes are cut along the bottom edge of the bag to allow excess nutrient solution to flow out, an access hole(s) cut in the top of the bag for placement of a plant, and then a drip tube is placed on the edge of the access hole next to the plant. The plant may initially be seeded in a rockwool cube or other similar substance and then placed on an opening on the bag, with the drip line placed at the base of the plant (Figure 9.6). A pot or bucket, such as the BATO bucket (Figure 9.7), filled with perlite or similar inorganic substance, can be used in place of the shipping bag. These systems, mostly using BATO buckets, are in wide use for the production of tomato and cucumber as described in Chapter 11.

Because this is an "open" system, the nutrient solution is not recovered and recirculated. The amount delivered should be sufficient for a slight excess flow from the openings cut on the bottom edge of the bag or from openings in the base of pots and buckets (the BATO bucket has a small reservoir in its base). Scheduling of the rate and timing of nutrient solution application is dependent on various factors, such as atmospheric demand, crop, and stage of growth. During the growing period, the effluent from the growing vessel can be monitored for its pH and EC and adjustments made in the nutrient solution delivered, or the medium leached with water to remove any accumulated salts. Also, an aliquot of solution can be drawn from the medium

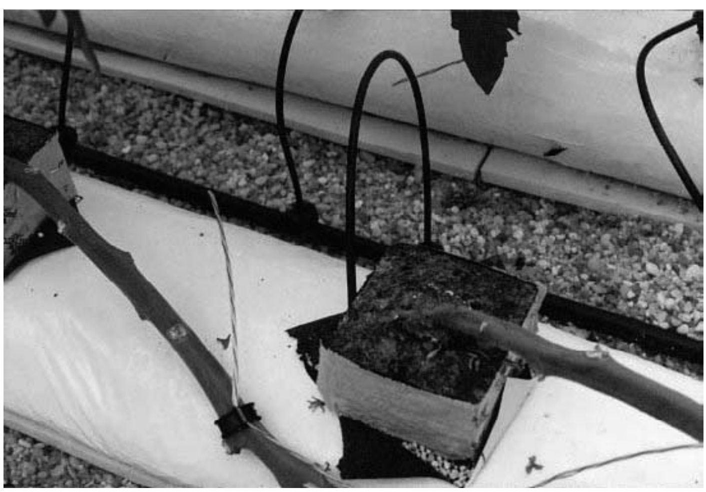

Figure 9.6 Drip irrigation line (black tubing) positioned on a rockwool block set on a perlite-containing bag.

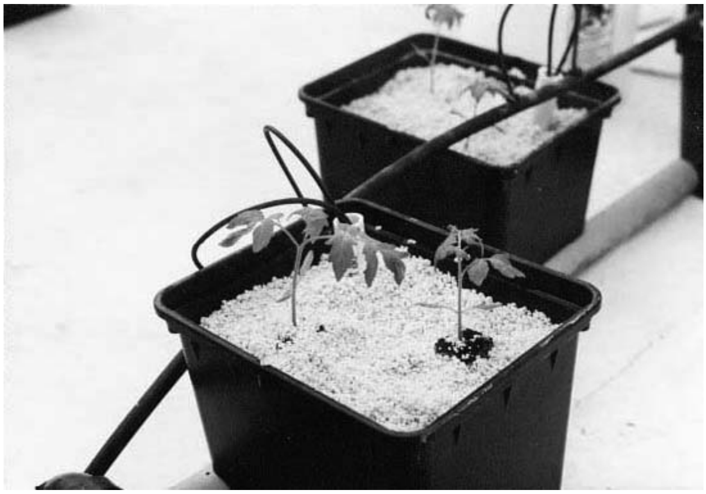

Figure 9.7 Drip irrigation line (large black tubing is the delivery line, the smaller tubing the drip tube) for delivering nutrient solution to perlite-filled BATO buckets.

itself shortly after an irrigation to make the same measurements as made on an effluent sample.

At the end of the growing season, the perlite-containing vessel may be used one more time or discarded, which makes the system relatively easy to install and replace at a reasonable cost. The nutrient solution formula normally is based on the Hoagland/Arnon nutrient formula (see Table 7.10) or some modification of it (see Chapters 7 and 11).

Various modifications of this system of growing have been made to accommodate different types of crops. One example is a vertical hanging bag with lettuce plants placed in holes in the side of the bag, a system described by DeKorne (1992–93). Another example is strawberry plants set in the holes in the side of the vertical polyethylene bag of perlite. The nutrient solution is applied at the top of the bag, usually through a dripper, and the solution passes down through the bag and out the bottom. The same problems associated with the NFT technique apply to this system, as the composition of the nutrient solution is modified as it passes down through the bag.

A very recent unique system consists of a column of interlocking styrofoam pots in which plants are placed at the four corners of each pot; the system is primarily designed for the growing of strawberry, lettuce, and herbs (Figure 9.8). The placement and flow of nutrient solution are similar to the vertical bag system.

An advantage of these vertical systems is gained from the utilization of vertical space, thereby conserving lateral space if plants are grown in an enclosed shelter or greenhouse. The bag or column of pots can be rotated slowly to obtain more uniform light exposure for the plants.

Figure 9.8 Column of interlocking styrofoam pots with plants placed at each corner of the pots (into the top pot nutrient solution is dripped which slowly flows down the column of interlocking pots). The column in the background has lettuce ready for harvest.

Rockwool Slab Medium

Rockwool is probably the most widely used hydroponic growing medium in use in the world today for the production of tomato, cucumber, and pepper (Bij, 1990; Ryall, 1993; Morgan, 2002a), although efforts are being made to find an adequate substitute because disposal of used slabs is becoming a major problem (Spillane, 2002a,b). Rockwool has excellent water-holding capacity, is relatively inert, and has proven to be an excellent substrate for plant growth (Sonneveld, 1989).

Rockwool is an inert fibrous material produced from a mixture of volcanic rock, limestone, and coke; melted at 1500 to 2000°C; extruded as fine fibers; and pressed into loosely woven sheets. The sheets are made into slabs of varying widths [16 to 18 inches (15 to 46 cm)], normally 36 inches (91 cm) in length, and ranging in depth from 3 to 4 inches (5 to 10 cm). The slabs are normally wrapped with white polyethylene sheets as shown in Figures 9.9-1 and 9.9-2.

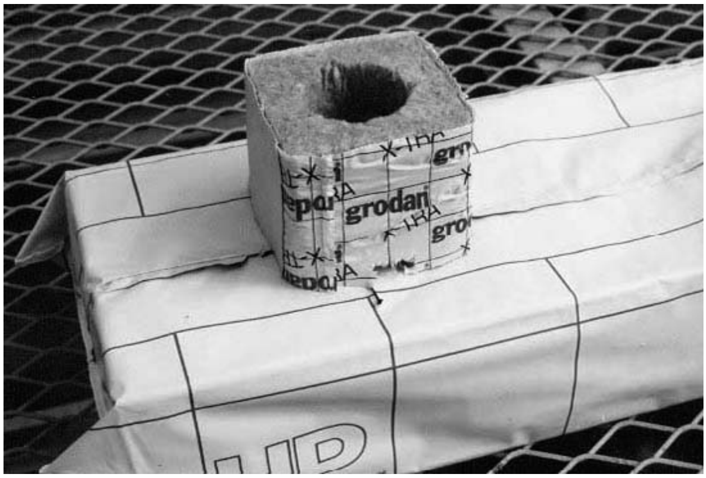

Figure 9.9–1 Rockwool slab wrapped with a white polyethylene sheet with a rockwool cube placed on a cut opening in the sheeting.

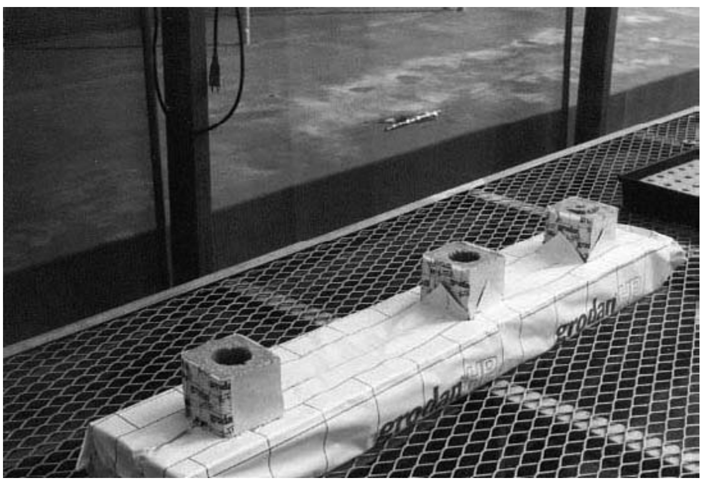

Figure 9.9–2 A typical rockwool slab with rockwool cubes spaced as would be appropriate for growing tomato.

The slabs are normally laid flat on a prepared floor surface, which is usually first covered by white polyethylene ground sheeting. Spacing among the slabs will depend on the configuration of the growing area and the crop to be grown. Once the slabs are set in place, cuts are made along the lower edge of each slab of the polyethylene slab covering on the bottom to allow excess nutrient solution to flow from the slab. An access hole is then cut on the top of the slab sheeting to accommodate a rockwool block containing a growing plant. Nutrient solution is then delivered to each rockwool cube by means of

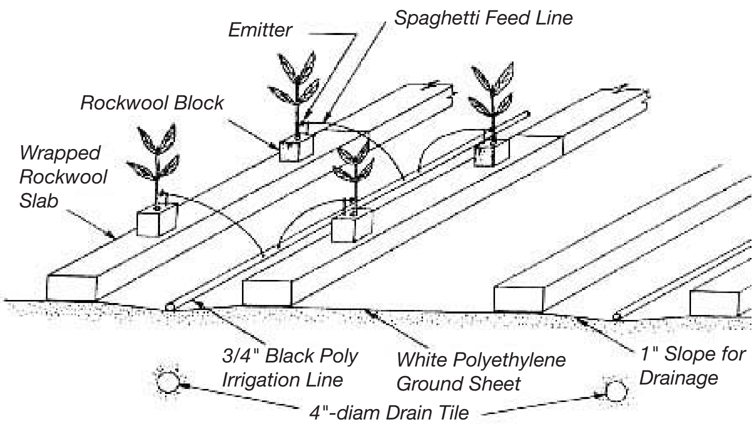

Figure 9.10 Visual sketch of a rockwool slab with a plant-containing cube placed on the slab and a drip line in place. ***Source*****: Resh, H.M., 1995,** ***Hydroponic Food Production*****, 5th ed., Woodbridge Press Publishing, Santa Barbara, CA.**

Table 9.15 Optimum Concentrations and Acceptable Ranges of the Nutrient Solution in a Rockwool Substrate (mg/L, ppm Unless Otherwise Specified)

	Tomato		*Cucumber*	
Determination	*Acceptable*	*Optimum Range*	*Acceptable*	*Optimum Range*
EC (μS/cm)	2.5	2.0 to 3.0	2.0	1.5 to 2.5
pH	5.5	5.0 to 6.0	5.5	5 to 6
Bicarbonate (HCO_3)	<60	0 to 60	60	0 to 60
Nitrate (NO_3)	560	370 to 930	620	440 to 800
Ammonium (NH_4)	<10	0 to 10	<10	1 to 10
Phosphorus (P)	30	15 to 45	30	15 to 45
Potassium (K)	200	160 to 270	175	140 to 270
Calcium (Ca)	200	160 to 280	200	140 to 280
Magnesium (Mg)	50	25 to 70	50	25 to 70
Sulfate (SO_4)	200	100 to 500	200	50 to 300
Boron (B)	0.4	0.2 to 0.8	0.4	0.2 to 0.8
Copper (Cu)	0.04	0.02 to 0.1	0.04	0.02 to 0.1
Iron (Fe)	0.8	0.4 to 1.1	0.7	0.4 to 1.1
Manganese (Mn)	0.4	0.2 to 0.8	0.4	0.2 to 0.8
Zinc (Zn)	0.3	0.2 to 0.7	0.3	0.2 to 0.7

Source: Ingratta, F.J., Blom, T.J., and Strave, W.A., 1985, in A.J. Savage (Ed.), *Hydroponics Worldwide: State of the Art in Soilless Crop Production*, International Center for Special Studies, Honolulu, HI.

a drip irrigation system. A visual sketch of a slab with a plant-containing cube and the drip tube in place is shown in Figure 9.10.

Because this is an "open" system, the nutrient solution is not recovered, and that delivered is sufficient for an excess flow from the cut openings on the bottom edge of the slab. Periodically, a solution sample is drawn from the slab, its EC determined, and if found to exceed a certain level, the slab is leached with water. A pH measurement may also be made, and the nutrient solution composition may be changed if required. Normally, the elemental content of the slab-retained nutrient solution is not determined, although Ingratta et al. (1985) have given optimum and acceptable ranges for the solution of two crops, tomato and cucumber; the values are given in Table 9.15. These same values would also apply to other inert substrates, such as perlite.

Chapter 10

Organic Media Soilless Culture

Sphagnum peat moss and composted milled pinebark are the primary ingredients in most organic soilless media. Commercially prepared organic soilless mixes that have been designed for a particular use and/or crop are readily available; the mix characteristics are usually set by the manufacturer. These organic rooting media have the advantages of low cost and ease of use. It is common practice to add other materials, including vermiculite, perlite, and sand, to the organic substrate to provide desired characteristics, such as increased porosity, water-holding capacity, or weight. Although much has been said and written about the constitution of a desirable mix (Bunt, 1988), few data to substantiate these claims are generally available. Therefore, most growers depend upon past experience when selecting a commercially made mix or when making their own. Adams and Fonteno (2003) describe the physical and chemical properties and biology of various media mixes.

Morgan (2003f) has given some of the physical and chemical characteristics of commonly used organic substrates (Table 10.1).

Physical and Chemical Properties

Organic media have physical and chemical properties that make their use unique compared to inorganic media. For example, sphagnum peat moss (Bunt, 1988) and composted milled pinebark (Pokorny, 1979; Ogden et al., 1987) exhibit to some degree both adsorptive and absorptive properties (Bruce et al., 1980) and thus act more like soil. These characteristics are not found in the inorganic substances, such as gravel, sand, perlite, and rockwool. These organic substances provide a buffering capacity that can work to the advantage of the grower, serving as a storage mechanism for the essential elements,

Table 10.1 Characteristics of Organic Hydroponic Substrates

Substrate	*Characteristics*
Coconut fiber	Made into fine (for seed germination) and fiber forms (coco peat, palm peat, and coir), useful in capillary systems, high ability to hold water and nutrients, can be mixed with perlite to form medium that has varying water-holding capacities, products can vary in particle size and possible Na contamination
Peat	Used in seed raising mixes and potting media, can become waterlogged and is normally mixed with other materials to obtain varying physical and chemical properties
Composted bark	Used in potting media as a substitute for peat, available in various particle sizes, must be composted to reduce toxic materials in original pinebark (from *Pinus radiata*), high in Mn and can affect the N status of plants when initially used, will prevent the development of root diseases
Sawdust	Fresh, uncomposted sawdust of medium to coarse texture good for short-term uses, has reasonable water-holding capacity and aeration, easily decomposes which poses problems for long-term use, source of sawdust can significantly affect its acceptability
Rice hulls	Lesser known and used, has properties similar to perlite, free-draining, low to moderate water-holding capacity, depending on source can contain residue chemicals, may require sterilization before use
Sphagnum moss	Common ingredient in many types of soilless media, varies considerably in physical and chemical properties depending on origin, excellent medium for seed germination and use in net pots for NFT applications, high water-holding capacity and can be easily waterlogged, provides some degree of root disease control
Vermicast and compost	Vermicast (worm castings) and composts are used for organic hydroponic systems, varying considerably in chemical composition and contribution to the nutrient element requirement of plants, can become water-logged, best mixed with other organically derived materials or coarse sand, pumice, or scoria to alter physical characteristics

Source: Morgan, L., 2003f, *The Growing Edge* 15(2):54–66.

which reduces the likelihood of both elemental excesses and shortages. In addition, the organic substances used may intrinsically contain some of the essential elements required by plants in sufficient quantity to satisfy the crop requirement. For example, there is sufficient Mn in composted milled pinebark to meet that element's requirement for most crops.

Many organic soilless mixes are various combinations of sphagnum peat moss, composted milled pinebark, and vermiculite. In some instances, the composition of the mix may reflect the cost and availability of the major ingredient materials more than the physical and chemical characteristics they give to the mix. For example, the increased cost and reduced availability of sphagnum peat moss have led to substitution of other materials, such as composted milled pinebark (Pokorny, 1979). More recently, coconut fiber (sometimes referred to as "coir") (Handrick, 1993), rice hulls, and sawdust have been used alone or added to a mix due mainly to their availability, low cost, and ease of disposal (Morgan, 2003f). Fresh coir can be toxic to plants; therefore, composting is required to decrease the presence of phenolic compounds (Ma and Nickols, 2004), similar to what is required for pinebark prior to use. The influence of coir particle size on the physical and chemical properties of a soilless medium was determined by Abad (2003).

Composts of various kinds, such as coarse sawdust, composted garbage, and other organic refuse and sewage sludges, have been added to mixes (Carlile and Sweetland, 1983; Handreck and Black, 1993). Their relatively low cost and the need for disposal have led to the introduction of these composted materials into some organic soilless mixes. Unfortunately, some composts contain heavy metal residues which, if present in high concentrations, are toxic to plants. Cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), and zinc (Zn) are common elements found in garbage and sewage composts (Chaney, 1983; Hayden, 2003). While these composts can be treated to reduce heavy metal concentrations to below levels toxic to plants, their use should be limited to the growing of nonedible crops.

Particle size and distribution in a soilless organic mix are important, as they determine both the water-holding capacity and aeration of the mix. High water-holding capacity and humid air spaces in the mix are important for germination and seedling and cutting growth, while good aeration and moderate water-holding capacity are essential for long-term plantings. A fine-particle mix is best for seed germination and short-term plant production of seedlings and cuttings; the coarse mixes are best for long-term use, such as growing potted flowering and woody ornamental plants. In a fine mix, the majority of the particles are less than 0.59 mm in diameter and will pass a NBS Sieve Number 20. The majority of the particles in a coarse mix will not pass a NBS Sieve Number 8, as they are 2.38 mm or larger in diameter.

For long-term container growing, the percentage of particles less than 0.59 mm in size should not exceed 20 to 30% to minimize waterlogging. On the other hand, for short-term use, coarse particles 2.38 mm or larger should be completely removed from the mix.

In general, mixtures of sphagnum peat moss and vermiculite and/or perlite are the majority ingredients in fine-particle organic mixtures, while composted milled pinebark alone or with perlite constitutes most of the coarser mixes. However, this is a generalization that does not entirely hold for composted milled pinebark, which can be processed to make a fine-particle mix similar to sphagnum peat moss–based mixes.

A common component added to some mixes is sand; it is added to provide porosity in fine mixes or weight when needed to keep plant containers upright in either fine or coarse mixes. However, sand should not constitute more than 20 to 25% of the mix. If more than 50% of a mix is sand, weight and reduced water-holding capacity become a problem. The recommended grade of sand is "builder's" sand, which is a coarse-particle sand; 100% passes a 10-mesh sieve but only 30% a 40-mesh sieve.

Segregation will occur during the preparation and handling of an organic soilless mix, as most of the components (sphagnum peat moss, composted milled pinebark, perlite, vermiculite, sand, limestone, fertilizer, etc.) vary in particle size and density. Therefore, care is required when preparing, mixing, and handling to prevent segregation. This is particularly important when fertilizer ingredients are being blended into a mix. Even when using an automatic potting machine, an organic soilless mix may be segregated as it is moved from the mixing bin to the pot-filling chute. Making or keeping the mix slightly moist during handling and mixing helps keep components from segregating easily.

Segregation of components is a common problem in prepared mixes due to separation during shipment, as the less dense and larger particles move upward through the mix. Upon receipt and prior to use, careful turning of the mix may be required to restore the materials to their original blend.

Organic Soilless Mix Formulas

While there are many formulas for preparing organic soilless mixes today, the basic concepts of formulation were established by Sheldrake and Boodley (1965) and Boodley and Sheldrake (1972) in their Cornell Peat-Lite mixes and from the University of California basic mix (Baker, 1957); the formulations are given in Table 10.2 and Table 10.3, respectively. From these basic formulas, a number of related mixes for various uses have been devised. A list of ingredients for some of these mixes is given in Table 10.4.

Long-term use of an organic soilless mix requires a different nutrient element charge, as illustrated by three different types of mixes and use: a composted milled pinebark mix for container-grown nursery stock (Table 10.5), a growing-on mix using sphagnum peat moss for ornamental plant production (Table 10.6), and a mix for the bag culture of tomato (Table 10.7).

The Tapia (1985) mix using composted milled pinebark is used for growing seedlings, vegetables, and nursery plants and is designed for use with low and high Ca-containing irrigation water; the formulas are given in Table 10.7.

At this point, the reader may be confused as to the proper constitution and use of an organic soilless mix, and indeed this confusion is widespread. There are no set rules. There is little commercial literature on the use of organic soilless mixes for plant production and little uniformity as to technique of growing. For example, in the *Ball Redbook* (Ball, 1985), a widely used 720-page text on the greenhouse culture of plants, only three pages are devoted to descriptions of soilless mixes and their use, while the more recent issue (Adams and Fonteno, 2003) devotes nine pages out of 724 to soilless mixes.

It is evident that for short-term growing, a wide range of conditions can be tolerated in terms of mix constitutes and methods of fertilization. The grower's observation and experience are the primary controls. By adding or withholding fertilizer, the rate of growth or plant appearance can be easily

Table 10.2 Instructions for Formulating Three Peat-Lite Mixes

Ingredient	*Amount*
Peat-Lite Mix A	
Sphagnum peat moss	11 bu
Horticultural vermiculite No. 2	11 bu
Limestone, ground	5 lb
Superphosphate 0-20-0	1 lb
5-10-5 fertilizer	2 to 12 lb
Peat-Lite Mix B	
Sphagnum peat moss	11 bu
Horticultural perlite	11 bu
Limestone, ground	5 lb
Superphosphate, 0-20-0	1 lb
5-10-5 fertilizer	2 to 12 lb
Peat-Lite Mix C (for Germinating Seed)	
Sphagnum peat moss	1 bu
Horticultural perlite	1 bu
Limestone, dolomitic	7.5 oz
Superphosphate, 0-20-0	1.5 oz
Ammonium nitrate	1 oz

Sources: Sheldrake, R., Jr. and Boodley, J.W., 1965, Commercial Production of Vegetable and Flower Plants, Cornell Extension Bulletin 1065, Cornell University, Ithaca, NY; Boodley, J.W. and Sheldrake, R., Jr., 1972, Cornell Peat-Lite Mixes for Commercial Plant Growing, Information Bulletin No. 43, New York College of Agriculture, Cornell University, Ithaca, NY.

Table 10.3 Basic Fertilizer Additions to Make the University of California Mix[a]

Added Ingredients	*Amount*
Hoof-and-horn or blood meal (13%)	2.5 lb
Potassium nitrate	4.0 oz
Potassium sulfate	4.0 oz
Superphosphate, 0-20-0	2.5 lb
Dolomite limestone	7.5 lb
Calcitic limestone	2.5 lb

[a] California Mix: 50% sand and 50% peat moss to make one cubic yard.

Source: Baker, K.F. (Ed.), 1957, The U.C. System for Producing Healthy Container-Grown Plants. California Agricultural Experiment Station Manual 23. Berkeley, CA.

changed. It is when an organic soilless mix is used for long-term growing that mix constitutes and fertilization technique become critical. Many of the problems that occur in other forms of soilless and hydroponic growing appear,

Table 10.4 Ingredients to Make One Cubic Yard of Soilless Organic Mix

	Type of Mix					
Ingredients	*Cornell Peat-Lite*[a]	*U. C. Mix #D*[a]	*U. C. Mix #E*[a]	Canada Mix *Seedling*[a]	NJ *Tomato* Greenhouse	*Georgia* Greenhouse Tomato
Sphagnum peat moss	11 bu	16.5 bu	22 bu	12 bu	9 bu	—
Milled pinebark	—	—	—	—	—	9 bu
Vermiculite	11 bu	—	—	10 bu	9 bu	—
Perlite	—	—	—	—	4 bu	—
Sand	—	5.5 bu	—	—	—	—
Limestone	5 lb	9 lb	7.5 lb	4 lb	8 lb	1 lb
Superphosphate, 0-20-0	2 lb	2 lb	1 lb	1 lb	2 lb	—
5-10-5 fertilizer	6 lb	—	—	—	—	—
10-10-10 fertilizer	—	—	—	2 lb	—	1 lb
Potassium nitrate	—	—	0.3 lb	0.5 lb	—	—
Calcium nitrate	—	—	—	—	1 lb	—
Borax	10 g	—	—	1 g	10 g	—
Chelated iron	25 g	—	—	—	35 g	—

[a] These mixes are mainly for short-term growth, whereas the other mixes are for long-term greenhouse tomato production.

Table 10.5 Composted Milled Pinebark Mix for Container-Grown Nursery Stock Developed at the Levin Horticultural Research Centre, New Zealand[a]

Added Ingredients	*mg/m*^{3}	*yd*^{3}
Superphosphate	1.0	1 lb 11 oz
Calcium ammonium nitrate	1.0	1 lb 11 oz
Osmocote, 18-11-10 (9-month)	3.0	5 lb
Dolomitic limestone	4–5	6–8.5 lb
Trace element mixture[b]		

[a] Pinebark particle size distribution: 100% < 5 mm, 70–85% < 2.5 mm, 30–60% < 1 mm, and 10–20% < 0.5 mm.

[b] Borax = 118 g/m^3; copper sulfate = 35.4 g/m^3; ferrous sulfate = 50 g/m^3; chelated iron = 14.2 g/m^3; manganese sulfate = 14.2 g/m^3; zinc sulfate = 24 g/m^3.

Source: Bunt, A.C., 1988, *Media and Mixes for Container-Grown Plants,* 2nd ed., Unwin Hyman, London.

such as soluble salt accumulation, disease control, pH shifts, and nutrient element stress. Only by observation and testing can the grower control these factors in order to prevent reduction in plant growth and yield.

Table 10.6 Sphagnum Peat Moss Mix for Ornamental Plant Production

Added Ingredients	*kg/m³*	*yd³*
Superphosphate, 0-20-0	0.9	1 lb 8 oz
Potassium nitrate	0.3	8 oz
20-19-18 fertilizer	0.15	4 oz
Dolomitic limestone	3.0	5 lb

Source: White, J.W., 1974, Dillon Research Fund, Progress Report on Research at Penn State, *Pennsylvania Flower Growers Bull.* 89:3–4.

Table 10.7 Peat Nodules (Sedge or Humified Sphagnum) in 20-l Bag for Greenhouse Tomato Culture

Added Ingredients	*mg/m³*	*yd³*
Superphosphate, 0-20-0	1.75	3 lb
Potassium nitrate	0.87	1 lb 8 oz
Potassium sulfate	0.44	12 oz
Ground limestone	4.2	7 lb
Dolomitic limestone	3.0	5 lb
Frit 253A	0.4	10 oz

Note: Additional slow-release nitrogen as 0.44 kg/m^3 urea-formaldehyde (167 mg N/l) is sometimes included. If a slow-release phosphorus fertilizer is required, magnesium ammonium phosphate ("MagAmp" or "Enmag") at 1.5 kg/m^3 is added.

Source: Bunt, A.C., 1988, *Media and Mixes for Container-Grown Plants,* 2nd ed., Unwin Hyman, London.

Limestone and Fertilizer Additions

Limestone has traditionally been added to organic soilless mixes to both raise the water pH of the mix and provide a source of both Ca and Mg, which are essential elements. However, recent research raises questions about this practice, as raising the pH of the mix even moderately can significantly reduce the availability of most of the essential elements (see Figure 7.2).

An organic soilless mix should not exceed a water pH of 5.5, with the optimum pH range between 4.5 and 5.5. Elimination of limestone from organic soilless mix formulas requires a substitute source for Ca either as calcium sulfate, $CaSO_4$, or calcium nitrate, $Ca(NO_3)_2{\cdot}4H_2O$, and for Mg as magnesium sulfate, $MgSO_4{\cdot}7H_2O$.

In addition, the quality of irrigation water can alter, with time, the pH of an organic soilless mix if the water contains sizable quantities (>30 mg/L, ppm) of either Ca or Mg, or both. With each irrigation, the mix is essentially "limed," and the water pH of the mix rises a bit. In time, the pH may reach the point where the availability of some of the essential elements is adversely affected and one or more nutrient element deficiencies occur. The problem can be partially solved by not adding Ca- or Mg-containing sources to the mix initially, thereby relying on the Ca and Mg content of the irrigation water to supply these two essential plant elements. In such a case, it is essential for the grower to know whether Ca or Mg has been added to the mix or whether the mix is for use where the Ca and Mg requirements of the plant are to be supplied by the irrigation water.

The addition of N, P, and K, usually as chemical fertilizer, is primarily determined based on the use of the organic soilless mix. From a practical standpoint and for short-term cropping (growth period of less than 8 weeks), these elements and the other essential elements would be added to the mix when constituted. However, from a control standpoint, and for all long-term cropping, adding the essential elements as required is best. For practical reasons, some of the elements, such as the micronutrients, may be added when constituting the mix, reserving the three major elements, N, P, and K, for addition as required by the crop being grown. Unfortunately, there is no one best way that can be recommended. The best compromise between considerations of practicality and control appears to be adding the micronutrients and the major elements P, K, Ca, and Mg to the organic soilless mix initially and then supplementing as required based either on a plant analysis and an assay of the mix or on plant growth and appearance. The major elements, primarily N and K, can be added periodically to satisfy the crop requirement based on growth and plant appearance. The element P may be added to the latter group if a complete NPK fertilizer is used to supply the required N and K.

Liquid fertilizers, such as 20-20-20 (N-P_2O-K_2O), are frequently used for supplementation by addition to the irrigation water. The concentration is varied depending on the crop requirement. A common recommendation is that the concentration of N be between 50 and 100 mg/L (ppm). A list of materials and the amount required to prepare fertilizer solutions with a N concentration of 50, 100, 150, and 200 mg/L (ppm) are given in Table 10.8, and ingredient concentrations to make a series of N-P-K-containing solutions are given in Table 10.9 and Table 10.10.

Growers should be aware that repeated long-term use of a fertilizer, such as 20-20-20 applied through the irrigation water, can lead to excesses in P if this element has already been added to the mix. Therefore, care should be taken to ensure that P excess does not occur either by not putting it into the mix initially or by selecting a liquid fertilizer that does not contain P.

Slow-release fertilizers are added to an organic soilless mix for elemental release control. Osmocote (Grace-Sierra Horticultural Products Co., 1001 Yosemite Drive, Mippitas, CA 95035), MagAmp, ureaform, and ordinary chemical-based fertilizer in small perforated polyethylene bags placed in the mix give some degree of control by providing a steady supply of essential elements to plants during their growth cycle, as well as reducing leaching losses. Osmocote, for example, can be obtained in various formulations with varying release-rate characteristics. However, the high cost of some of these slow-release fertilizers must be balanced against the advantages of the control obtained.

Table 10.8 Elements and Liming Materials Added to Pinebark for Growing Seedlings, Vegetables, and Nursery Plants Using Two Calcium Regimes (g/cm^3)

	Mixture	
Added Elements	*General*	*Low-Calcium*[a]
Nitrogen (N)	450	450
Phosphorus (P)	150	150
Potassium (K)	200	200
Calcium (Ca)	2300	—
Magnesium (Mg)	650	—
FRIT	300	300
Liming Materials		
Dolomitic lime	4000	—
Calcitic lime	4000	—

[a] Mix for use where Ca will be supplied by the irrigation water.

Source: Tapia, M.L., 1985, in A.J. Savage (Ed.), *Hydroponics Worldwide: State of the Art in Soilless Crop Production*, International Center for Special Studies, Honolulu, HI.

Table 10.9 Pounds of Fertilizer per 100 Gallons of Water to Make Solutions with Nitrogen Concentrations of 50, 100, 150, and 200 mg/L (ppm) for Fertilizer Supplementation

	Milligrams Nitrogen per Liter (ppm)			
Fertilizer	*50*	*100*	*150*	*200*
	Pounds per 100 Gallons Water			
Calcium nitrate, $Ca(NO_3)_2{\bullet}4H_2O$	0.24	0.48	0.72	0.96
Potassium nitrate, KNO_3	0.32	0.64	0.96	1.28
5-10-5	0.83	1.66	2.49	3.32
10-10-10	0.41	0.83	1.29	1.66
20-20-20	0.20	0.41	0.63	0.83

Growing Techniques

Traditional organic soilless media culture is carried out with the medium placed in a bed, pot, or can. Water, with or without fertilizer added, is applied periodically by either overhead irrigation or by drip irrigation into the container in quantities relative to the atmospheric demand on the plant. As is the case in gravel and sand systems, the medium may require periodic flushing with water to remove accumulated salts; the need to flush is determined by a soluble salt reading of the medium itself or the effluent from the container. Commonly, the container is discarded after one use, although some growers have devised interesting schemes to use the medium for more than one crop; one example is growing a crop of tomato followed by an outdoor ornamental

Table 10.10 Preparation of Liquid Feeds from Complete NPK Water-Soluble Fertilizer (Based on U.S. Gallon)

Fertilizer			*Element Equivalent (%)*			*Ounces per U.S. Gallon Diluted*	*mg/L (ppm)*		
N	P_2O_5	K_2O	*N*	*P*	*K*	*1 in 200*	*N*	*P*	*K*
20	20	20	20	8.8	16.6	26.6	200	88	166
15	30	15	15	13.2	12.5	35.5	200	176	167
14	14	14	14	6.2	11.6	38.0	200	88	166
21	7	7	21	3.1	5.8	25.3	200	30	55
20	5	30	20	2.2	24.9	26.6	200	22	249
25	10	10	25	4.4	8.3	21.3	200	35	66

Note: To obtain 100 mg N/L (ppm), use one-half the above weights of fertilizer; for 150 mg N/L (ppm), use three-quarters of the weight.

tree or shrub. The sale of the ornamental plant also provides a means of disposal of the container and medium.

Another growing technique is to plant directly into the medium shipping bag, adding the required essential elements and water by drip irrigation. Normally, the mix is supplemented with micronutrients, and the major elements are applied in a nutrient solution whose composition may be comparable to that of a Hoagland/Arnon nutrient solution (see Table 7.10), with or without micronutrients, or some other formulation. An example of nutrient solutions recommended for preenriched composted milled pinebark and sawdust for cucumber and tomato is given in Table 10.11.

The flow of the nutrient solution through the drip irrigation system must be sufficient to meet the water requirement. If plant growth is normal, elemental utilization should be sufficient to prevent a significant accumulation of excess salts. When plant growth is slow due to poor external growing conditions, then applying only water without elements added is best, and the nutrient solution application is resumed when growth conditions improve. Some growers substitute a mixture of an equal ratio of potassium and calcium nitrates, KNO_3 and $Ca(NO_3)_2 \cdot 4H_2O$, respectively, to give a solution containing 100 mg/L (ppm) N in place of the Hoagland/Arnon formula. If this is done, the medium must contain sufficient P and Mg to meet the crop requirement.

Unique Application

A unique application of an organic soilless mix for long-term growing is a system employing subirrigation based on a technique first introduced by Geraldson (1963) for growing staked tomatoes in the sandy soils of southwestern Florida (Geraldson, 1982). In fields where the water table level can be controlled, raised plastic-covered beds are prepared with a band of fertilizer placed down each side of the bed. Tomato plants are set in the center of the

Table 10.11 Weight of Fertilizer (in Grams) Required to Prepare One Liter of Stock Solution for Dilution at 1 in 200 to Give a Range of Liquid Feeds

Fertilizer[a]	*N50 P7.5*	*N100 P15*	*N150 P22.5*	*N200 P30*	*N250 P37.5*	*N300 P45*	
Ammonium nitrate	16.0	42.3	68.9	95.4	121.8	148.3	
Monoammonium phosphate	6.1	12.3	18.4	24.5	30.6	36.7	K50
Potassium nitrate	26.3	26.3	26.3	26.3	26.3	26.3	
(EC)	(0.32)	(0.57)	(0.80)	(1.04)	(1.28)	(1.51)	
Ammonium nitrate	5.4	31.9	58.4	84.8	111.3	137.8	
Monoammonium phosphate	6.1	12.3	18.4	24.5	30.6	36.7	K100
Potassium nitrate	52.6	52.6	52.6	52.6	52.6	52.6	
(EC)	(0.41)	(0.65)	(0.89)	(1.12)	(1.35)	(1.58)	
Ammonium nitrate	[b]	21.4	47.8	74.3	100.8	127.3	
Monoammonium phosphate	6.1	12.3	18.4	24.5	30.6	36.7	N150
Potassium nitrate	78.9	78.9	78.9	78.9	78.9	78.9	
(EC)	(0.58)	(0.73)	(0.96)	(1.20)	(1.43)	(1.66)	
Ammonium nitrate	—	10.8	37.3	63.8	90.2	116.7	
Monoammonium phosphate	—	12.3	18.4	24.5	30.6	36.7	N200
Potassium nitrate	—	105.3	105.3	105.3	105.3	105.3	
(EC)	—	(0.82)	(1.04)	(1.29)	(1.52)	(1.74)	
Ammonium nitrate	—	nil	26.8	53.3	79.8	106.3	
Monoammonium phosphate	—	12.3	18.4	24.5	30.6	36.7	K250
Potassium nitrate	—	131.5	131.5	131.5	131.5	131.5	
(EC)	—	(0.90)	(1.11)	(1.37)	(1.60)	(1.84)	
Ammonium nitrate	—	[c]	16.3	42.8	69.2	95.7	
Monoammonium phosphate	—	12.3	18.4	24.5	30.6	36.7	K300
Potassium nitrate	—	157.8	157.8	157.8	157.8	157.8	
(EC)	—	—	(1.22)	(1.44)	(1.69)	(1.87)	

Note: Numbers following N, P, and K are mg/L (ppm) of nitrogen, phosphorus, and potassium in the prepared solutions.

[a] This table was computed using the following fertilizer analysis: ammonium nitrate 35% N; monoammonium phosphate 12% N, 24.5% P; potassium nitrate = 14% N, 38% N. The EC values of the diluted fertilizer solutions are expressed in mmhos/cm at 25°C.

[b] 58.9 mg/L (ppm) nitrogen.

[c] 117.8 mg/L (ppm) nitrogen.

Source: Bunt, A.C., 1988, *Media and Mixes for Container-Grown Plants,* 2nd ed., Unwin Hyman, London.

beds, and the roots grow into the area of the soil which is balanced in water and elemental content, as illustrated in Figure 10.1. The author duplicated the same system by placing a coarse organic soilless mix into a watertight box so that a constant water table could be maintained under the mix.

A 4 × 30 ft (1 × 9 m) growbox system, employing composted milled pinebark as the growing medium supplemented with limestone and fertilizer (as shown in the last column of Table 10.4), was successfully used to grow

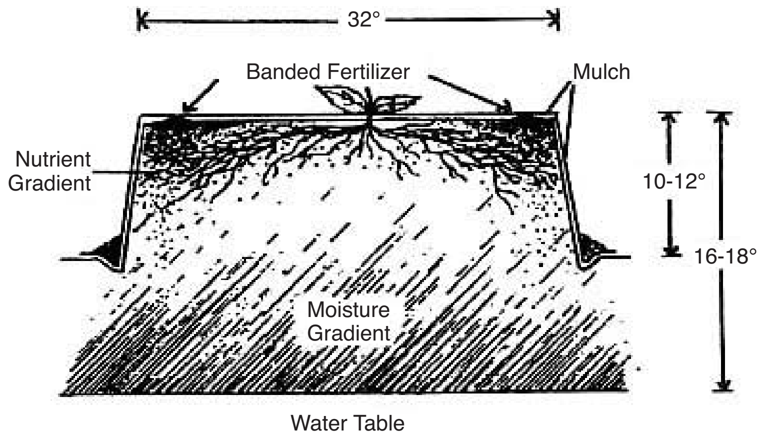

Figure 10.1 Control of the root ionic environment obtained by balancing fertilizer placed on the surface of a raised bed, using a plastic mulch cover and maintaining a definite water table (*Source*: Geraldson, 1963. Quality and balance of nutrients required for best yields and quality of tomatoes, Proc. Fla. State Hort. Soc. 76:153–158.).

greenhouse tomatoes, cucumbers, and snapdragons over an 8-year period. The constant water table of 1 inch (2.5 cm) depth is maintained below 7 inches (18 cm) of composted milled pinebark with an automatic float value system. No water is applied overhead. Fertilizer is added to the medium between crops based on an elemental assay of the medium. The tomato crop is supplemented periodically with a mixture of potassium and calcium nitrates, KNO_3 and $Ca(NO_3)_2{\cdot}4H_2O$, respectively, at a N concentration of 100 mg/L (ppm) based on a need determined by the physical appearance of the plant and/or periodic plant analyses.

The composted milled pinebark maintained its original physical properties over the 8-year period of use, requiring only small yearly additions of new composted milled pinebark to maintain the initial volume. Initially, some boxes were filled with a peatlite mix, which failed to maintain a good physical character beyond the first year and therefore was discarded and replaced by composted milled pinebark.

The success of this subirrigation growbox system is due in large part to the constantly maintained water table, which allows the roots to grow into that portion of the medium ideal in terms of water, aeration, and elemental supply. The grower does not need to be concerned about watering on high atmospheric demand days, as water is always available to the plant. As the growing system is essentially self-regulating, the grower can concentrate on the cultural management of the crop.

The grow-box can be made in almost any size to accommodate a wide range of uses, even outdoor family vegetable gardening (Jones, 1980); a design

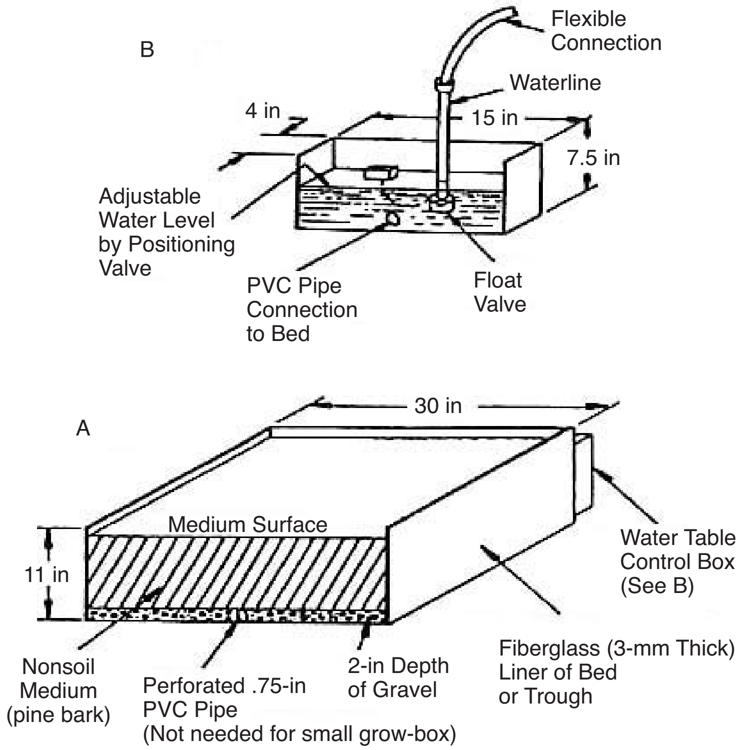

Figure 10.2 Pinebark grow-box system employing a constant water table with automatic water level control. ***Source*****: Jones, J.B., Jr., 1980. Construct your own automatic growing machine.** ***Popular Science*** **216(3):87.**

of the grow-box is shown in Figure 10.2. The only critical dimension is the depth of the organic soilless medium, which must not be more or less than 7 inches (18 cm) above the water table. Composted milled pinebark seems to be the best of all the organic substances for this application.

Chapter 11

Hydroponic Cropping

Introduction

When hydroponics was initially applied commercially, only three crop species were commonly grown: tomato, herbs, and lettuce. Today a wide range of crops (i.e., cucumber, pepper, strawberry, roses, and potatoes) is being successfully grown hydroponically. Even so, most commercially available hydroponic systems are still based on the requirements for growing either tomato or herbs and lettuce. In the early 1970s, the author visited a hydroponic greenhouse where the grower had successfully switched from growing tomato to chrysanthemum flower production in a gravel-sump ebb-and-flow (sometimes referred to as flood-and-drain) system using the same procedures as those given for tomato (Figure 11.1). This suggested to me that many different kinds of plants can be successfully grown hydroponically, although the selected hydroponic system was not specifically designed for that crop. Since that initial experience, this continues to be proven true. Today, a wide range of vegetables, flowers, and even tree crops are being grown hydroponically using primarily two nutrient solution delivery techniques, ebb-and-flow (Figure 11.2) and drip irrigation (Figure 11.3-2). The only exceptions would be for herbs and lettuce, where the Nutrient Film Technique (NFT) method (see pages 127–141) (Christian, 1997, 1999; Furukawa, 2000; Morgan, 2000b; Alexander, 2001a; Smith, 2002c) is preferred; the raft system (Figure 11.4) is also used by some lettuce growers (Morgan, 2002f; Spillane, 2001).

An excellent example of what is possible hydroponically can be seen on display at the Kraft Exhibit in the Disney EPCOT Center, Orlando, Florida (Ricks, 1996). Visitors taking the boat ride through the exhibit will see many different crop plants being grown in various hydroponic configurations. A closer view of these growing systems, plus what experiments are being conducted but not on display, can be observed if the visitor takes the "behind the scenes tour."

Figure 11.1 Gravel bed flood-and-drain hydroponic growing system designed for tomato greenhouse production that was successively switched to chrysanthemum flower production using the same growing procedures as for tomato. On the far left (just beyond the walkway) is a gravel bed ready to be planted.

Another interesting application of hydroponics is at the Hydroponicum, located on the west coast of Scotland (Savage, 1995; Farquhar, 2003). A number of temperate-to-tropical plants are being grown hydroponically in three different climatic regimes within the Hydroponicum. Most of the plants are being grown in a specially designed Pyramid Pot (see Figure 4.1) in which the nutrient solution is supplied by a passive Wick System, both developed by the founder of the Hydroponicum, Robert Irvine (Savage, 1995).

For most, hydroponics and growing in an environmentally controlled climate, such as a greenhouse, are correlated, as hydroponics is not generally considered a method of growing in the open (outdoor) environment. However it is interesting to note that open environment hydroponic systems were in wide use during WWII, when vegetables were grown hydroponically to provide fresh produce for troops operating in the Pacific campaign areas. After WWII in 1950, the author visited a number of hydroponic farms in south Florida; the crop grown was tomato in the open environment in ebb-and-flow gravel beds. Some of the early literature on hydroponics in the 1950s and 60s

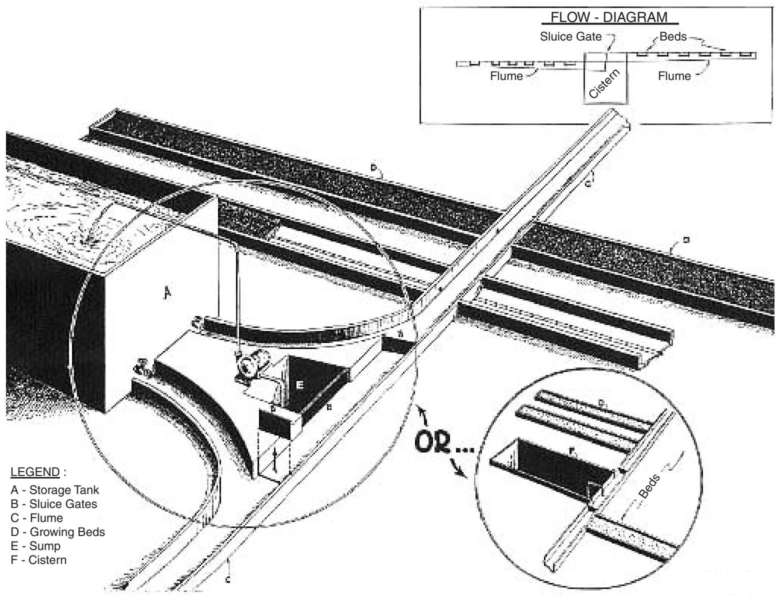

Figure 11.2 Basic drawing of an ebb-and-flow (flood-and-drain) hydroponic growing system in common use in the past for growing a wide range of crops. Stored in the base or sump under the growing bed, a nutrient solution is pumped into the growing bed above (usually containing gravel of similar inert coarse material), flooding the bed, and then after a short time, the nutrient solution flows by gravity back into the sump. In this drawing, the nutrient solution is pumped into a storage tank and then flows into the growing beds through a sluice and plume system. *Source:* Eastwood, T., 1947, *Soilless Growth of Plants*, 2nd edition, Reinhold Publishing, New York; also see Texier, 1995.

discussed methods of growing in the open field (Eastwood, 1947; Schwarz, 2003).

Today, much of the current literature on hydroponics discusses this topic as a form of "controlled environment agriculture (CEA)" (see page 305–307). Therefore, much of the success associated with hydroponics may be more related to environmental control advances than those associated with the hydroponic method being employed. One wonders whether the future of hydroponics as a major method for crop production lies in other than open field settings as it was in its initial years of application.

Hydroponic growing systems vary as to design, operational characteristics and reliability, and are generally more expensive and complex to operate than most other growing methods. Therefore, high-value cash crops (such as tomato) or specialty crops (such as herbs) are more frequently chosen for hydroponic production than are crops of lower cash value. Although initial costs may be high, hydroponics can be highly profitable as a method of crop production. Several of the major disadvantages of hydroponics are the high capital cost for most of the commonly used growing systems, frequent inci-

Figure 11.3–1 BATO buckets come in two colors, black for cool season use and off-white for warm season use.

Figure 11.3–2 Drip irrigation system set in place for perlite-filled BATO bucket growing system (the large black tubing running down the length of the line of buckets is the main nutrient solution delivery line and from that delivery line, dripper lines are attached for placement in each bucket).

dences of root disease, and the potential for nutrient element insufficiencies. However, these factors are being addressed and advances made to solve the problems of cost and insufficiencies related to the hydroponic method of growing.

Figure 11.4 Small raft system for lettuce production (a styrofoam sheet is floated on nutrient solution in the large container with openings in the sheet for placing lettuce plants set in lattice pots).

It should be remembered that hydroponics is not a panacea for success, no matter what crop is being grown or what growing system is employed. In general, the cultural requirements for a crop do not change even though a hydroponic growing technique is employed. In some instances, it may require greater skill on the part of the grower to be successful when a hydroponic method is used.

Hydroponics does not invalidate the genetic character of plants; plant growth and fruit production will not exceed what is genetically possible irrespective of the growing method used. Resh (1995, see Table 1.2 in Chapter 1) compared yields per acre in soil versus in soilless culture, suggesting that such differences are due to efficient nutritional regulation by controlled use of water and fertilizers and higher-density planting. Hydroponics does offer the ability to control the supply of water and the essential elements to plant roots, thereby ensuring a continuous optimum supply, which can in turn enhance plant performance. Greenhouse grown crops, such as tomato, cucumber, pepper, and lettuce, can be grown over a longer time period than that possible for field grown. Therefore yield comparisons for that hydroponically grown versus soil field-grown can be misleading, for if equably compared, yields are probably similar.

When growing conditions are such that no other system of growing is suitable, due to poor soil conditions and extreme climatic regions, and for growing in outer space and roof-top gardening (Wilson, 2002a), for example, hydroponic production may be the only option.

The public's increasing interest in wanting to purchase "organically grown" produce may significantly impact the future of hydroponics (Parker, 1989; Morgan, 1997c; Landers, 2001). Being just pesticide/herbicide free is no longer the single factor that attracts the environmentally sensitive consumer who is looking for food products that are "organically grown." Schoenstein (2001) states that "in addition to the organic angle, controlled-environment greenhouse agriculture allows farmers to reach more niche markets due to their ability to extend a crop into a much longer season than that available to outdoor growers. With the rise in the huge, large-scale greenhouses in North America, the value of conventional off-season produce is decreasing while the value for organic crops remains high." The switch from inorganic to organic hydroponics will require the development of suitable growing media and nutrient solution formulations that will qualify as being organic. Schoenstein (2001) describes a greenhouse operation that is producing lettuce and herbs using an organic NFT growing system.

Progressive Developments

The initial hydroponic growing system was the standing aerated nutrient solution method, a method considered not suited for commercial use (see Figure 9.1). However, Cunningham (1997) describes the use of this technique (which he identifies as the updated Gericke system, Figure 11.5-1) for the growing of green bean, tomato, and zucchini squash, a system that does not require electrical power and is fairly simple to put into use. Kratky (1996) describes the general principles and concepts of a noncirculating growing system for hydroponically growing lettuce, tomato, and European cucumbers (Figure 11.5-2).

Wilcox (1983) published an extensive review of those hydroponic systems in use throughout the world at that time, water or solution culture, sand culture, aggregate culture, and the nutrient film layout. For commercial applications, the ebb-and-flow method (Fischer et al., 1990) was the initial hydroponic growing system, closely followed by the gravity flow bed system. There

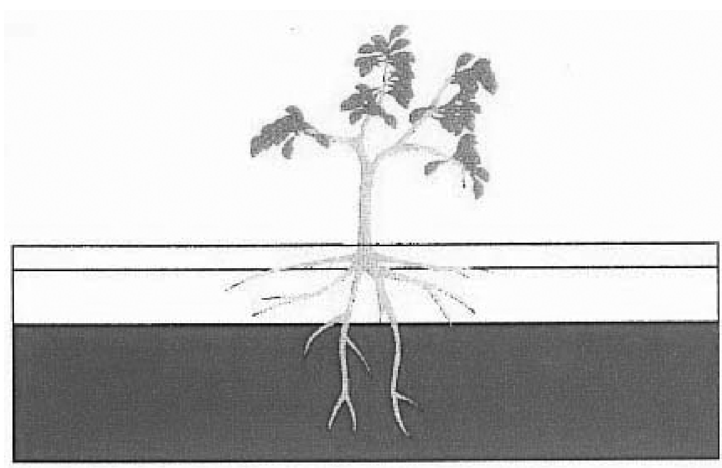

Figure 11.5–1 Updated Gericke system for growing garden vegetables. Plants are suspended over a nutrient solution reservoir with an air gap between the base of the plant and suspended roots. ***Source:*** **Coene, T., 1997,** ***The Growing Edge*** **8(4):34–40.**

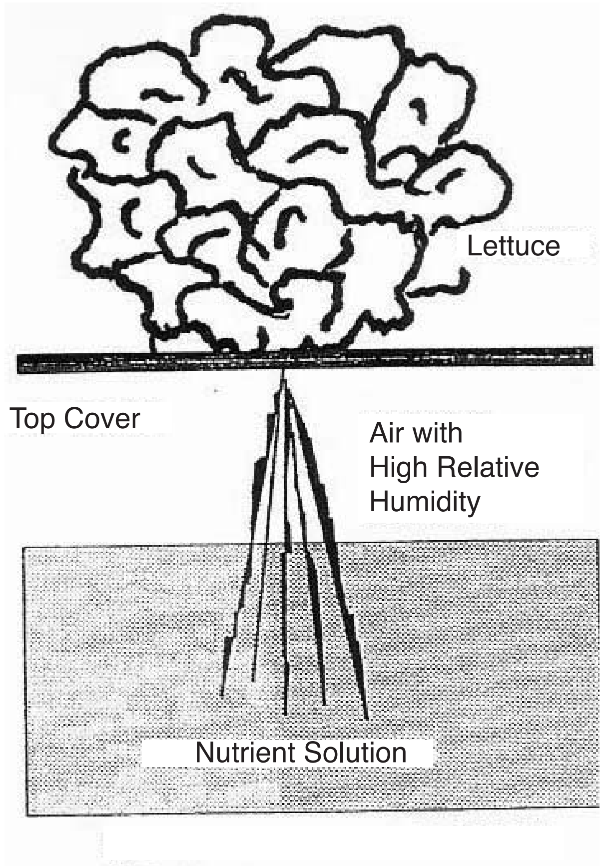

Figure 11.5–2 A similar growing system has been devised by Kratky, in which lettuce plants are suspended over nutrient solution with a gap of high relative humidity air between the base of the plant and suspended roots. *Source*: Kratky, B.A., 1996, *Non-Circulating Hydroponic Methods,* DPL Hawaii, Hilo, HI.

are other techniques that have specific applications, such as the raft system for lettuce production (Spillane, 2001; Morgan, 2002f) and aeroponics (see pages 142–143) (Nichols, 2002; Wilson, 2002b).

In 1979, the Nutrient Film Technique (NFT) developed by Cooper (1979b) was hailed as a revolutionary step forward that would alter the method of hydroponic growing for all crops. But this did not prove to be true (see pages). Smith (2000), however, identifies several locations where the NFT method is in use for growing tomato (Christian, 1999), strawberry, and pepper. Smith (2001e) provides instructions on the use of this method for growing tomato. Today, the NFT method (Alexander, 2001; Smith, 2002c,d) as well as deep water NFT (Jones, 1990) are primarily used for the hydroponic production of lettuce and herbs. Morgan (l999c) describes the various designs for gullies and channels for use in NFT applications. Smith (2004) also gives instructions for the design and construction of NFT gullies.

With the introduction of drip irrigation, water and/or a nutrient solution could be dispensed at a specific point and precise volume. Using this method, growers are able to grow hydroponically in containers of inert media, such as perlite (Day, 1991) in bags (see Figure 9.6) (Bauerle, 1984) or BATO buckets (see Figure 9.7) or in rockwool blocks and slabs (Figures 9.9–1 and 9.9–2) (Smith, 1987; Sonneveld, 1989; Van Patten, 1989, 1991; Johnson, 2001a). Today, this is the primary technique of choice for the growing of tomato, cucumber, and pepper. Organic substances are also being used as the rooting medium, such as composted milled pinebark (Pokorny, 1979) and coconut fiber (Morgan, 1999b), which have an environmental advantage over perlite and rockwool (Spillane, 2002a) since they are biodegradable (Johnson, 200lb). Morgan (2003e) describes the properties and use of a wide range of growing media (substrates) (rockwool and stonewool, vermiculite, perlite, coconut fiber, peat, composted bark, pea gravel and metal chip, sand, expanded clay, sawdust, pumice, scoria, polyurethane grow slabs, rice hulls, spaghnum moss, and vermicast and compost). She then matches substrate characteristics with a particular hydroponic growing method (Table 11.1).

Propagation substrate selection is based on properties suited to germination and seedling growth (Morgan 2003f; 2004c). Other factors, such as seed size, drainage requirements, and continued use beyond germination, can determine which substrate is best. Rockwool is probably the most widely used germination substrate. Fine-textured (particle size) germination substrates are peat, sand, perlite, vermiculite, sphagnum moss, and coconut fiber. Coarse-textured substrates are gravel, scoria, and expanded clay. Combinations of these materials can be used to establish a particular characteristic, such as moisture retention, drainage rate, and weight.

Table 11.1 Substrate Characteristics Matched to a Particular Hydroponic Growing Method

Hydroponic Method	*Substrate Characteristics*
Ebb-and-flow	Must be reasonably heavy so that it will not float away, drain reasonably well although hold some moisture, materials such as expanded clay, gravel, coarse sand, pumice, or rock-like material
Drip irrigation systems	Must hold a reasonable amount of moisture, high percentage of air filled pores
Warm climates	Heavy media types that hold more water and are slow to heat up, materials such as coconut fiber, ground bark, rockwool, or stonewool
Cooler climates	Prevention of continually cold wet root system important, freer draining, materials such as perlite, pumice, sand, and expanded clay

Source: Morgan, L., 2003f, *The Growing Edge* 15(2):54–66.

Nutrient Solution Formulations and Their Use

A detailed discussion on nutrient solutions, their formulation and use, may be found in Chapter 7 of this book. The hydroponic literature is filled with specific formulations that have been prescribed for a particular crop or application. For example, in *The Growing Edge* magazine in issues published between 1989 and 2002, Jones and Gibson (2003) found 19 articles related to the formulation (see Table 7.17) and use of nutrient solutions and some 32 specific nutrient solution formulas recommended for various crops. Crop requirement is a major factor that would specify the need for a particular formulation or application procedure. In most instances, use instructions are sketchy, which would leave the reader confused as to how the nutrient solution is to be dispensed to the plant (frequency of application and volume, for example, are not given). Automated methods for dispensing the nutrient solution are generally used, such as the dosing devices described by Smith (2001f) and Christian (2001).

In this chapter, formulations that have appeared in the literature for use with a particular crop and/or hydroponic growing technique are given. These formulation recommendations should be carefully evaluated before their acceptance and use. It has been the author's experience that only a few formulations are suitable for wide use (see pages113–115). The type of hydroponic growing system, crop being grown, and the environmental conditions are influencing factors that would require formulation/use recommendation modification. Those wanting to make their nutrient solution from scratch will find the instructions by Musgrave (2001) helpful, covering the Rule of Conversion, Determining Elemental Percentages, and the Rest of the Conversion Theory.

Cultivar/Variety Availability and Selection

Crop cultivars/varieties identified as best suited for only hydroponic growing do not exist. Breeding and selection are based on developing plants best suited to a specific environment, such as day length and light intensity, or plant characteristics, such as disease resistance, drought and/or heat tolerance, fruiting habit, and fruit characteristics (Waterman, 1993–94, 1996b, 1997, 1998b). Much has been written about "genetically modified" varieties, modified in order to obtain a particular characteristic, a topic that has stirred much comment and controversy (Baisden, 1994; Waterman, 1997). Much of the breeding work has focused on those crops most commonly grown and those that would be classed as "high cash valued," including tomato.

Recently there has been interest in "heritage" varieties (Male, 1999; Johnson, 1999), those that have a significant history of acceptance and use. However, many varieties, including heritage, do not perform well in some types of growing systems, whether hydroponic or not. Also, many heritage varieties lack specific disease resistance, one of the major focuses in the introduction of new varieties. In addition, much of the breeding work has been focused on cultivar development where the need is greatest. For example, greenhouse tomato cultivar breeding and selection have been for adaptation to low-light, low-temperature conditions, while little attention has been given for cultivars that would have high-light, high-temperature tolerance. In addition, fruit quality in terms of physical appearance, color, firmness to withstand rough handling, storage quality, etc., are some of the qualities being bred into the newly issued cultivars. Cultivar/variety selection is a major decision that the grower faces, where a misselection can lead to poor plant performance and low fruit quality.

Grower Skill and Competence

As with any plant growing venture, the skill of the grower can mean the difference between success and failure irrespective of the operational quality of the growing system. Some attribute this to a green thumb ability that some individuals seem to have — that sense to know what to do and when that leads to maximum plant performance. The author has visited many greenhouses, and just by looking around, it does not take long to easily assess the skill and ability of the grower to manage the crop and greenhouse facility. For example, just the physical appearance of the crop, such as its freedom from insect and disease infestations, is a good indicator of grower skill. Answers to questions such as "what has been the timeliness of applied cultural practices? What is the general condition of the greenhouse structure, inside and out, its cleanliness, the condition and efficiency of the heating, cooling and air distribution systems?" provide further information. These are some of the observable things that can be used to determine the competence of the grower and workers. Smith (2002a,b), for example, gives advice on what a NFT tomato grower needs to do when the crop is in full production to sustain fruit yield, advice that can be applied to any hydroponic grower evaluation (Table 11.2). What have been the past training experiences? Much can be learned from practical experience and/or hands-on-training under the tutelage of a knowledgeable instructor.

It has been the author's experience that most hydroponic growing system failures occur due to a mix of factors. During the 1970s, I witnessed the collapse of a hydroponic industry in the state of Georgia. It occurred due to two primary factors, the poor design and inefficiencies of both the greenhouse and hydroponic growing system, and the lack of experience and professional skill on the part of the growers required to successfully manage the greenhouse/hydroponic system. At about the same time, I observed the success of a small group of tomato–greenhouse growers in southeast Georgia who were trained and guided by a skilled experienced professional. When that individual left to take another position, many of the growers he trained and guided closed their greenhouses, fearing that trying to continue without his guidance would eventually lead to failure.

An entrepreneur in central Florida had a successful hydroponic business growing tomatoes in semienclosed structures using an ebb-and-flow gravel medium system. When the root disease *Phytium aphanidermutum* entered

Table 11.2 Instructions on Procedures for Managing a NFT Tomato Crop

Immediately apply a fungicide on plant wounds, particularly if *Botrytis* is a commonly occurring disease.
Remove laterals and then immediately lower the plant [see *The Growing Edge* 13(1):82 (2001)].
Before fruit harvesting, remove all senile leaves (will reduce potential for disease and other plant problems).
Keep the nutrient solution barrels and measure and correct the pH if outside the pH range of 6.0 to 6.5.
Cut fruit using sharp pruning scissors — keep the calyx on the fruit to maintain fruit quality, and refrigerate at a temperature just above 55˚F (13˚C).
In cold weather conditions, keep the rooting medium and nutrient solution at a temperature above 59˚F (15˚C), and the air temperature within 70 to 77˚F (21 to 25˚C).

Sources: Smith, B., 2002b, *The Growing Edge* 13(4):75–79; Smith, B., 2002, *The Growing Edge* 13(5):79–82.

the growing medium, he was unprepared to deal with this infestation, and his business failed in less than 6 months.

Grower success is hinged on many factors other than the innate skill of the individual. Having the input of professionals in all aspects of the growing method can significantly contribute to success. However, no amount of grower skill and professional guidance can overcome the effects of a poorly designed greenhouse or hydroponic growing system.

Home Gardener/Hobby Hydroponic Grower

Hydroponics offers the home gardener and hobbyist a challenge that some have undertaken. Most have devised their own hydroponic growing systems based on information found in books, manuals, and magazine articles, and from the Internet. Smith (2001a,b,c,d), in a four-part series, describes how to design and build your own hydroponic system. He states, “my introductory hydroponic series delved into the fundamentals of what makes hydroponics tick. We discussed the quality of your water supply, the different types of systems, and the hydroponic nutrition required by your plants.” “Hydroponics for the Rest of Us” is the title of an article that details various hydroponic growing systems (passive — wick system and active — flood-and-drain, top feed, NFT) and their operating requirements. The two recommended for the home gardener are the flood-and-drain and top feed hydroponic systems because they “lend themselves well to home design and construction without sacrificing durability and efficiency” (Van Patten, 1992). In addition, Van Patten (1992) divides systems into two additional categories, recovery or nonrecovery (recirculation or discard, respectively) of the nutrient solution.

Coene (1997) provides basic information on soilless gardening, focusing on media- and water-based culture systems, nutrient solutions, artificial lighting, and pest control, and then she describes how to build a drip system growing vessel (Figure 11.6). Similarly, Creaser (1997) gives instructions for

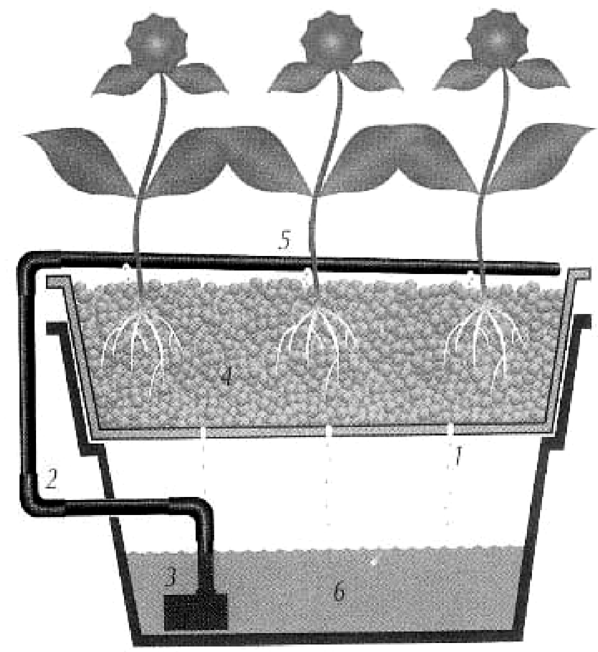

Figure 11.6 Drip system hydroponic growing vessel for growing vegetables (1: small holes in the base of the growing vessel allows applied nutrient solution to flow back into the nutrient solution reservoir (6), 2: nutrient solution delivery line, 3: pump, 5: drop irrigation line). *Source:* Coene, T., 1997, *The Growing Edge* 8(4):34–40.

the construction of a drip system growing tray that he has been using to grow an array of vegetables and house plants (Figure 11.7).

Peckenpaugh (2002a) recognized the need of hobby growers to have a reliable source of information on hydroponic techniques and procedures. He describes the design and operation for four hydroponic systems (NFT, floating raft, ebb-and-flow, and drip), the formulation and use of nutrient solutions including organic, and identifies those crops (cucumber, lettuce, pepper, strawberry, and tomato) most commonly grown plus how to deal with insects and diseases. For one who wants to just experiment with small growing systems, Peckenpaugh (2002a) describes hydroponic growing techniques that "can be built by anyone with the time and patience to go through the process." In his article, he describes three different growing systems, Passively Wicking Pot, Styrofoam Cooler Grower, and Dutch Pot Dripper, lists the materials needed to construct each of the systems (Table 11.3), and describes how to assemble and operate each.

For those wanting to construct their own drip irrigation hydroponic growing system, Peckenpaugh (2003b) lists the following items required: growing container, drip irrigation lines, drip emitters, nutrient reservoir, submersible pump, nutrient return line, growing media (expanded clay), and timer. He states that "drip irrigation approaches the pinnacle of growing sophistication due to its

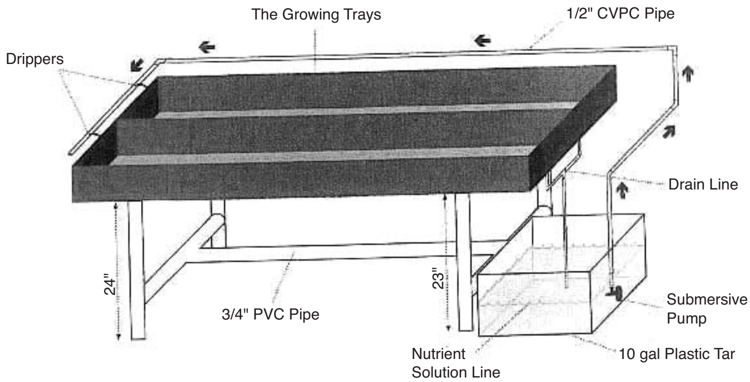

Figure 11.7 Drip system hydroponic growing tray for growing vegetables. ***Source:*** **Creaser, G., 1997,** ***The Growing Edge*** **8(3):68–73.**

highly economical use of water and precise application of nutrients to the plant's root zone." Expanded clay is the growing medium since it "holds some moisture and nutrient for plant use after the irrigation cycle but doesn't get soggy or overly wet." In addition, expanded clay can be easily sterilized after use by baking at 400°F (204°C) for an hour. In a follow-up article, Peckenpaugh (2003c) describes his success in using his homemade hydroponic growing system.

Alexander and Coene (1995–96) focused on those hydroponic systems that would attract the cost-conscious grower who does not want to make a significant investment in equipment. A simple passive hydroponic system, described by Christensen (1994b), may be a good place to begin one's initial venture into hydroponics; it is a spin off of an earlier-described noncirculating hydroponic system (Christensen, 1994a). The recent book by Roberto (2001) provides a "guide to build and operate indoor and outdoor hydroponic gardens, including detailed instructions and step-by-step plans." Resh (2003) has a book on hobby hydroponics "to provide the reader with information on the basics of hydroponics that can be applied to a small-scale or hobby setup."

Table 11.3 Materials Needed to Construct Your Own Hydroponic Growing System

Growing System	*Materials*
Passively wicking pot	Two pots or buckets, wicking material, wire (optional), utility knife or drill, growing media
Styrofoam cooler grower	Styrofoam cooler, polythylene or garbage bag, duct tape, propagation cubes, utility knife, aquarium pump, tubing, and air stone (optional)
Dutch pot dripper	Pots, nutrient solution reservoir, submersible pump, runoff collection trough (optional), fine mesh screening, drip irrigation tubing, emitters, and support stakes

Source: Peckenpaugh, D.J., 2002b, *The Growing Edge* 13(4):81–83.

Even the houseplant grower can switch from soil-growing to hydroponics. Angus (1995–96) gives instructions for how a hydroculture system consisting of five basic parts — clay pellets, nutrients, water level indicator, culture pot insert, and outer container — works (Figure 11.8).

All these articles and experiences tell of the wide range of opportunities as well as growing systems that can be used by those interested in experimenting with the hydroponic technique. Video tapes and CD-ROMs on hydroponics that would be useful to the hobby grower are listed in Table 11.4.

Outdoor Hydroponics

The form of hydroponics least studied today is its outdoor application potential. Although hydroponics was initially practiced outdoors (Eastwood, 1947; Schwarz, 2003), most hydroponic growing systems in use today are found in greenhouses or other enclosures. The challenge is to find a hydroponic growing system that is not significantly affected by rainfall, unless the growing vessel is covered. The least applicable hydroponic methods for outdoor use would be those systems that use the drip nutrient solution delivery technique.

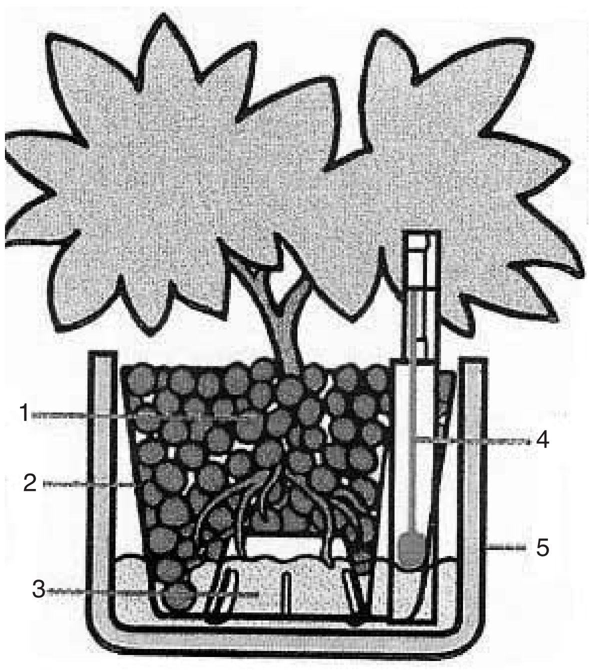

Figure 11.8 Hydroculture system for growing plants in a small pot (1: clay pellets, 2: culture pot insert, 3: nutrient solution, 4: water level indicator, 5: outer container). A constant level of nutrient solution is maintained in the bottom of the outer container, with nutrient solution added through the water level indicator opening. *Source:* Angus, J., 1995–96, *The Growing Edge* 7(2):48–55.

Table 11.4 Video Tapes and CD-ROMs on hobby hydroponics

Hobby Hydroponics: Nelson/Pade Multimedia, Mariposa, CA, 1996. $29.95, 30 min
Hydroponic Farming: Nelson/Pade Multimedia, Mariposa, CA, 1999, $29.95, 36 min
Inside Hydroponics: InterUrban Water-Farms, Produced by Hygro Technologies, Riverside, CA, 2000, $29.95, 60 min
Hydroponics: The Growing Solution? InterUrban WaterFarms, Produced by Hygro Technology, Riverside, CA, 2000, $29.95, 62 min
Hydroponic Systems: Hydrofarm Hydroponic Gardening Systems, InterUrban WaterFarms, Produced by Hydro Technologies, Riverside, CA, 2000, $19.95, 36 min

Bradley and Tabares (2000 a,b,c,d) and Bradley (2003), from their extensive knowledge and experience, describe how simplified hydroponic growing systems are being built by those in developing countries not only to fight hunger but to create small business ventures. Included are easy-to-follow instructions and operational principles for growing systems that would be of value to anyone interested in getting started in hydroponics.

The personal experience of Ray Schneider, an energetic hobbyist, who first began indoors (Schneider, 1998) and then went outdoors (Schneider, 2000, 2002, 2003, 2004) with his NFT hydroponic system, is an example of the successes and pitfalls that can occur. In an article by Schneider and Ericson (2001), the learning experiences of Ericson, who used 6-inch sewer pipes as the growing vessel to grow hydroponic lettuce, bell pepper, tomatoes, cabbage, parsley, and herbs, are described. Christian (1997) describes a NFT lettuce-growing system that was designed based on what had been done elsewhere, and how crop protection devices were designed and used to deal with weather extremes that occurred from time to time. Kinro (2003) describes how Larry Yamamoto in Honolulu, Hawaii turned a hobby into a career growing hydroponic lettuce using a simple raft floating system.

The author has had good success growing hydroponically in a system in which a depth of nutrient solution is maintained in the bottom of a watertight vessel (box or trough). The growing medium is either pure perlite or a 50/50 mixture of perlite and composted milled pinebark. The box and trough growing vessels are shown in Figures 11.9-1 and 11.9-2 and Figures 11.10-1 and 11.10-2, respectively. A detailed description of the basic principle of operation for this method can be found at the Web site www.GroSystems.com.

Hydroponic Crops

In the crops portion given later in this chapter, instructions on the hydroponic procedures for those crops most commonly grown hydroponically (tomato, cucumber, pepper, lettuce, and strawberry) in the greenhouse are initially given. The author has also grown these crops successfully outdoors hydroponically, so comments will be made on my experiences. The author has had

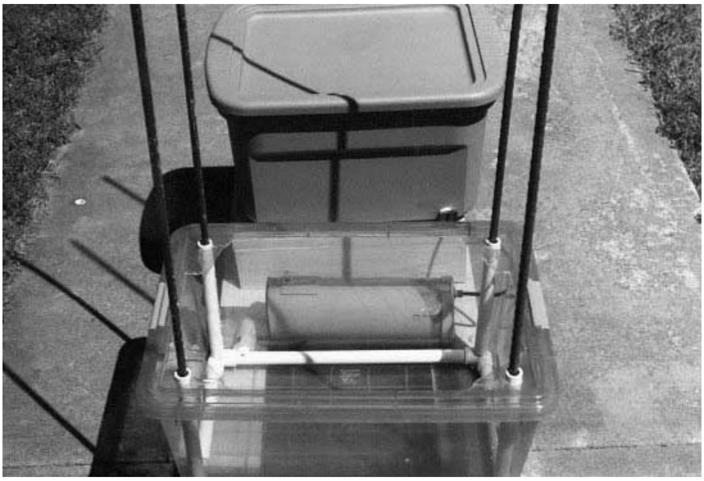

Figure 11.9–1 GroSystem GroBox hydroponic system. (The PVC piping in the rooting box is used to support the four corner plant stakes, the blue PVC pipe houses a float value used to maintain a constant level of nutrient solution in the base of the rooting box, and the green plastic box contains the nutrient solution. A tube is inserted in the base of nutrient solution box to deliver nutrient solution to the float value.)

good success growing hydroponically outdoors the garden vegetable crops, green bean, okra, sweet corn, and melons (water and cantaloupe). Instructions for growing these crops are also included.

The advantages of growing hydroponically outdoors are many; the primary ones are control of water and plant nutrient elements, and the avoidance of soil-related challenges, such as weeds, poor soil physical and chemical properties, disease, and poor control of soil moisture. Frequent references to articles in *The Growing Edge* magazine are made since many articles contain valuable instructions for the hydroponic grower, whether a commercial or hobby grower. The extent of coverage for the crops included depends on the literature base for that crop.

Morgan (2000d) gives details on growing "Baby Veggies," which are "appealing due to their appearance and tender flavor, and are standard cultivars that are harvested in their immature stage." Snow peas, squash, pumpkin, potato, eggplant, tomato, hot and bell pepper are grown in NFT systems; while globe artichokes, carrots, onions, beets, and corn are grown in medium-based hydroponic systems.

Factors for Success

There is no uniform hydroponic technique that is applicable to every situation in terms of method (ebb-and-flow, NFT, media systems plus drip irrigation), and control of the supply of water and nutrient solution (and its formulations)

Figure 11.9–2 The GroSystem GroBox is primarily designed for growing tomato. The rooting medium is a 50/50 mix of perlite and composted milled pinebark. (The box on the right contains the nutrient solution; the white-capped PVC pipe houses the float value which continuously maintains about 1-in. depth of nutrient solution in the bottom of the GroBox.)

to a crop. A critical factor is where the hydroponic system is being put into use, whether in a greenhouse with its wide variance in design and function, in a controlled environmental chamber, or outdoors. The physical location of a greenhouse or outdoor site in terms of specific location at a particular site, and/or in regions with varying weather conditions (high and low temperatures, and high and low light intensity and duration), will govern what will be required to be successful (see Chapter 12).

The wealth of information on hydroponics that is available can easily lead to the making of wrong choices in the design of the growing system and operating procedures. A common error is to adopt a growing system and/or set of operating procedures that are only applicable to a particular environmental situation. For example, what would be required under low temperature

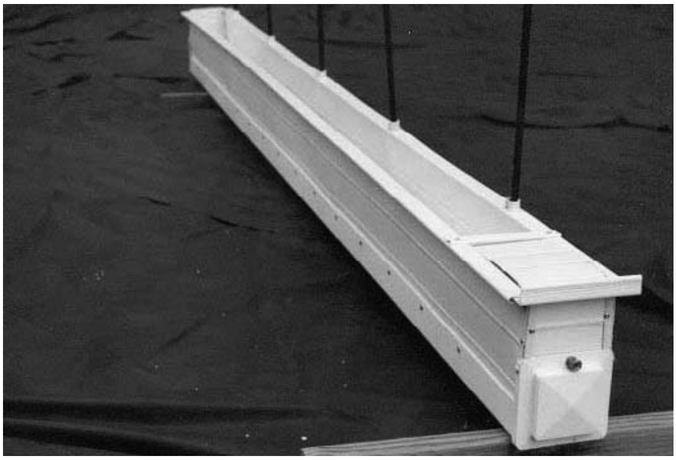

Figure 11.10–1 GroSystem GroTrough hydroponic system. (The lid on the front end of the trough covers the chamber that houses the float value which is use to continuously maintain about a 1-in. depth of nutrient solution in the bottom of the GroTrough. The PVC side tubes are used to support the side walls of the trough and can be used to mount plant support stakes.)

Figure 11.10–2. The GroSystem GroTrough can be used to grow a wide variety of crops; tomato is shown here. (The growing medium is a 50/50 mix of perlite and composted milled pinebark.)

and light would not necessarily apply under high temperature and light. What would be required for a crop under declining light, from summer into the winter months, would not apply for that under increasing light conditions, from winter into the summer months, for example, what would occur for a fall versus spring crop.

Crop and cultivar selection should be based on adaptability to the growing system and environmental conditions as well as the marketability of the harvested crop. A common error is to produce a crop that either exceeds or does not meet the market requirements, and/or is not of sufficient quality for consumer acceptance. A grower may be very successful in producing a crop but may not be able to adequately market it. As mentioned earlier (see page 176), one of the reasons a group of southeastern Georgia tomato greenhouse growers were successful was that each grower had his own local market, but in addition they were able to pool their surplus fruit which was taken to a centralized market in a large nearby city.

The skill of the grower and experience with a particular growing method may not be easily transferable to an inexperienced grower. The author has visited with growers whose success could be directly related to their innate skill, a sense (the green thumb phenomenon) that directs what to do and when to do it. It is always better to be proactive than reactive to changing conditions of the crop or growing system. This is particularly true when dealing with insect and disease infestations, or when there are changing environmental conditions that would alter the water and nutrient element requirements of plants, or when there is need for shade or increased light. Failure to anticipate significant weather events, such as unexpected low or high air temperatures, snowfall, or high winds, can result in damage to the greenhouse structure as well as to the status of an enclosed crop.

When dealing with plant nutrition and pest problems, relying on knowledgeable professionals for identification and recommendations is essential. Monitoring and periodic testing are required to ensure that the crop is being maintained nutritionally sufficient (see Chapter 13). Use of monitoring devices, such as yellow sticky boards, will indicate the level of insect populations. Knowing the tolerance level for both disease organisms and insects can assist in determining when control measures are needed since total absence of these pests does not normally exist (see Chapter 14).

Unfortunately, not even the best-designed growing systems and greenhouse structures will initially perform well even in the hands of a skilled grower. It may take a "shakedown" period to make the total system work efficiently and the growing crop to perform to expectations. What might work under one set of environmental conditions may not work under another. This was the experience of four growers located in the southeastern United States, who initially produced high-yielding and -quality fruit, and then experienced low yield and quality in the following years (Jones and Gibson, 2001). It is the ability to find the source of a problem and then to adjust to or correct it that makes for success as well as minimizing losses. Record keeping is essential if a grower is to continue to produce high-yielding crops of high quality. Environmental conditions should be recorded daily. The dates when major events occurred and the changing status of the crop should also be recorded. Accurate yield records plus quality evaluations are essential. A greenhouse tomato grower kept accurate weekly fruit production records and then correlated these yields with the amount of weekly sunshine, data that were gathered from local weather records. The highest correlation found between fruit yield and weekly sunshine was obtained 2 or 3 weeks prior, demonstrating that the effect of weather conditions did not appear in the crop until several weeks later. In addition, if yields are compared with daily and/or weekly growing conditions, these data can be used to guide the grower when making decisions in the future (Nederhoff, 2001).

The author knew a grower who kept daily logs on every event that occurred in his greenhouse, even the exact time he entered and left daily. These logs provided to be essential when a successful lawsuit was brought against the supplier of the greenhouse and hydroponic growing system. The grower was able to successfully demonstrate to the court that what the supplier had stated in his printed brochures and manuals — expected yield based on stated inputs — did not prove to be so.

Constancy of growing conditions leads to high yields and quality product production. It is not possible to precisely control every aspect of the environment, the amount of radiation received, for example, or to adequately control the continuous cycling of atmospheric conditions within the greenhouse or outdoors. In most greenhouses, it is possible to minimize the cycling of the air temperature, CO_2 content, humidity, etc. by the use of computer-driven control devices (Lubkeman, 1998, 1999; Nederhoff, 2001). Growth chamber experiments have demonstrated what effects precise control of the aerial environment can have on the growth and development of plants. Therefore, the greenhouse system must be so designed to mimic what is possible in a growth chamber if those environmental conditions required for high growth are to be obtained and maintained.

For most of the commonly used hydroponic growing systems, the cycling of water and nutrient element availability are not easily controlled. As a nutrient solution is introduced into the growing medium, three things occur. Plant roots absorb the water and nutrient elements in the nutrient solution at varying rates (Bugbee, 1995), water and nutrient elements not absorbed begin to accumulate in the rooting medium (Jones and Gibson, 2002), and some of the applied water and nutrient elements leach from the rooting vessel. The result is a continuously varying rooting environment that can adversely affect plant growth. This is one of the influencing factors that is not being adequately addressed by those engaged in hydroponic system research and development. Geraldson (1963, 1982) has addressed this problem in his research on the effect of quantity and balance of the nutrient elements on the growth of field-grown staked tomatoes. This basic concept is being used by Jones and Gibson (2002) in their development of the *Aqua-Nutrient* growing method and is the basis for a commercial product called the "EarthBox" (Figure 11.11).

There is much yet to be learned about how best to grow plants hydroponically. There have not been any significant breakthroughs in the last several decades. Most of the hydroponic growing systems in use today were developed in past years. What the future holds for new developments is uncertain since few are engaged in developmental research on hydroponic methods.

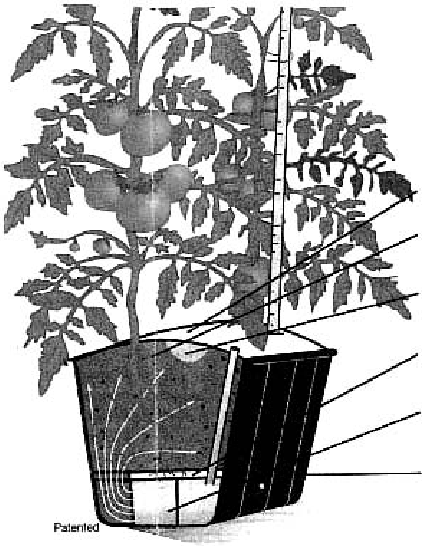

Figure 11.11 Commercial product called the "EarthBox" (Earthbox, P.O. Box 420, St. Petersburg, FL 33731-0420)

Tomato (*Lycopersicon esculentum* Mill)

Introduction

"The story of tomato is a tale of three continents: South America, Europe and North America." The European chapter began in the 1500s, when Spanish and Portuguese explorers brought unusual vegetables, of which tomato was one, back to their respective countries (Bennett, 1997). The tomato has its origins in the narrow, dry, tropical coastal areas of Ecuador and Peru, but its domestication occurred in Mexico where it was discovered and brought to Europe. It is suggested that the name "tomato" comes from the Nahuati language of Mexico. Tomato was brought into the United States in the 1700s and is a major vegetable in the diet plus being a component in numerous food products (Smith, 1994; Jones, 1999). The per capita consumption of fresh tomato fruit in the United States is 19.5 lbs (8.8 kg), and that amount is expected to increase, mainly due to the health benefits that occur when it is included in the daily diet. There has been a major shift in tomato type from beefsteak to cluster tomatoes; 30-40% are the former, 60% the latter. Less than 10% of the total production is in cherry, plum, and bell-shaped types.

The largest acreages of greenhouse–hydroponic tomato are in the Netherlands, followed by Spain and England. In the Western hemisphere, production statistics are difficult to obtain, with an estimated 1134 acres (460 hectares) in Canada, 2134 acres (864 hectares) in Mexico, and 766 acres (310 hectares) in the United States. The acreage in Mexico is rapidly increasing. In the United States, the state of Colorado has the largest acreage, with Arizona and Texas close behind. Some have suggested that the future potential in the United States could bring the total acreage of greenhouse tomato production to 7000 acres (2833 hectares). Large acreage [>20 acres (8 hectares)] greenhouse facilities are being located at high-elevation [5000 ft (1524 m)] sites, with high light (minimum cloud cover) and cool nights prevailing. Readily available supplies of high-quality water and natural gas are equally important site selection criteria. Since greenhouse tomato is not a crop monitored by the United States Department/Agriculture Research Service (USDA/ARS), statistical data on acreage, production levels, fruit types, etc. are difficult to obtain.

Tomato is the most commonly grown hydroponic crop in the world, primarily grown in environmentally controlled greenhouses and less frequently in open-sided shelters. Initially, some form of an ebb-and-flow (see Figure 9.3) (Fischer et al., 1990) hydroponic growing system was used, but in recent years, the nutrient solution drip irrigation procedure has been preferred. The tomato plant is either rooted in pure perlite (Bauerle, 1984; Day, 1991) (or mixtures of composted milled pinebark and perlite), rockwool blocks and slabs (Van Patten, 1989, 1991a,b; Robinson, 2002; Smith, 2003c), or some other substrate, such as coconut fiber (Morgan, 1999b). Johnson (2001b) compared the characteristics of rockwool versus cocopeat (coir) as a growing medium, finding that cocopeat has a high buffer capacity with respect to nutrients and pH and is environmentally biodegradable. Handreck (1993) gives the properties of cocopeat (frequently referred to as coir) for inclusion in a soilless potting medium and Ma and Nickols (2004) give instructions on the detoxification of coir dust and coconut shell. Morgan (2003f) describes media-based (expanded clay, scoria, pumice, sand, and gravel) growing systems and media-free methods, such as NFT (Peckenpaugh, 2002; Smith, 2003a,b,c) and DFT (deep flow technique) (Alexander, 2003b) and aeroponics (see pages 142–143). Papadopoulos (1991) describes growing in various systems, bags of organic medium, rockwool slabs, and NFT. In a series of three articles, Smith (2003c,d,e) describes the evolution of the PTO (Percy Tregida Otahuhu) growers, who first began to grow tomatoes in soil in 1949. Today in 1.5 million square feet of greenhouses, they are now growing tomato by both the NFT and drip irrigation rockwool slab systems. Most large hydroponic tomato operations [>20 acres (>8 hectares)] grow in rockwool slabs since it is generally believed that this substrate provides the best water and nutrient element control. Most of the developing technology is coming from the Dutch growers, who grow almost exclusively in rockwool.

The requirements for successful growing, whether in a substrate or a media-free system, have been described in numerous articles (Rudder-Hasenohr, 2000), manuals (Tite, 1983; Papadopoulos, 1991; Hochmuth, 1991a,b; Snyder, 1997), proceedings (Anon., 1996b), and books (Wittwer and Honma, 1969, 1979; Harris, 1977; Resh, 1995, 1998, 2001; Dalton and Smith, 1999), and on various Web sites (Table 11.5).

Those seeking general information on tomato culture will find the books by Henrickson (1977), Smith (1994), Bennet (1997), Ibsen and Nielsen (1999), Jesiolowski and Hager (1999), Jones (1999), and McGrath (2002a) of value.

Table 11.5 Internet Hydroponic Web Sites

The World Wide Web has become a major source of information on all subjects including hydroponics. For example, entering the word "hydroponics" using the Google search engine identifies 261,000 Web sites. Narrowing the search to specific crops that can be grown hydroponically, the following site numbers are obtained:

Site	*Number*
Hydroponic tomato	5670
Hydroponic cucumber	1460
Hydroponic lettuce	5030
Hydroponic herbs	31,600
Hydroponic green beans	7
Hydroponic sweet corn	1140
Hydroponic strawberry	1820

Searching some of these sites, one finds that many of the sites are not specifically related to hydroponic growing systems. In addition, there are repetitions of sites, making the number of useful sites less than indicated.

Web Site Reviews

The editors of *The Growing Edge* magazine have been reviewing Web sites that would be of interest to their readers. growweb@growingedge com

***The Growing Edge* 11(6)**

hydrorus.com
hydroponicsbc.com
hydroponics.net

***The Growing Edge* 12(1)**

Bad Axe Intermediate School, Michigan; http://hatchet.badaxe.k12.mi.us/intermed/hydroponics/index.html
Hawaii Department of Education's Electronic School Project; http://www.k12.hi.us/~churoda/hydroponics.html
South Carroll High School, Maryland; http://www.carr.lib.md.us/schs/science/aquaculture/enter.html
Springfield Estates Elementary School, Virginia; http://www.fcps.k12.va.us/SpringfieldEstatesES/seesonian.html

***The Growing Edge* 12(3)**

ag.arizona.edu/hydroponictomatoes/index.htm
cals.comell.edu/dept/flori/cea
nfrec-sv. ifas.edu/hydroponics.htm
ext.msstate.edu/pubs/pub1828.htm
ag.ohio-state.edu/-abe/veg/veg/htm
usu.edu-cpl/hydropon.html
res2.agr.ca/harrow

***The Growing Edge* 12(5)**

organic.resources ams.usda.gov/nop/

Table 11.5 Internet Hydroponic Web Sites (continued)

***The Growing Edge* 13(2)**
forums.gardenweb.com/forums/hydro
hydromall.com/cgi-bin/messages/index.cgi
sherrysgreenhouse.com
nysaes.cornell.edu/pubs/ask/vegdr.html
garden.org

***The Growing Edge* 13(4)**
user.shentel.net/rschneid/hydro.htm
angelfire.com/fl4/hydro/hydroponics.html
hydroponicsonline.com
hobbyhydro.com
fesersolt.com/hydro/

***The Growing Edge* 13(5)**
hydro.eng.br/
soilfoodweb.com/index.html
echonet.org/tropicalag/technotes/ChickenM.pdf
ces.ncsu.edu/depts/hort/greenhouse_veg/
ces.ncsu.edu/depts/hort/greenhouse_veg/topics/organic-production-article.htm; atta.org/attra-pub/ghve.g.,html
attra.ncat.org/attra-pubflDF/organicfert.pdf
aftra.ncat.org/attra-pub/PDF/vegetabel-guide.pdf

Sources: Harrington, M., 2001, *The Growing Edge* 12(1):87; Harrington, M., 2001, *The Growing Edge* 13(2):85–87; Peckenpaugh, D.J., 2001, *The Growing Edge* 11(6):87; Peckenpaugh, D.J., 2001, *The Growing Edge* 12(3):81–87. Peckenpaugh, D.J., 2001, *The Growing Edge* 12(5):80–86; Peckenpaugh, D.J., 2002, *The Growing Edge* 13(4):81–83; Peckenpaugh, D.J., 2002, *The Growing Edge* 13(5):83–86.

University and Other Web Sites
University of Arizona, College of Agriculture and Life Sciences, Growing Hydroponic Tomatoes, http://agr.arizona.edu/hydroponictomatoes/index.htm
Cornell University College of Agriculture and Life Sciences, Controlled Environment Agriculture — An Interdepartmental Program at Cornell University, http://.cals.cornell.edu/dept/flori/cea/
University of Florida Institute of Food and Agricultural Sciences, North Florida Research & Educational Center (NFREC), http://nfrec-sv.i fas.ufl.edu/hydroponic.htm
Mississippi State University Extension Service, Greenhouse Tomato Handbook, http://ext.msstate.edu/pubs/pub1828.htm
North Carolina State University Greenhouse Food Production Web Site — Organic Hydroponics, http://www.cec.ncsu.edu/dept/hort/greenhouse—veg/
The Ohio State University Agricultural Business Enhancement Center Hydroponic Vegetable Program, http://www.ag.ohio-state.edu/-abe/veg/ve.g.,htm
Utah State University, Crop Physiology Laboratory-Hydroponics, http://www.usu.edu/-cpl/hydropon.html
Agriculture and Agri-Food Canada, Research Branch, Harrow, Greenhouse & Processing Crops Research Centre, http://res2.agr.ca/harrow/

Table 11.5 Internet Hydroponic Web Sites (continued)

Soilless Resources and More Appropriate Technology Transfer for, Rural Areas (ATTRA) The Greenhouse & Hydroponic Vegetable Production Resources, http://www.attra.org/attra-pub/ghwebRl.htm
New York State Agricultural Experiment Station, http://www.nysaes.cornell.edu/pubs/ask/vegdr.html
The World of Hydroponics, http:///vvww.hydro.eng.br/
Resource Guide to Organic & Sustainabel Vegetable Production, http://www.attra.ncat.org/attra-pub/PDF/vegetabel-guide.pdf
Hydroponic Resource list, http://www.oardc.ohio-state.edu/hydroponics/links/links.htm

Factors that influence tomato fruit production in an environmentally controlled greenhouse are:

1. Light, its intensity and spectral characteristics, and day length (optimum: 1400 fc illumins, photoperiod 14 hours)
2. Carbon dioxide (CO_2) level in the greenhouse, particularly within the plant canopy
3. Air and root temperatures (optimum day/night air temperature, 86/77°F (30/25°C)
4. Relative atmospheric humidity (optimum 50%)
5. Disease and insect infestations
6. Nutrient element composition of the applied nutrient solution and rooting medium
7. Nutritional status of the tomato plant
8. Cultivar characteristics
9. Days to bloom 50, days to maturity 100
10. Management skill of the grower (high)

From seeding to final harvest, the tomato plant goes through four stages, seedling stage (4 to 6 weeks), vegetative stage (2 to 3 weeks), early fruiting stage of first flowers to first fruit (6 to 8 weeks), and mature fruiting stage of first harvest until plant removal. Just prior to plant removal, the growing point is removed to stimulate rapid fruit development of those fruit still remaining on the plant.

Transplant Seedlings

The quality of seed will determine germination rate, which should be greater than 95%. If seed is stored, it should be at 32–40°F (0–4.4°C). Normally, overseeding at 15 to 25% will ensure a sufficient number of seedlings for transplanting. The optimum temperature range for seed germination is 72–75°F (22–24°C).

Tomato seeds will germinate in 8 to 11 days at 70°F (21°C). One of the important quality factors is seed age, and some growers will not accept seed if the date on the package indicates that the seed is more than 6 months old.

As in soil growing, tomato seeds are not directly seeded into a hydroponic growing medium, but are seeded in germination cubes or trays of soilless medium to produce a seedling that will then be transplanted into the hydroponic growing medium. Seeding and seedling growing procedures that will produce transplants which will set fruit early have been given by Leskovar and Cantliffe (1990), Vavrina and Orzolek (1993), Snyder (1995), Meyer (1998), Fauly (1998), and Morgan (2002c, 2004c). The critical factors are temperature and light as well as sufficient nutrition to ensure development of a hardy seedling. It is the so-called "hardening or conditioning" process that will determine how quickly seedlings will adapt to their new environment after transplanting. Morgan (2003e) found that when seedlings are raised under low temperatures [53–57°F (12–14°C)], the number of flowers found on the first truss increases. After transplanting, initial plant growth and the timing and position of the first cluster will be determined by the character of the seedling. Morgan (2002a) suggests that the time for transplanting is when the young plant is about to flower, and the first fruit will then set in about 7 to 10 days under good growing conditions. The author has found that transplanting seedlings shortly after the first "true" leaves appear generally results in best initial plant growth and early setting of the first fruit truss under high light and temperature conditions. For the production of seedlings, Hochmuth (1991a) applies a nutrient solution with the following composition

Major Elements	*ppm*	*Micronutrients*	*ppm*
Nitrogen (N)	50	Boron (B)	0.5
Phosphorus (P)	20	Copper (Cu)	0.1
Potassium (K)	50	Iron (Fe)	1.0
Calcium (Ca)	100	Manganese (Mn)	0.5
Magnesium (Mg)	20	Zinc (Zn)	0.2
Sulfur (S)	20		

Grafting

Grafting of seedlings to create a double-stem plant (two plants on one root, Figure 11.12) or the grafting onto a rootstock to increase plant vigor is becoming an increasingly common practice. Grafting is done at the seedling stage on 17- to 18-day-old plants. It requires considerable skill to accomplish a successful graft; therefore, this is not a task recommended to be performed by most growers. Grafting instructions are given in Table 11.6 and are also described by Papadopoulos (1991).

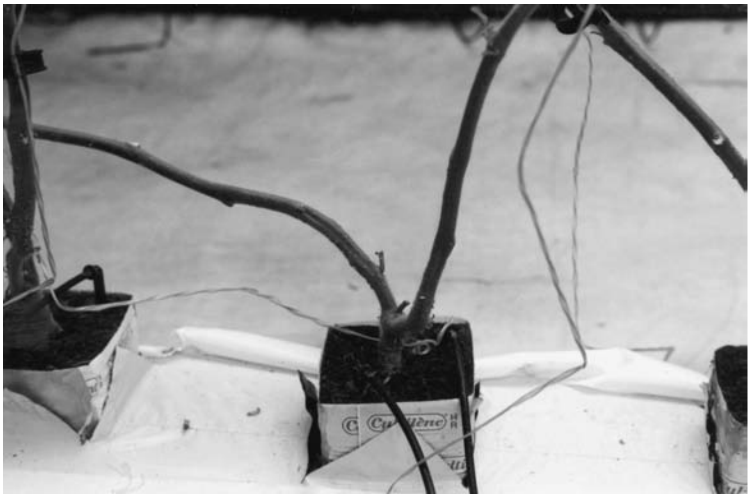

Figure 11.12 Grafting of seedlings is used to create a double-stem tomato plant so that at one rooting station, two plants can be grown.

Crop Scheduling

Depending on light and temperature conditions, a two-crop system is employed to avoid low-light months, and a single-crop system to avoid the high-temperature months. In the two-crop system, for example in the northern hemisphere, a fall crop is planted in August and terminated in December, and then a summer crop planted in March and terminated in June or July. For the single-crop system, the crop is planted in September and terminated in June. With supplemental lighting during the low-light months and shading during the high-temperature months, adjustments can be made in plant scheduling in either cropping system.

Growing Containers and Medium

The most frequently used growing medium for tomato is rockwool slabs (Figure 11.13). Perlite in either bags (Figure 11.14) or BATO buckets (Figure 11.15) would be the next most frequently used. Growers have also used a variety of other substrates (cocopeat, composted milled pinebark, expanded clay, pumice, sand, gravel, or mixtures of these substances made to create particular physical and chemical properties) placed in containers of varying depths and physical size. The physical and chemical properties of these growing media are described by Morgan (2003f) (see Table 9.14 and Table 10.1, in Chapters 9 and 10, respectively). The number of plants per slab, bag, or bucket would depend on the crop spacing configuration. The volume of medium in either bags or buckets will determine the frequency of irrigation; the smaller the volume of medium, the more frequently irrigation is required.

Table 11.6 Guidelines for Grafting Tomato Plants

The Japanese Top Graft Method

With this method, the scion (variety) and the rootstock are cut off at a 45° angle and the scion is put straight on top of the rootstock. They are kept together with a silicon grafting clip.

Grafting consists of the following actions:

1. Seeding the rootstock
2. Seeding the variety
3. Preparations
4. Grafting
5. Fusion
6. Potting and spacing

1. Seeding the Rootstock

   Seed the rootstock, Beaufort, according to DRS recommendations about 5 to 10 days before the variety, in rockwool plugs at 240 cells per tray.

   Due to the uneven emergence, the seedlings must be selected. This is usually done at the third true leaf stage (after 18 days). The selected seedlings are placed in 240-cell trays at only 120 cells per tray (it is too difficult to graft a full tray). Selection is done every 4 or 5 days. The first time usually produces about 100 plants per tray.

   Keep this in mind for the required number of plants within one period.

   Experienced plant raisers have a success rate of 95%.

   Selected rootstock seedlings should be kept at a lower temperature to make them thicker and sturdier (18 to 20°C).

   In case a different rootstock is used (i.e., PG3) with a more uniform germination, the flats may be seeded at 120 per tray right away. Special seeding equipment is available for this.

2. Seeding the Variety

   Seed according to the standard recommendations.

   Graft after about 17 or 18 days.

   Recommended germination conditions:

Temperature	25°C day and night
RH	78%
EC	1.8 to 2.0 μS/cm
pH	6.0–6.5
Light (D/N)	17 h/7 h (120 $\mu mol/cm^2/sec$)

3. Preparations

   Grafting must be done in an area with no direct sunlight.

   Make a plastic tent, about 30 cm high. Clear plastic is preferred. The film must have sufficient strength. Under high light conditions, a white film may be used. However, clear plastic is preferred and strong sunlight can be reduced by a retractable screen or Styrofoam sheets.

   Disinfect hands with, for instance, Virkon.

   Razor blades: it is recommended to always use new blades and to replace them often.

Table 11.6 Guidelines for Grafting Tomato Plants (continued)

Climate: temperature: 21 to 22°C; Relative humidity (RH) inside the tent should be approximately 95% (wet floor or misting of plants as well as the inside of the plastic tent).
No smoking during grafting (virus).
Make sure that the rockwool plug is very wet, EC 2 to 3 mS.

4. Grafting Procedure
Cut off the rootstock with a razor blade at a 45° angle. This can be done either above or below the cotyledons, depending on the weather. When light and warm, cut below the seed leaves to avoid sucker growth from the rootstock. When it is dark, make the cut above the cotyledons in order to benefit from the extra photosynthesis. Put the grafting clip in place.
Cut off the variety at an angle. (Suggestion: if hot or low RH, store the scion briefly in a tray with clean or sterile water)
Place the scion in the clip making sure of good contact with the rootstock (air between the two parts will result in failure).

Note:
1. Cutting at an angle (45°) is preferred over a straight cut because the fusion surface is larger and the chance of success better.
2. The ideal situation is to cut the rootstock as well as the variety above the cotyledons.
3. Cut the rootstock at a maximum of 2 cm above the rockwool plug. If higher, there is a risk of the graft falling over; if lower, the variety may root into the media.
4. If the variety grew too fast, it is advisable to cut it higher (even as high as the 2nd or 3rd true leaf).

Put the grafted plants immediately in the plastic tunnel. The optimum fusion temperature is 21 to 22°C. The maximum temperature under sunny conditions is 28 to 29°C.

5. Fusion
It is important to avoid direct sunlight onto the plants and to maintain a uniform climate. Until the plants have been hardened, shading will be necessary when it is sunny.
The most common procedure is to keep the tent closed for three days and to test whether the graft will hold on the fourth day. The plants must not wilt. Should this happen, lightly mist the plants (do not use warm water).
On the fifth day, ventilate a little. It is preferred to make a small gap and to check each hour the condition of the plants. Should they wilt, lightly mist the plants with clean water and close the tent again. In the evening or the next morning, the gap can be made again. On day 6, make the gap larger if the plants can handle it and remove the plastic on the seventh day (preferably in the morning or evening).

6. Potting and Spacing
After day 7, the normal plant raising procedures can be followed. Transplanting into a rockwool block is recommended from 9 to 10 days after grafting (when the rootstock and the variety have joined solidly). (If the grafting clips were silicon, removal is not necessary.)

Source: http://www.deruiterusa.com/products/Tomato/tombot.html

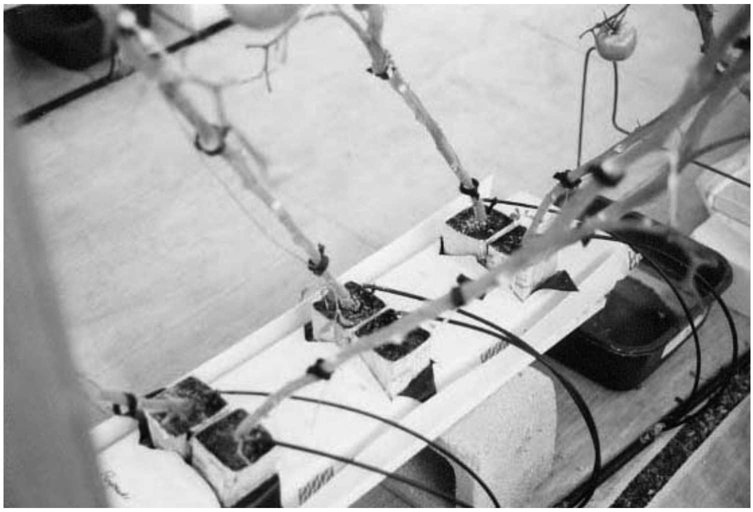

Figure 11.13 Tomato plants growing in a rockwool cube set in an opening in a rockwool slab.

Figure 11.14 Tomato plants growing in a rockwool cube set in an opening in perlite-filled bags.

The commonly used rockwool slab is 36 in. (91 cm) long, 6 in. (15 cm) wide, and 3 in. (7.6 cm) deep, a volume of 0.375 in.^{3} (0.0106 m^3). A standard perlite grow bag contains 1-1/3 ft^3 (0.037 m^3) of perlite; the bag is 44 in. (111 cm) long, 8 in. (20 cm) wide, and 6 in. (15 cm) high. The volume of the BATO bucket is 0.57 ft^3 (0.02 m^3). Jensen (1997) reported on growing six tomato plants in a 130 × 15 × 7.5 cm; each plant had a rooting volume of 2438 cm^3 and required irrigation 30 times per day. He also indicated that at the University of Arizona, tomatoes were being successfully grown in a rooting volume of 956 cm^3, although continuous irrigation was required during the day. The

Figure 11.15 Tomato plants growing in perlite-filled BATO buckets. The black tube is the nutrient solution delivery line from which drip lines are attached to dispense nutrient solution into each bucket.

configuration and size of the rooting medium is driven primarily by economics, using as little medium as possible in order to minimize initial cost and disposal requirements.

The author has grown tomato plants to fruiting in 20 oz (591 mL) beverage bottles containing perlite (Figures 11.16-1 and 11.16-2) into which nutrient solution is continuously supplied to maintain a 1-in. (2.5-cm) depth of solution at the base of the bottle.

After 6 months of commercial tomato production in three greenhouses located in the southeastern United States, the root mass was removed from a number of perlite-containing BATO buckets. The author found that much of the root mass was around the outer edge of the perlite mass with few roots in the center where the two nutrient solution delivery drip emitters were surfaced-placed. This suggested that during much of the growing period, the frequent applications of nutrient solution necessary to supply needed water for the plants kept the center of the perlite mass anaerobic and therefore not a suitable environment for active root growth. This may have been one explanation why plant growth and fruit production began to decline as the season progressed (Jones and Gibson, 2001).

The effect of root size, growth, and function on tomato plant growth and fruit production when frequent irrigation is required to meet high transpiration demands has not been thoroughly investigated. The general knowledge regarding root growth and function is discussed in Chapter 4. What effect root physical restriction has on plant growth has been studied under field soil conditions but not to the same extent hydroponically. If the plant can be adequately supplied with water, a relatively small root volume can meet the demand if there are no restrictions, such as high or low temperature, low O_2, and high EC, in the

Figure 11.16–1 Tomato plants growing in beverage bottles. The bottles on the left are 1 liter and on the right 2 liters. The bottle on the left of each set contains the nutrient solution through which an attachment at the base of each bottle a constant level of nutrient solution is maintained in the base of the rooting bottle.

rooting medium. The author has demonstrated this in experiments conducted in 20 oz (591 mL) beverage bottles (see Figure 11.16-1); actively growing tomato plants under high atmospheric conditions remained turgid. However, plant wilting is not unusual when atmospheric demand is high, suggesting inadequate uptake and transport of water from roots to the transpiring leaves. Under such conditions, reducing the atmospheric demand by shading and/or misting would be possible solutions. Under ideal rooting conditions, the minimum root surface required for a mature, actively growing and fruiting tomato plant is not known. Even under the very best of conditions, that minimum could fluctuate with time since it not possible to continuously maintain the rooting medium at the ideal condition. Therefore, there is still much to be investigated.

Plant Spacing

The area that a plant occupies is determined by plant spacing. In general, the area each plant occupies influences fruit yield per plant, as high plant densities usually result in reduced fruit yield per plant. What plant spacing is optimum for maximum yield is determined by light intensity. The greater the light intensity during the flowering and fruiting stage, the closer plants can be spaced. In Alberta, Canada, Mirza and Younes (1977) recommend 2.7 plants per square meter. Morgan (2003e) suggests a standard spacing of 2.5 plants per square meter. The PTO growers in New Zealand use a plant density of 2.2 m^2 per plant (Smith, 2003e). Papadopoulos (1991), in a Canadian manual,

Figure 11.16–2 Tomato plants can be grown to fruiting in small beverage bottles. The small size of the rooting container reduces plant size and initiates early fruiting.

suggests the optimum space per plant as 0.35 to 0.40 m², with in-row spacing of 31.5 in. (80 cm), the same as that between rows in a double row configuration, with 3.9 ft (1.2 m) between each set of double rows. Resh (1995), in a rockwool slab growing system under low light conditions, spaces plants in the row at 30 in. (75 cm) with 18 to 20 in. (45 to 50 cm) between rows, which is equivalent to 6 ft² (0.6 m²) per plant. With improved lighting conditions, the per square foot spacing is 3.0 ft² (0.3 m²). In a double row configuration, rows are spaced 16 to 20 in. (40 to 50 cm) apart and in row plant spacing 12 to 14 in. (30 to 36 cm). In southern latitudes, the author spaces plants in the row and between double rows at 18 in. (45 cm) with 3.0 to 3.5 ft (0.9 to 1.06 m) between the double rows. Wittwer and Honma (1979) gave as the optimum spacing of 3.5 to 4.5 ft² (0.32 to 0.41 m²) per plant.

Currently, greenhouse tomato growers in Mississippi space plants at a configuration to obtain 4 to 5 ft^2 per plant, with 3 to 4 plants in 2-ft^3 laid-flat perlite bags, and 2 plants per 5 to 7.5 gallon upright perlite-filled bags.

It is obvious that plant spacing and number of plants per area are parameters that have not been standardized. Many configurations can be used, such as single and double row arrangements, with between-row space being frequently determined so that sufficient working space is provided. The physical design of the greenhouse may be such that a narrowing of the between-row space is needed to fit in a certain number of rows.

Cultural Plant Practices

Training the plant up a support wire, prompt removal of leaf axial suckers (Figure 11.17) and vegetative stems from the fruiting truss (Figure 11.18), leaf pruning, flower pollination, fruit thinning on the truss (Figure 11.19), and lowering the developing plant are essential daily activities for successful fruit production (Smith, 2001e). The objective of all these practices is to keep the plant in a high fruit-productive condition (Smith, 2002a). The extent and timing of fruit truss thinning (removing small slow-developing fruit) and the removal of leaves below the fruiting trusses (in general, leaves below the lower fruiting truss contribute little to the developing fruit above) will vary depending on the cultivar and characteristics of the plant. In an unique experiment, a “single truss, single cluster” method developed by the Rutgers University Cook College

Figure 11.17 Tomato leaf axial sucker. If not removed, the sucker will develop into another plant, flowering and producing fruit. The sucker will draw photosynthate from the main plant and if not removed will reduce fruit yield; therefore, to sustain main plant growth and fruit yield, suckers must be promptly removed once appearing.

Figure 11.18 Vegetative stem growth from a tomato fruiting truss. If not removed, vegetative stems will slow fruit development. Their appearance also indicates that the plant is in a strong vegetative growth condition, which is not conducive to high fruit set and production.

Figure 11.19 Fruit thinning on the truss, removing smaller, slower developing fruit. As shown here, the one green fruit (bottom right) should have been removed earlier as it has taken away photosynthate from the other four maturing fruit, making them smaller than would have been the case if the fruit now appearing green had been removed. Some recommend fruit thinning to four fruit per truss.

of Agriculture is being tested by limiting the tomato plant to one main stem and one cluster of fruit. The ebb-and-flow hydroponic technique is used, with the tomato plant grown in a 3-inch rockwool cube. Harvestable fruits are obtainable in 90 days after transplanting (Simon, 2003).

Environmental Conditions

The tomato plant is sensitive to both low and high air temperatures as well as radiate energy intensity. The optimal daytime air temperature range for tomato is between 70 and 82°F (21 and 28°C), night time air temperature 62 to 64°F (17 to 18°C). Papadopoulos (1991) relates recommended minimum air temperatures with light conditions, at high light a minimum night temperature of 64°F (18°C), minimum day temperature of 70°F (21°C), and at low light a minimum night temperature of 62.6°F (17°C), minimum day temperature of 66°F (19°C). At mean air temperatures above 86°F (30°C), no fruit set occurs. Although air temperature is critical for best plant growth and fruit set, it is leaf temperature that is equally or even more important. For example, if the air temperature surrounding the plant is above that recommended, air movement over the plant leaf surfaces and normal transpiration (loss of water from plant tissues, usually through the stomata) can keep the plant "cool," and therefore in an active growing and fruit setting status. The author has observed as much as a 10 degree Fahrenheit lower temperature between air and leaf temperature measured by infrared reflectance when the plants are actively transpiring in a moving air environment. An approximate air movement through the plant canopy of 3.2 feet per second (1 meter per second) is recommended. Air movement up through the canopy will keep the plants actively transpiring, which will translate into sustained photosynthetic activity (Srivastava and Kumar, 1995). The optimum relative humidity ranges between 60 and 70%.

The optimum root temperature was observed by Harssema (1977) to be between 60 and 86°F (20 and 30°C); at temperatures less than 60°F (20°C), plant growth was significantly reduced. In addition, the transpiration rate increased with increasing root temperatures between 54°F (12°C) and 95°F (35°C). Root temperature did not have the same effect on plant growth and fruit development as air temperature, and therefore root temperatures within the range 60 to 86°F (20 to 30°C) may not be a significant factor affecting plant growth and fruit production.

Jones and Gibson (2001) found that in southern latitudes where there is more than 10,000 minutes of monthly sunshine, fruit set and yield will be reduced. Under high light intensity conditions, shading is normally required to control the amount of light that enters the greenhouse, light radiation that in turn generates heat. For polyethylene-covered greenhouses when the greenhouse temperature begins to exceed 85°F (29°C), it is normally recommended that a 40% white shade material be pulled over the greenhouse, while 50% white shade material would be recommended for high altitudes and high light intensity areas (see Figure 12.15). The ideal greenhouse design would be to have movable shade that can be pulled over the crop when light conditions are intense and then can be easily pulled away when lower light conditions occur.

The irradiance requirement for tomato is 13 Mj/m^2/d as given by Manrique (1993). Papadopoulos and Pararajasingham (1997) report a low of 2.01 to 2.65

kg fresh weight of fruit harvested for every 100 Mj of solar radiation received by the crop. Therefore, short days and low radiation fluxes in the winter months in northern latitudes are the major factors limiting fruit yields. The effectiveness of supplemental light to overcome low radiation flux in the winter months is questionable. Benefit, if obtained, occurs by extending the light period rather than attempting to enhance the light flux during daylight. Photon flux in the 400 to 700 nm wavelength range [photosynthetically active radiation (PAR)] is that which is efficiently used in photosynthesis, with light measurements expressed as photosynthetic photon density (PPFD) (Mplekas, 1989; Parker, 1994a,b). Solar photosynthetically active radiation (PAR) by location in the United States is given in Table 12.1 in Chapter 12.

Because tomato is a C3 plant (the first product of photosynthesis is a three C–containing carbohydrate, see page 378), the rate of photosynthetic activity peaks at relatively low light intensities and is significantly responsive to the CO_2 content of the air surrounding the plant. Under low light conditions, the rate of photosynthetic activity can be enhanced when the CO_2 content of the air is sustained at 1000 ppm (Slack, 1983). The ambient atmospheric CO_2 content ranges between 300 and 400 ppm. At normal CO_2 levels, individual leaves reach maximum assimilation rates at about one quarter the radiation available from full summer sunlight, with some leaves actually absorbing 80 to 90% of the PPFD incident light.

When tomato plants reach the wire that supports the plant tie lines, the plant canopy becomes dense, and little air movement within the canopy occurs unless air is introduced at the bottom of the canopy so that air flows up through the canopy. Having air moving up through the canopy has two important advantages, maintenance of the CO_2 content at that of ambient air (300 to 400 ppm) and an enhancement of transpiration, which keeps the plant foliage cool. The author believes that air movement up through the plant canopy also keeps white flies (*Bemisia argentifolli* Bellows and Perring) from easily landing on the plant foliage. It is very difficult to push air from above down into the plant canopy even with the use of high-velocity fans.

Water uptake by tomato plants is also significantly reduced as the root temperature decreases (Figure 11.20). Water use drops sharply as the rooting temperature declines below 68˚F (20˚F) and when above 86˚F (30˚C) (Tindall et al., 1990). For example, on high atmospheric demand days, the tomato plant can wilt even though sufficient water is available when the rooting medium is cool [less than 68˚F (20˚C)] or the EC is high (>4 dS/m). The result of moisture stress is slow plant growth and poor fruit set, as well as the increased occurrence of fruit blossom-end rot (BER).

In addition, nutrient uptake is significantly reduced as the root temperature decreases. Tindall et al. (1990) found that as the rooting temperature ranged from 50˚F (10˚C) to 104˚F (40˚C), the uptake of the major elements (Figure 11.21-1) and the micronutrients (Figure 11.21-2) by tomato plants was significantly affected. The temperature effect did not equally affect all major elements and ions as K, Ca, and NO_3^-, while P, Mg, and NH_4^+ were not. For the micronutrients, Fe, Mn, and Zn were significantly affected while B, Cu, and

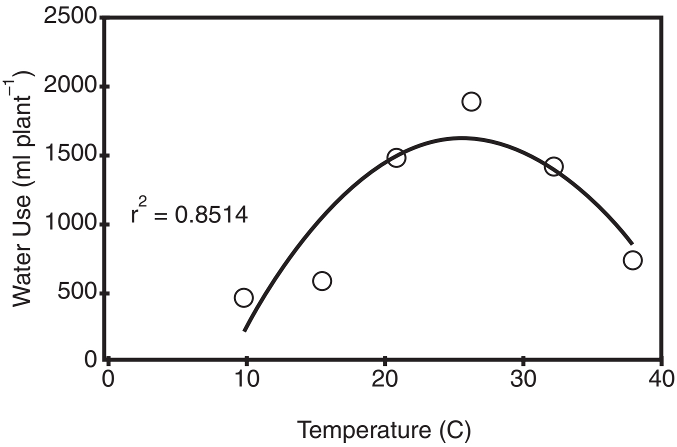

Figure 11.20 Influence of Root Zone Temperature on Tomato Plant Water Use. Source: Tindall, J.A., Mills, H.A., and Radcliffe, D.E., 1990. The effect of root zone temperature on nutrient solution uptake of tomato, *J. Plant Nutr.* 13:939–956.

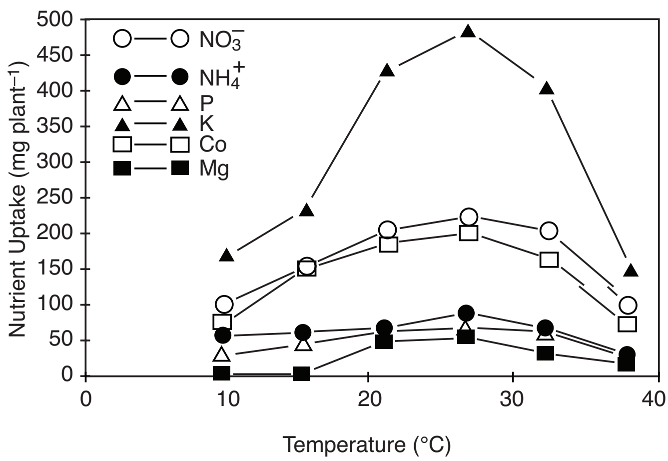

Figure 11.21–1 Influence of root zone temperature on major nutrient element uptake. *Source:* Tindall, J.A., Mills, H.A., and Radcliffe, D.E., 1990. The effect of root zone temperature on nutrient solution uptake of tomato, *J. Plant Nutr.* 13:939–956.

Mo were not. Maximum uptake occurred when the rooting temperature ranged between 68°F (20°C) and 86°F (30°C).

Water Requirement

Plant water needs have been discussed earlier in this book (see pages 19–21). One of the most important decisions that a grower must make is when to water and how much. Most hydroponic delivery systems are set on a time clock so

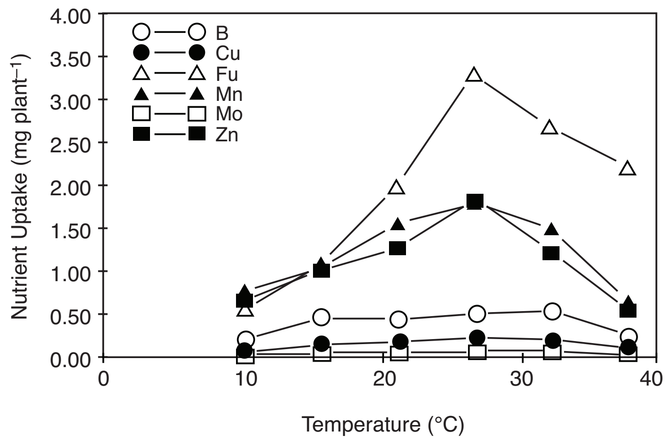

Figure 11.21–2 Influence of root zone temperature on micronutrient uptake. *Source:* Tindall, J.A., Mills, H.A., and Radcliffe, D.E., 1990. The effect of root zone temperature on nutrient solution uptake of tomato, *J. Plant Nutr.* 13:939–956.

that at periodic intervals, the nutrient solution and/or water is applied to the rooting medium whether needed by the plant or not. When to water and how much can be determined based on accumulated radiation, a method that requires radiation measuring devices and a computer program designed to estimate water needs based on past atmospheric demand plus plant size and fruiting status (Rudder-Hasenohr, 2000). Some of the commonly occurring fruit disorders, such as BER and cracking, are due to either under- or over-watering.

In general, the tendency is to overwater, which can lead to anaerobic conditions within the growing medium. Carefully removing the perlite from a number of BATO buckets in which tomato plants had been growing for more than 6 months, the author found that most of the roots were encircling the perlite mass. In almost every instance, few if any roots were present in the center where the nutrient solution was being surface applied through the drippers. Therefore, examining the position of the roots in the rooting medium can tell much about the existing aeration conditions.

At low water availability, there are fewer flowers per truss, low fruit set, and increased incidence of BER. Under high water supply (overwatering), poor plant growth, later flowering, fewer flowers, and lower fruit set occur. With frequent changes in water availability, fruit cracking incidence increases. Because of the PTO growers' concern for water availability and the possibility that the root zone could be periodically too dry, they switched from NFT to a rockwool substrate growing system (Smith, 2003c).

In most hydroponic nutrient solution supply systems, the water needed by the plant is supplied through the nutrient solution. So bringing water to the plant roots includes all the elements in the nutrient solution, elements that may not be needed by the plant. Some of the high nutrient element levels found in plants can be attributed to overfertilization from unneeded elements being applied when only water is needed. The ideal design would be to have two delivery systems, one for the nutrient solution and another for water, so that when only water is needed, it can be applied alone.

Under normal growing conditions when the tomato plant is flowering and setting fruit, water usage will range from 17 oz (500 mL) to 0.26 gal (1 L) a day. Ward (1964) determined water use by tomato plants to be 3 gal (11.3 L) per plant per week. In order to produce 1 lb (0.45 kg) of harvested fruit, it is estimated that it will require 4 gal (15 L) of water. During flowering and the fruit setting and development period, the exact amount of water needed will depend on the rate of plant transpiration, which is correlated to level of incoming radiation; the higher the radiant energy, the greater the water usage. In addition, the extent of air movement as well as high air temperature and low relative humidity within the plant canopy will also increase water usage.

The author and Wignarajah (1995) are of the opinion that aeroponics is the "ideal" hydroponic growing system where "nutrients are continuously run down along the roots, which have access to a ready supply O_2." Unfortunately, aeroponics is not an economically suitable method for growing crops, such as tomato, cucumber, and pepper.

Flower Pollination

In the field, naturally occurring insects are usually sufficient to adequately pollinate tomato flowers. In the greenhouse, however, either hand pollination of flowers every other day at mid-day when the relative humidity is minimal using an electric hand pollinator (Figure 11.22-1) and/or the introduction of bumblebees (*Bombus* spp.) (a hive is pictured in Figure 11.23) into the greenhouse is required. The size and the number of the hives needed will depend on the number of plants in the greenhouse. During flowering and fruiting, there will be approximately 4 flowers in bloom on each plant. It is

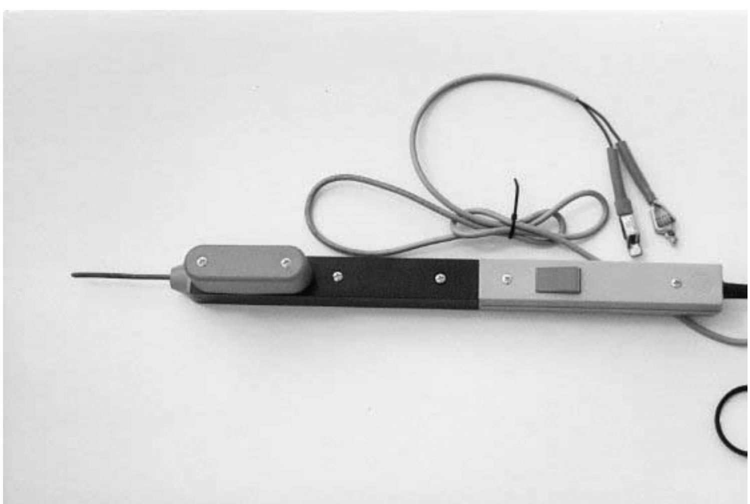

Figure 11.22–1 Electric vibrator for pollinating tomato blossoms.

Figure 11.22–2 The tip of the vibrator probe should be placed at the base of the fruit truss, avoiding contact with the flowers or any newly developing fruit. When the flower is ready for pollination, when the truss is vibrated, a small cloud of yellow pollen can be seen falling from the flower. If the vibrating probe makes contact with the flower itself or any developing fruit, however small it may be, a scar will appear later on the fruit.

possible to have an insufficient number of bumblebees to adequately pollinate all the emerging flowers (Figure 11.24) as well as too many bumblebees, which can result in flower damage and loss of fruit. Those who supply bumblebees can advise on the size and/or number of hives needed based on the number of plants and greenhouse configuration. Greenhouse environmental conditions will determine the effectiveness of the bumblebees and how long a hive will survive. The use of pesticides and supplemental lighting as well as other greenhouse conditions will affect bumblebee activity. Details about those conditions that will affect bee activity can be obtained from bumblebee suppliers.[1]

Some pollination occurs when the plants are subjected to movement by wind or the flowering truss is moved by physically shaking the plant. However these forms of pollination are usually not sufficient to ensure complete pollination, and, in turn, result in misshapen fruit.

Those flowers not pollinated will abort the fruiting truss. Flower loss can also occur due to other factors, such as low light conditions, high air temperature, plant wilting, and nutritional insufficiencies (such as high N). In addition, when plants carry a high fruit load and when environmental conditions are less than optimal, emerging flowers will abort.

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[1]Koppert Biological Systems, 28465 Beverly Road, Romulus, MI (www.koppertonline.com).

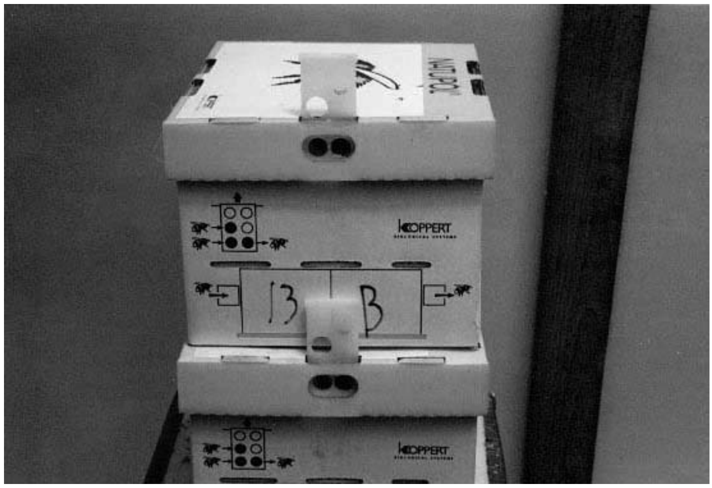

Figure 11.23 Bumblebee hives. The plastic holed slide is in the open position allowing bumblebees to leave and enter the hive.

Figure 11.24 Bumblebee pollinating tomato flower. A tomato flower that has been visited by a bumblebee can be easily identified by its off-yellow color.

When hand pollinating using a vibrator (see Figure 11.22-2), sufficient force is needed to dislodge the pollen. If the pollen is mature, a yellow cloud of pollen can be seen falling from the flower when vibrating the truss stem. Care must be taken to ensure that the vibrator does not make contact with small developing fruit. If contact is made, a scar will appear on the fruit as it matures.

Fruit Development and Yield

In order to understand how fruit develops, one needs to have an understanding of the source–sink relationship. Through the process of photosynthesis, carbohydrates (the source) are produced and partitioned into one of three plant parts (sinks), that for supporting the plant roots, for expanding new plant growth, and for fruit development. The partitioning is influenced by the growing conditions surrounding the plant, such as light intensity and duration, air temperature and CO_2 content, and plant water status, as well as how the crop is managed (suckering, leaf removal, flower and fruit removal, etc.). Maximum transport of generated carbohydrates to the fruit occurs when the air temperature is between 73 and 75°F (23 and 24°C) and when plants are adequately supplied with water and plant nutrient elements needed to sustain sufficiency. Fruit will mature from 40 to 75 days after pollination; the time required reflects an interaction between cultivar-determined factors and growing conditions. As long as a fruit remains on the plant, its size will continue to increase. Fruit that is in shade will be slower in ripening, and therefore at harvest will be larger than fruit that is in light. The weight of fruit will depend on its water content; the higher the content, the greater its weight. Ninety-five percent of tomato fruit is water.

There is no consistent expression for reporting the weight of fruit yield so that easy comparisons can be made among the various methods of production. Fruit yield (weight) can be expressed on an area basis, on a per plant yield for a specified time period, or total yield for a production unit (i.e., entire greenhouse) over a specified growing season. For example, a "good" fruit yield would be identified as either 63 kg/m^2, 1.0 to 1.5 lbs of fruit per plant per week during the fruiting/harvest period, or a total of 40 to 50 pounds per plant for the entire growing season (about 7 months). The author believes that a "high" fruit yield would be a sustained per week production level of 1.5 to 2.0 lb per plant. Smith (2003b) reported that "the Dutch have traditionally been the trendsetters for greenhouse cropping and commitment to research has some Dutch growers now yielding around 70 kg/m^2 (around 50 lb/plant)."

Another factor that is not normally identified is the actual number of fruit harvested. In addition, most fruit yield data only include "marketable" fruit — fruit that is free of blemishes and is of acceptable size. The major factor determining fruit yield is fruit numbers and weight. Fruit weight (size) is determined primarily by cultivar but it can be affected by growing conditions, such as air temperature [higher than 72°F (22°C) increases rate of fruit ripening] and shading, whether naturally shaded by the plant's foliage, or artificially shaded, which slows the rate of fruit ripening. The rate of fruit development and ripening can be enhanced by topping (removal of the plant's growing point), a procedure used prior to the end of the growing season.

The author conducted a hydroponic greenhouse tomato experiment in which the fruit yields were unusually high, mainly due to the weight of individual fruit, weights that were in the 12 to 14 oz (340 to 397 g) range, when 8 to 10 oz (227 to 283 g) fruit weights were expected. One factor that determines yield (based on fruit weight) is the water content of the fruit.

Those factors that would increase the water weight of fruit will increase fruit yield.

Ripe tomato fruit should be stored at a temperature between 40 and 50°F (4.4 and 10°C) in a relative humidity atmosphere of 85 to 90%, and if so stored fruit quality can be maintained for 6 to 12 days. Fruit should not be stored with ethylene-producing fruit, such as apple or banana.

Fruit Quality and Flavor

The quality of fruit is determined by several factors, grade (U.S. No. 1, U.S. No. 2, U.S. No. 3; Table 11.8), color classification (green, breakers, turning, pink, light red, red; Table 11.7), classification of defect level (damage, serious damage, very serious damage), and similar varietal characteristics (Jones, 1999). For "beefsteak" type varieties, fruit can be divided by size (diameter) and/or weight and marketability [freedom from blemishes, i.e., cracking (Peet, 1992), catfacing, misshapen, puffiness, BER, sunscald, green shoulders, russetting, anther scarring, splitting, and blotchy ripening. Morgan (2001e) identifies possible causes of fruit abnormalities and then identifies what measures can be taken to minimize their occurrence (Table 11.9). Uniformity of color, color intensity, and firmness are also be factors that will determine the marketability of tomato fruit. Fruit can be harvested at the "breaker" stage, when the fruit begins to initially turn from dark green to light green, and then allowed to naturally ripen, or be treated with ethylene gas to speed the ripening process. Color development pictures of tomato fruit from 10 to 100% ripe can be found

Table 11.7 Tomato Fruit Color Classification

The following terms may be used when specified in connection with the grade statement, in describing the color as an indication of the stage of ripeness of any lot of mature tomatoes of a red-fleshed variety:

Green	The surface of the tomato is completely green in color. The shade of green color may vary from light to dark.
Breakers	There is a definite break in color from green to tannish-yellow, pink or red on not more than l0% of the surface.
Turning	More than 10% but not more than 30% of the surface in the aggregate shows a definite change in color from green to tannish-yellow, pink, red, or a combination of these.
Pink	More than 30% but not more than 60% of the surface in the aggregate shows pink or red color.
Light red	More than 60% but not more than 90% of the surface in the aggregate shows pinkish-red or red color, provided that not more than 90% of the surface is red.
Red	More than 90% of the surface in the aggregate shows red color.

Table 11.8 Tomato Fruit Grade Classifications[a] and Classification of Defects

To allow for variations incident to proper grading and handling in each of the grades, the following tolerances by count are provided as specified.

U.S. No. 1 Grade

Basic requirements include:

1. Similar varietal characteristics
2. Mature
3. Not overripe or soft
4. Clean
5. Well developed
6. Fairly well formed
7. Fairly smooth

The fruit should be free from:

1. Decay
2. Freezing injury
3. Sunscald
4. Damage by any other cause

U.S. No. 2 Grade

Basic requirements include:

1. Similar varietal characteristics
2. Mature
3. Not overripe or soft
4. Clean
5. Well developed
6. Reasonably well formed
7. Not more than slightly rough

The fruit should be free from:

1. Decay
2. Freezing injury
3. Sunscald
4. Serious damage by any other cause

U.S. No. 3 Grade

Basic requirements include:

1. Similar varietal characteristics
2. Mature
3. Not overripe or soft
4. Clean
5. Well developed
6. May be misshapen

The fruit should be free from:

1. Decay
2. Freezing injury
3. Serious damage by sunscald or any other cause

Table 11.8 Tomato Fruit Grade Classifications[a] and Classification of Defects (continued)

Classification of Defects
Defect Factors are classified as to level, damage, serious damage, or very serious damage; and the factors include cuts and broken skins, puffiness, catfacing, scars, growth cracks, hail injury, and insect injury.

[a] In the grade designation, defects are specified at the point of shipment, and defects en route or at destination.

Table 11.9 Common Causes for Tomato Fruit Disorders

Disorder	*Causes*
Cracking	Occurs during warm rainy seasons due to uneven moisture conditions
Catfacing	Incomplete pollination
Misshapen	Incomplete pollination, physical contact with stems, other fruit, support wires or posts
Puffiness	Occurs in early-harvested fruit, result of temperature and moisture stress, excessive N fertilization
Blossom-end rot (BER)	Moisture/temperature or other plant stresses
Sunscald	Exposure of fruit to direct sunlight
Green shoulders	Due to sun exposure
Russetting	Related to varying temperature or stress
Anther scarring	Due to early injury of the flower
Blotchy ripening	High uneven temperature during ripening and low K (can be due to high N availability to the plant)

opposite the inside title page of the book by Wittwer and Honama (1969). Tomato fruit harvested when green will never naturally ripen.

Although flavor is not a measured factor for fruit identification, high flavor (organoleptic properties) sensed by the consumer can result in repeat sales for labeled fruit of known origin. There are two measured factors that are associated with "high" flavor, a fruit EC of 5.8 to 6.2 dS/m, and a BRIX measurement of 4.8 to 5.0. Flavor can be a subjective factor since not everyone can sense the same thing. In general, high acid- and sugar-containing fruit is normally judged as "flavorful." Most of the flavor in the tomato fruit resides in the gel portion. Therefore, the ratio of gel to wall in the fruit can affect flavor.

High flavor stems from two fruit components, sugar (glucose and fructose) content and level of volatile organic compounds. Forty-six percent of the dry weight of fruit is sugar, 12% organic acids, 8% minerals, and the remaining other organic compounds. The longer the fruit remains on the plant, the higher will be its flavor. The cooler the air temperature, particularly nighttime temperature, the higher the fruit flavor. In general, plants under stress produce higher-flavored fruit; this is the reasoning behind the common procedure of increasing the EC of the nutrient solution to about 4 dS/m or adding NaCl to the nutrient solution at a concentration of 35 ppm in solution during the fruiting period. There is a varietal component, as some varieties produce more flavorful fruit than others do. In general, small-fruit varieties (cherry) tend to produce more flavorful fruit than large-fruited (beefsteak) varieties do.

Two other factors that will influence consumer-judged quality are skin toughness and fruit firmness, factors that give a certain "mouth feel."

Plant Nutrition

The tomato plant is classed as a high nutrient element requirement plant. The nutrient elements of primary concern for this crop are N, P, Mg, and Zn. Among the micronutrients, the tomato plant has a high requirement for Fe and Cu and moderate requirement for B, Mn, and Mo. Excess N is more likely to occur than its deficiency; excess results in blossom abortion, reduction in fruit set, and stimulation of vegetative over reproductive growth. Plant characteristics that indicate excess N are dark green foliage, vigorous vegetative plant growth, fast development and growth of suckers (see Figure 11.17), and the appearance of vegetative stems on fruit trusses (see Figure 11.18). The plant N level considered excessive varies with stage of plant growth and environmental conditions. For example, Moreno et al. (2003) found that cultivars that are less efficient in their utilization of N produced higher fruit yields than those more efficient. In addition, they found that total N in the leaf tissue declined with time; the average content was about 4.50% during the vegetative stage and then decreased at a slow declining rate plateauing to 3.00% during the fruiting period. The 3.00% N level is considerably less than what has been reported by some (Jones, 1999) as that optimum during fruiting, although in agreement with Wilcox (personal contact), Ward (1964), and Reisenauer (1983). During this same period, Moreno et al. (2003) observed a decline in leaf K (4.00 to 2.00%), Mg (0.90 to 0.70%), and S (0.32 to 0.20%), while P (0.75 to 0.95%) and Ca (2.90 to 3.10%) increased. Mason and Wilcox (1982) suggest that the NO_3-N content (>14,500 ppm is excess) of the petiole of mature leaves is a better indicator of the N-status of the tomato plant than is total N of the whole leaf.

Although fruit quality is generally thought to be closely associated with the elements K and B, little attention has been given to N as a significant element affecting fruit quality. The author is of the opinion that manipulating the K supply to the plant will not influence fruit quality unless the N status of the plant is sustained at the lower end of the sufficiency range (3.0 to 3.5%). Light intensity may also play a significant role in the N nutrition of the tomato plant; higher N levels are needed under low light conditions and lower N levels at high light conditions.

Blossom-end rot (BER) is a Ca-deficiency symptom due to insufficient Ca reaching the blossom end of the developing fruit (Figure 11.25). However, a severe Ca deficiency must exist if no other stress condition occurs resulting

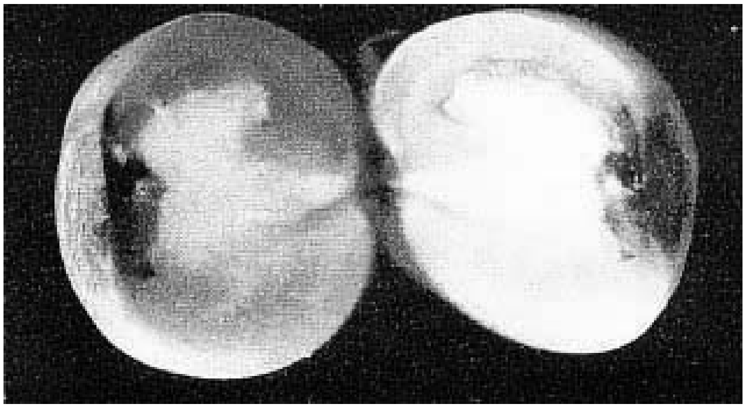

Figure 11.25 Symptoms of blossom-end rot (BER) on tomato fruit. Normally, the symptom — browning (decay) of the blossom end of the fruit — occurs early in fruit development. Such fruit should be removed when first observed. BER fruit will early turn red.

in BER-affected fruit. More frequently, BER occurs primarily as a response to plant stress, usually moisture stress and/or low transpiration rate. Calcium moves in the xylem conductive tissue of the plant, and if that movement is slowed by impaired water uptake and/or movement through the plant, then Ca movement up the plant is also impaired, particularly movement into developing fruit. In addition, sufficient Ca in the rooting medium, although essential, does not guarantee freedom from the occurrence of BER. As stated by Taylor and Locascio (2004), "BER is related to many factors including: high salinity, high Mg, NH_4, and or K concentration, inadequate xylem tissue development, accelerated growth rate, unfavorable moisture relationships (high, low, or fluctuating), low soluble medium Ca, high temperature, and high and low transpiration."

An application of a soluble Ca-containing compound to the plant foliage or even on the developing fruit will not affect the Ca nutrition of the plant, and therefore reduce the incidence of BER. Calcium is not readily absorbed into the plant through the leaves and then transported into the vascular tissue for transport throughout the plant or taken through the fruit epidermis.

There also exists a balance among the major cations, K, Ca, and Mg, and if these elements are out of balance with each other, then Ca uptake and movement can be impaired. The author has observed BER-affected fruits when there were visual leaf Mg-deficiency symptoms. The presence of NH_4 in the nutrient solution, if greater than 10%, can significantly increase the incidence of BER (Hartman et al., 1986).

Phosphorus excess is more likely to occur than its deficiency, and its excess (greater than 1.00% of the dry weight) in recently mature leaves can result in Zn deficiency (Jones, 1998a).

The source of Fe can not only affect its uptake but can significantly impact the plant. For example, the chelate ethylenediaminetetrateacetic acid (EDTA) form of Fe is not recommended since EDTA is toxic to the plant (Rengel, 2002). The chelate diethylenetriaminepentaacetic acid (DTPA) form of Fe is the accepted chelated form since DTPA toxicity is thought not to exist. Rengel (2002) observed that the inclusion of Fe-EDTA in a nutrient solution resulted in reduced uptake and translocation of the micronutrients Cu and Zn within the plant. It is not known if the DTPA form of chelated Fe will have the same effect on these two micronutrients. Other chelated forms of Fe, HEEDTA, NTA, and EDDHA, have been used, but to a lesser degree than either EDTA or DTPA. Several inorganic forms of Fe have been found suitable as Fe sources in nutrient solution formulations, such as iron ferrous sulfate, $FeSO_4{\bullet}7H_2O$; iron ferric sulfate, $Fe_2(SO_4)_3$; ferric chloride, $FeCl_3{\bullet}6H_2O$; and iron ammonium sulfate, $FeSO_4(NH_4)_2SO_4{\bullet}6H_2O$.

The author has frequently observed low Cu and Zn contents in tomato leaf samples submitted for analysis and interpretation. The questions that need to be answered are, "do these low levels reflect an inadequate amount of Cu and Zn in the nutrient solution," or "is it a factor related to cultivar adsorption capacity, or is it the influence of the Fe chelate in the nutrient solution on Cu and Zn adsorption?" My best guess would be the influence of the presence of the chelate in the nutrient solution. In earlier experiments, I have found that if the Fe source was an inorganic one (see pages 57 and 398), low Cu and Zn leaf contents were not frequently observed.

Under varying environmental conditions, the nutrient element status of the plant is critical for normal vigorous growth and sustained fruit set and development. For example, under high radiation (bright long sunny days combined with high transpiration rates), best plant performance is obtained when the nutrient element content of the plant for the major elements, primarily N, P, and K, is at the minimum concentration required for their sufficiency (Table 11.10). Under low radiation (short and/or cloudy days with low transpiration rates), best plant performance occurs when the nutrient element content of the plant for these same major elements is at the mid or higher end of the concentration range required for their sufficiency.

The uptake rates for the essential nutrient elements are not all the same as has been found by Halbrooks and Wilcox (1980). Active uptake occurs for the elements P, K, and Mn and for the ions NO_3^- and NH_4^+; intermediate uptake for the elements Mg, S, Fe, Zn, Cu, and Mo; and passive uptake for the elements Ca and B (Bugbee, 1995). Actively transpiring plants will easily take up the ions NO_3^- and K^+ from the solution surrounding the roots, resulting in high levels of N and K in the plant which, in turn, leads to imbalances between these elements and others. Therefore, a need exists to adjust the nutrient solution formulation in order to avoid imbalances among the elements.

Morgan (2003d) found that the concentration of the major elements in a nutrient solution will change over a 40-day period when the plant is flowering and setting fruit. For example, the K concentration declined from 750 to 200 ppm, while Ca increased from 500 to 700 ppm, and Mg increased from 125

Table 11.10 Sufficiency Range and Comments for Essential Element Concentrations in Dry Matter of a Tomato Leafa for Interpretative Purposes

Essential Element	*Sufficiency Range*	*Comments*
Major Elements	%	
Nitrogen (N)	2.50-4.00	During the vegetative growth stage, N at the higher end of the sufficiency range is recommended but at the lower end during the fruit setting and development stage. High plant N can reduce fruit set and be detrimental to fruit quality. High N content plants is more common than low.
Phosphorus (P)	0.30-0.75	When the P level in the leaf tissue exceeds 1.00%, the plant is under stress and both Zn (more likely) and Fe deficiency is likely to occur. High P contents in plants is more common than deficient levels.
Potassium (K)	1.25-2.50	The balance among the cations, Ca and Mg, may be more important than the concentration of K alone, adversely affecting fruit yield and quality. During fruit set and development, the level of K and Ca in the tomato leaf should be about equal.
Calcium (Ca)	1.50-3.00	See above for K. Low Ca in the leaf tissue can lead to the occurrence of blossom-end-rot in developing fruit
Magnesium (Mg)	0.35-0.75	Low Mg is a very common occurrence in greenhouse tomato, the result of a lack of balance among the major cations, K, Ca, and Mg. Blossom-end-rot in fruit can occur in low Mg content plants.
Sulfur (S)	0.50-1.00	Sulfur deficiency is not common and S levels higher than the sufficiency range are not uncommon and probably have no detrimental effect on the plant.
Micronutrients	mg/kg (ppm)	
Boron (B)	20-100	Low B can affect fruit development and plant growth, while high levels are probably not detrimental.
Copper (Cu)	5-15	Copper insufficiencies are uncommon, however, if a chelated form of Fe is used in the nutrient solution, Cu uptake and trans-location in the plant can be impaired.
Iron (Fe)	50-250	This is a difficult element to access in terms of evaluating a plant analysis result. Soluble Fe is probably a better determinator of sufficiency (see page 55).

Table 11.10 Sufficiency Range and Comments for Essential Element Concentrations in Dry Matter of a Tomato Leafa for Interpretative Purposes (continued)

Manganese (Mn)	30-200	High concentrations in the plant are not uncommon and probably not detrimental to the plant. High P levels in the growing medium will stimulate Mn uptake.
Molybdenum (Mo)	0.5	Uncommon deficiency and difficult element to evaluate.
Zinc (Zn)	25-100	The critical level in the plant is 15 mg/kg (ppm) and low Zn can affect plant growth and fruit set. If a chelated form of Fe is used in the nutrient solution, Zn uptake and translocation in the plant can be impaired. High P (>1.00%) in the plant can induce a Zn deficiency.

[a] Tip of recently mature (at or just below the forming flower cluster) compound leaf as shown in Figure 13.4 (see page 324)

to 200 ppm. In order to compensate for these changes, Morgan (2003b) recommended that the nutrient stock solution should be so constituted, as given in Table 11.11, to compensate for these changes.

By frequent sampling (every 2 to 3 weeks) and analysis (see Chapter 13), the nutrient element content of the plant can be monitored. The proper sample is the end leaf from a recently mature leaf (Figure 13.4). Visual plant symptoms suspected to be due to nutrient element deficiency should be verified by means of a plant analysis. Typical visual nutrient element deficiency symptoms are given in Table 11.12. Color pictures of visual symptoms of nutrient disorders in tomato can be found in the book by Roorda van Eysinga and Smilde (1981). Visual deficiency symptoms for the elements Ca, B, Cu, Fe, Zn, and Mo are shown in the book by Bould et al. (1984). Sufficiency range values for

Table 11.11 Nutrient Element Stock Solution Element Levels for Each Stage of Growth in a Commercial Tomato Crop (ppm Required)

	Days				
Element	0	10	20	30	40
Nitrogen (N)	350	350	345	322	315
Phosphorus (P)	170	176	188	202	215
Potassium (K)	750	866	948	1035	1125
Magnesium (Mg)	150	157	165	172	180

Note: 0 = flowering, 10 and 20 = first fruit set, 30 and 40 = full fruit loading.

Source: Morgan, L., 2003d, *The Growing Edge* 1(6):56–57.

Table 11.12 Typical Visual Essential Element Deficiency Symptoms for Tomato

Essential Element	*Visual Deficiency Symptoms*
Nitrogen (N)	Stunted and/or slow growing plants, light green colored foliage with lower leaves appearing yellow in color (see deficiency symptoms for S since they can be confused with N), dark green foliage, vigorous vegetative growth with little or no fruit set, fast emerging suckers and vegetative stems from fruiting trusses
Phosphorus (P)	Stunted plants with thin stems, abnormally dark green plants with reddish or purplish pigmentation, sometimes chlorosis occurrence on the older leaves no specific symptoms for this element as high P will result in possible micronutrient deficiency, other either Fe and Zn, Zn being the one most likely to occur
Potassium (K)	Chlorosis starts at leaf tips and margins of older leaves, progressing between the veins, chlorosis on the tip and border of lower leaves, followed by the death of the tissue, fruit formation and development may be slow
Calcium (Ca)	Chlorosis generally begins at tips and margins of young leaves, progressing between the veins followed by necrosis, leaf tips and margins turn brown to black, the growing point emerges slowly, may be deformed and die, emerging flowers and small fruit abscess, apical decay of the fruits (BER). Symptoms not known, excess K will result in a possible Ca, and more likely induced Mg deficiency
Magnesium (Mg)	Chlorosis starts between veins of older leaves and leaves become yellow, intervein chlorosis of the older leaves, possible appearance of BER in fruit symptoms not known, excess may influence the function of K and Ca
Sulfur (S)	Entire plant becomes light green in appearance with chlorosis most pronounced on young leaves, new leaves bear as light green or yellow coloration depending on the intensity of the deficiency (see deficiency symptoms for N since they can be confused for S)
Boron (B)	Plants become brittle as leaves easily break from the main stem, some browning of the leaf tips which turn black, growing point will be slow emerging and may die, fruits bearing brown spots near the blossom end element accumulates in the leaf margins and excess can result in tissue death of the leaf margins and possibility of slowing or killing of the terminal growth
Copper (Cu)	Plants are slow growing and the plant tops easily wilt, the borders of the old leaflets curl upward. High Cu in the rooting medium can cause significant root damage before any symptoms occur in the vegetative top
Iron (Fe)	Newly emerging leaves are light green to yellow in color depending on degree of deficiency, with interveinal chlorosis of new leaves, when severely deficient, new leaves grow totally yellow in color, symptoms not known, high Fe may interfere with the normal function of Zn in the plant

Table 11.12 Typical Visual Essential Element Deficiency Symptoms for Tomato (continued)

Manganese (Mn)	Interveinal chlorosis of young leaves, chlorosis followed by a necrosis of the border and tips of new leaves; accumulates in the leaf margins and can result in death of the leaf margins, high accumulation of Mn in the leaf results in the occurrence of small black specks (MnO) on the leaves
Molybdenum (Mo)	Older leaves bear intervein chlorosis, with flowers and small fruits abscess
Zinc (Zn)	Symptoms not known, high Zn may interfere with the normal function of Fe in the plant

interpreting a leaf analysis result are given in Table 11.13. In a review article, Jones (2000) describes the nutritional characteristics of the tomato plant and how one can interpret visual plant appearance and elemental leaf content as means of ensuring nutrient element sufficiency. Visual nutrient element insufficiencies in tomato are in video form (Jones, 1993c).

Varieties (Cultivars)

For outdoor production, many varieties are available; the plant types are determinate (the plant will end its growth by producing a flowering truss) or indeterminate (the plant continues to produce a vegetable stem), and range widely in fruiting characteristics as to size, color, and form. In a survey conducted by *Organic Gardening* magazine (vol. 50, issue 4, page 4, July/August 2003), responders listed the following favorite tomatoes: Beefsteak — 37%, Cherry — 27%, Slicer — 20%, and Plum — 15%.

Bennett (1997) lists "the favorite tomatoes for home gardens," including 19 varieties of cherry tomatoes, 59 varieties of medium-size tomatoes (average fruit weight from 2 to 10 ounces), 27 varieties of large tomatoes (average fruit weight 12 ounces), 15 varieties of paste tomatoes, and 22 varieties of unusual tomatoes.

There is growing interest in heirloom varieties (Male, 1999), although many of these varieties are susceptible to various diseases and may lack adaptability to climatic stress (Johnson, 1999).

For greenhouse production, varieties used in earlier periods were beefsteak types, such as "Tropic" and "Jumbo"; while in more recent times, varieties developed by Dutch researchers such as "Trust," "Match," "Quest," or "Blitz" have been used. Initially, most grew the so-called beefsteak cultivars, but today cluster tomatoes are becoming the variety of choice due to their unique market presentation (Figure 11.26). It is estimated that about 60% of all greenhouse tomatoes grown today are cluster, and that percentage may continue to increase. The characteristics of the more commonly grown greenhouse tomato cultivars are given in Table 11.14 and their seed sources listed in Table 11.15.

Table 11.13 Sufficiency Range for Tomato Based on a Recently Mature Leaf Sample[a]

Element	*Normal Range*	*Deficient*
Major Elements		%
Nitrogen (N)	2.80–4.50	<2.00
Phosphorus (P)	0.30–0.75	<0.20[b]
Potassium (K)	2.50–4.00	<1.50 vegetative
		<2.50 fruiting
Calcium (Ca)	1.50–4.00	<1.00
Magnesium (Mg)	0.40–1.30	<0.30
Sulfur (S)	0.30–4.00	Not known
Micronutrients		**ppm**
Boron (B)	25–100	<20
Copper (Cu)	5–20	<4
Iron (Fe)	40–300	<40[c]
Manganese (Mn)	40–400	<30
Molybdenum (Mo)	0.1–10	Not known
Zinc (Zn)	20–100	<15

[a] See Figure 13.4.

[b] Excessive at 1.00%, high P can result in Zn and possibly Fe deficiency.

[c] Total Fe is not a good measure of Fe sufficiency (see page 55).

Nutrient Solution

For a detailed discussion on nutrient solutions, their characteristics and formulations, see Chapter 7. The following is a discussion of those aspects of the nutrient solution that have particular relevance to the hydroponic growing of tomato.

pH

Normal plant growth for both tops and roots occurs when the nutrient solution and rooting substrate pH is between 5.0 and 6.5. A pH higher than 7.0 can result in micronutrient deficiencies; particularly, for the elements Fe, Mn, and Zn. In general, most plants will not be adversely affected if the pH of the nutrient solution and/or that of the inert growth medium is less than 5.0. Some would recommend that pH adjustment is needed to maintain the rooting solution environment within a particular pH range based on the crop grown, but such adjustment is probably not justified unless the pH is greater than 7.0.

Ikeda and Osawa (1981) observed that when the nutrient solution pH was 5.0 and equally supplied with NO_3 and NH_4, tomato plants absorbed more of the NO_3 than the NH_4 form of N, while when the pH was 7.0, both N forms were equally absorbed. The NH_4 form of N, when more than 10% of the total

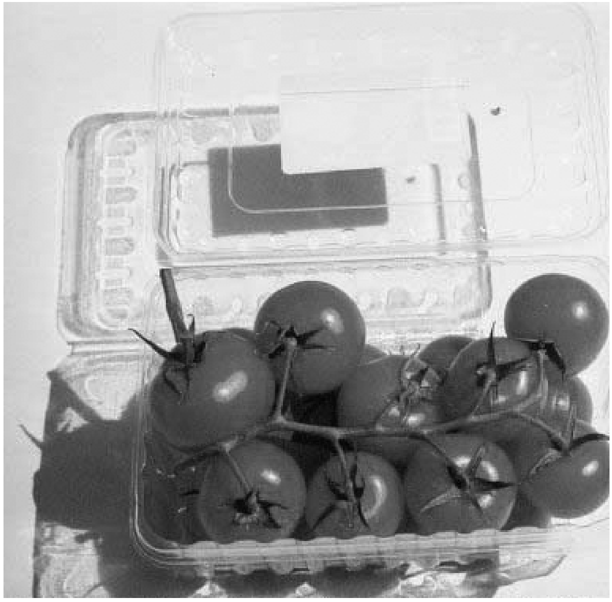

Figure 11.26 Cluster tomato fruit. Cluster cultivar producing plants will have on one truss four to eight fruits that will mature at the same time so that the entire truss can be harvested with the fruits attached as shown.

N is in solution, can lead to high incidences of BER in the fruit as well as other plant abnormalities (Wilcox et al., 1973; Hartman et al., 1986).

Electrical Conductivity (EC)

The EC of the nutrient solution, and particularly that of the solution in the medium, becomes critical when it exceeds 4.0 dS/m (see page 106 for further explanation about EC). Electrical conductivity adjustment of the nutrient solution is recommended when the plants are to be stressed, as water uptake by the plant is reduced when the EC of the nutrient solution and/or rooting medium is increased. However, if the EC of the effluent from the rooting medium exceeds 4.0 dS/m, leaching of the rooting medium with water is required. High EC in the rooting medium can result in plant wilting on high atmospheric demand days because insufficient water is being taken up through the plant roots to keep the plant turgid. When plants wilt, growth is slowed, flowers abort, and the incidence of fruit BER increases. Morgan (1997a) suggests that fruit flavor can be enhanced by a slight water stress of the plant and raised salinity in the nutrient solution, plus other factors that will add sugar to the fruit and therefore enhance flavor. The author does not recommend the use of EC adjustment for influencing fruit quality and flavor. A common recommendation is to add NaCl to the nutrient solution formulation at a rate of 35 ppm.

Table 11.14 Commonly Grown Greenhouse Tomato Cultivar Characteristics

Cultivar	*Fruit Size (oz)*	*Vigor*	*Internodes*	*Disease Resistance*
Beef Steak				
Caruso	7.1	Normal	Normal	Mosaic virus, cladosporium, verticillium, fusarium
Laura	7.1	Normal	Short	Mosaic virus, cladosporium, verticillium, fusarium
Jumbo	8.0	Normal	Short	Cladosporium, verticillium, fusarium
Kastalia	7.5	Strong	Short	Mosaic virus, verticillium, fusarium races 1 and 2
Blitz	8.2	Strong	Normal	Mosaic virus, cladosporium, verticillium, fusarium, fusarium crown root rot, nongreenback
Match	8.2	Normal	Normal	Mosaic virus, cladosporium, verticillium, fusarium, fusarium crown root rot, nongreenback
Trust	8.0	Normal	Normal	Mosaic virus, cladosporium, verticillium, fusarium, fusarium crown root rot, nongreenback
Calico	7.8	Strong	Normal	Mosaic virus, cladosporium, verticillium, fusarium, fusarium crown root rot
Grace	7.4	Normal	Normal	Mosaic virus, cladosporium, verticillium, fusarium, fusarium crown root rot, nongreenback, powdery mildew
Rapsodie	8.6	Strong	Normal	Mosaic virus, cladosporium, verticillium, fusarium, fusarium crown root rot, silvering

Note: Early Maturing Varieties: Jumbo, Kastalia, Calico, Rapsodie; Normal Maturing Varieties: Carsuso, Laura, Favorita, Cheresita, Blitz, Match, Trust, Ambiance, Clarance, Romance, Tradiro, Grace.

Table 11.15 Sources of Seeds for Greenhouse Tomato Cultivars

De Ruiter Seeds, 3001 Bethel Rd., Suite 118, Columbus, OH 43220; tel: 614-459-1498; www.deruiterusa.com

Enza Zuden BV, PO Box 7,1600 AA Enkhuizen, The Netherlands

Zuden North-America, Inc., 1352 Burton Ave., Salinas, CA 93901; e-mail: seed@enzasalinas.com; tel: 831-751-0937; www.enzazaden.nl

Bruinsma Hydrokutuur, Noorddammerweg 1 AIS, 1424 NV De Kwakel, 0297-325709; e-mail: info@brusinsma-hydro.nl

Formulations

A number of nutrient solution formulations have been recommended for tomato, depending on the hydroponic system used and growing conditions. Jones and Gibson (2003) reviewed articles on nutrient solution formulations and use that appeared in issues of *The Growing Edge* magazine from 1989 to 2002. Some of these formulations for tomato plus those from other sources are given in Table 11.16.

Nutrient solution formulations using the NFT growing systems can be found in Tables 9.3, 9.9, 9.11, 9.12, and 9.13. Smith (2001f) describes a nutrient solution dosing system that is designed to take the guesswork out of supplying the crop with its essential nutrient elements.

Nutrient Element Accumulation in the Rooting Substrates

With each addition of nutrient solution (whether in an ebb-and-flow or drip irrigation system) to a rooting substrate, an accumulation of elements occurs. A portion of this elemental accumulation can be leached with water since a portion of some elements continues to exist as ions. That which can not be leached from the substrate with water exists as precipitates, mainly a mix of calcium phosphate and calcium sulfate. In the process of precipitate formation, other elements, primarily Cu, Fe, Mn, and Zn, will be either adsorbed on the surface of the precipitate or exist as compounds within the precipitate. After several months of use in an ebb-and-flow gravel substrate system, these precipitates can be observed by running your hand down into the gravel; on

Table 11.16 Nutrient Solution Formulations for Tomato [mg/L(ppm)]

Element	*Concentration (ppm)* Modified Steiner[a]	*Stage of Growth* 1[b]	2[b]	3[b]	4[b]	5[b]
Nitrogen (N)	171	70	80	100	120	150
Phosphorus (P)	48	50	50	50	50	50
Potassium (K)	304	120	120	150	150	150
Calcium (Ca)	180	150	150	150	150	150
Magnesium (Mg)	48	40	40	40	50	50
Sulfur (S)	—	50	50	50	60	60
Boron (B)	1.0	0.7	0.7	0.7	0.7	0.7
Copper (Cu)	0.2	0.2	0.2	0.2	0.2	0.2
Iron (Fe)	3.0	2.8	2.8	2.8	2.8	2.8
Manganese (Mn)	1-2	0.8	0.8	0.8	0.8	0.8
Molybdenum (Mo)	0.1	0.05	0.05	0.05	0.05	0.05
Zinc (Zn)	0.4	0.3	0.3	0.3	0.3	0.3

[a] *Greenhouse Tomato Handbook*, 1997, Mississippi State University.

[b] Proceeding of the Greenhouse Tomato Seminar, 1995, ASHS Press.

removal, the light gray sludge covering your hand is that precipitate. In other substrates, such as perlite or rockwool, it will take chemical extraction to determine what is being accumulated and how much. Treating the substrate as a soil and assaying it as such (Jones, 2001), the author has found that these substrates after several months of use contain substantial quantities of P, K, Fe, and B; moderate levels of Ca and Mg; and low levels of Mn and Zn (Table 11.17). The high P, Fe, and K levels in the perlite may explain why plant levels of Zn and Mg are frequently low (P and Fe interfere with Zn uptake and K with Mg uptake), and Mn levels are high (P enhances the uptake of Mn). It may be that the uptake of Ca is restricted by high K, which could be a factor in the occurrence of BER in fruit. Although cultivation may begin with a nutrient element-free substrate (such as perlite or rockwool), with time the substrate becomes a significant source of nutrient elements, and the plant begins to respond to the elements accumulated in the substrate rather than those applied in the nutrient solution. For example, I advised a hydroponic tomato grower after about 5 months of growing in a gravel ebb-and-flow system that a nutrient solution made up of only KNO_3 and borax would be sufficient to sustain plant growth. This proved to be true as there were sufficient quantities of the other essential elements that had accumulated in the gravel as precipitates. Plants are able to utilize this source of nutrient elements since the root rhizosphere is strongly acidic, dissolving a portion of the precipitate and releasing the elements for root absorption as plants do when grown in soil (Jones, 1998b). This nutrient element accumulation poses a significant factor when the growing substrate is reused, which can significantly influence the nutrient element supply and balance in succeeding crops.

The author participated in a master's degree research program in which snap bean plants were grown hydroponically to evaluate the effect of changing

Table 11.17 Elemental Content of Perlite After 6 Months of Use Growing Greenhouse Tomato

Element	*ppm*	*Interpretation*
Phosphorus (P)	85–98	Very high
Potassium (K)	373–720	Very high
Calcium (Ca)	283–398	Medium
Magnesium (Mg)	36–57	Low-medium
Boron (B)	1.7–3.0	Very high
Copper (Cu)	0.12–1.5	Medium
Iron (Fe)	20–25	Very high
Manganese (Mn)	4–12	Low
Zinc (Zn)	0.88–1.44	Low

Note: Perlite samples were from three sources, leached with water to remove soluble elements and then assayed using the Mehlick No. 3 extraction procedure.

Source: Jones, Jr., J.B., 2001, *Laboratory Guide for Conducting Soil Tests and Plant Analysis*, CRC Press, Boca Raton, FL.

N source (NH_4-N versus NO_3-N) on plant growth at various stages in the growth cycle (Cosgrove et al., 1985). What was unique about this experiment was the way the nutrient solution/medium was managed. Plants were grown in perlite in pots. Each day prior to the application of the nutrient solution, sufficient water was added to leach the pot. After allowing the pot to drain, a measured quantity of nutrient solution was added to replace the water held in the perlite. Plant growth was excellent, and pod yield was considerably greater than what had been obtained in other, similar experiments in which the plants were either grown in aerated nutrient solution that was periodically replenished or grown in perlite that was wetted with nutrient solution as needed to meet the water requirement of the plants. The explanation lies in the fact that the snap bean plant roots were exposed to a consistent nutrient element environment during their entire life cycle, while with the other two growing techniques, the nutrient element rooting environment was constantly changing. Asher and Edwards (1978b) demonstrated that with rapid movement of a nutrient solution through the root mass, they were able to grow plants successfully using a very dilute nutrient solution, from 1/10th to 1/100th that of a Hoagland/Arnon nutrient solution (see Table 7.10). Therefore, it is not the absolute concentration of elements in solution but the constancy of concentration that affects plant growth.

Organic Production

National interest in "organic foods," food items that have been grown without the use of chemical fertilizers and pest control agents, has resulted in both national [The National Organic Program (http://www.ams.usda.gov/nop/)] and state programs. These programs are designed to identify and register growers that are producing organically grown foods [see The Organic Trade Association (http://www.ota.com/)]. State organic certification procedures vary considerably as to their requirements. Therefore, the grower needs to make contact with the appropriate state certification agency in order to know what the requirements are for certification as an organic grower.

Tomatoes grown hydroponically using current methodology cannot be labeled as being "organically grown." A growing method that uses a naturally occurring organic medium (such as peat, composted milled pinebark, coconut fiber, etc.) supplemented with either natural and/or organically based fertilizer could meet the criteria for producing and labeling tomatoes as being organically grown. The challenge is to find natural sources for the major essential elements, particularly N that is required by the tomato plant in substantial quantities. The next step is to make a formulation that provides the proper level and balance among the major elements necessary to sustain plant growth as well as those needed for high fruit set and quality fruit development.

Parker (1989) lists how various indigenous materials can be used to make an organic fertilizer (Table 11.18). There are nonchemically produced substances that will contain the plant-required major elements (N, P, K, Ca, Mg, and S) as well as some or all the micronutrients (B, Cl, Co, Fe, Mn, Mo, and

Table 11.18 Indigenous Materials for Making an Organic Fertilizer

Organic mix for 4 to 5 gallons of water:
430 g hoof and horn meal
228 g bonemeal
171 g ground chalk
513 g ground magnesium rock
570 g fresh wood ashes
120 g mature oilcake (compressed and aged flax or cottonseed)
10 g scrapings from a rusty nail

Organic mix for 100 L of water:
16 kg bloodmeal
7 kg bonemeal
5 kg fishmeal
8 kg wood ashes
6 kg well-rotted compost or farmyard manure
50 g Epson salts
450 g lime
Several rusty nails

Zn). Morgan (1997c) describes various procedures for preparing organic formulations using both inorganic and organic substances using so-called naturally occurring inorganic minerals or organically produced materials (such as composts and manure), as listed in Table 11.19. Jones (2003) lists the elemental content of inorganic and organic materials commonly used as fertilizer plus several organic fertilizer formulations (Table 11.20) and then gives instructions for preparing organic fertilizers (Table 11.21). Landers (2001) describes how a lettuce and salad greens grower developed a "biofertilizer" as a workable organic nutrient solution for use by hydroponic growers. The biofertilizer is based on the aerobic digestion of animal manure.

Outdoor Hydroponics

The form of hydroponics least studied today is its outdoor use potential. Although hydroponics was initially practiced outdoors (Eastwood, 1947; Schwarz, 2003), most hydroponic growing systems in use today are found in greenhouses or other enclosures. The challenge is to find a hydroponic growing system that is not significantly affected by rainfall, unless the growing vessel is covered. The least applicable hydroponic method for outdoor use would be those systems that use the drip nutrient solution delivery technique. An example of an outdoor application is described by Schneider (2000, 2004), who grew tomatoes and cucumbers in a NFT system with good success until the plant support system failed. Also, Kinro (2002) describes an outdoor tomato hydroponic operation in Hauula, Hawaii.

Table 11.19 Naturally Occurring Inorganic Minerals or Organically Produced Substances Used for Making Organic Fertilizers (% Dry Weight)

Substance	*N*	*P*	*K*	*Ca*	*Mg*	*S*
Dried Material						
Dried blood	9 to 15	1.5	0.8 to 1.0	—	—	0.5
Bone meal	2 to 4	4 to 7	—	33	0.5	—
Hoof and horn meal	12 to 14	1 to 2	—	2.5	2	—
Fish meal	10	4-7	—	0.5	[a]	[a]
Guano: bird (Peru)	13	8	2	[a]	[a]	[a]
Guano: bat	8 to 10	4	1 to 2	[a]	[a]	[a]
Guano: cricket	4	3	2	[a]	[a]	[a]
Wood ashes	—	2 to 8	5 to 14	33 to 45	3.5	1
Wood waste	3.5	0.5	2	0.5	—	—
Animal Manures						
Poultry	2 to 5	2.5 to 3	1.3 to 1.5	4	1	2
Sheep	2	1.5	3	4	2	1.5
Goat	1.5	1.5	3	2	—	—
Horse	3 to 6	1.5	2 to 5	1.5	1	0.5
Cow	2	1.5	2	4	1.1	0.5
Mineral Sources						
Reactive rock phosphate	—	14	—	35	—	1
Dolomite	—	—	—	20	11	—
Potash feldspar	—	—	8.5	—	—	—
Granite	—	—	8, trace elements			
Gypsum	—	—	—	32	—	18
Greensand	—	—	4, trace elements			
Lime	—	—	—	35 to 40	—	—
Serpentine	—	—	—	—	23, trace elements	

Source: Morgan, L., 1997c, *The Growing Edge* 9(2):32–39.

[a] Trace levels

The author has had good success growing hydroponically in a system in which a depth of nutrient solution is maintained in the bottom of a watertight vessel (box or trough). The growing medium is either pure perlite or a 50/50 mixture of perlite and composted milled pinebark. The box and trough growing vessels are shown in Figures 11.9-1 and 11.9-2 and Figure 11.10-1 and 11.10-2 respectively (Jones and Gibson, 2002). A detailed description of the basic principle of operation for this method can be found at the Web site www.GroSystems.com.

The author has found that those cultivars that are recommended for greenhouse use (see Table 11.14) will not perform well outdoors. For outdoor

Table 11.20 Elemental Content of Inorganic and Organic Substances Commonly Used as Fertilizer in Organic Fertilizer Formulations

Substance	*Nutrient Elements Supplied*
Organic	
Blood meal	15% N, l.3% P, 0.7% K
Dried blood	12% N, 3.0% P, 0% K
Bone meal	3.0% N, 20.0% P, 0% K, 24 to 30% Ca
Cottonseed meal	6% N, 2 to 30% P, 2% K
Fish emulsion, fish meal	10% N, 4 to 6% P, 1% K
Hoof and horn meal	14% N, 2% P, 0% K
Leatherdust, leather meal	5.5 to 22% N, 0% P, 0% K
Kelp meal, liquid seaweed	1% N, 0% P, 12% K
Minerals	
Calcite, calcitic limestone	95 to 100% calcium carbonate
Colloidal phosphate or soft omission	0% N, 18 to 20% P, 27% Ca, 1.7% iron phosphate, silicas, 14 other trace elements
Dolomite, dolomitic limestone	51% calcium carbonate, 40% magnesium carbonate
Granite dust, granite meal, crushed granite minerals	0% N, 0% P, 3 to 5% K, 67% silica, 19 trace
Greensand, glauconite	0% N, 10% P, 5 to 7% K, 50% silica, 18 to 20% iron oxide, 22 trace minerals
Gypsum (calcium sulfate)	23 to 57% C, 17.7% S
Langbeinite	0% N, 0% P, 22% K, 22% S, 11% Mg
Rock phosphate	0% N, 22% P, 0% K, 30% Ca, 2.8% Fe, 10% silica, 10 other trace minerals
Sulfur	100% S
Manures	
Composted cow manure	2% N, 1% P, 1% K
Guano (bat)	8% N, 40% P, 29% K average, but varies widely, 24 trace minerals
Guano (bird)	13% N, 8% P, 20% K, 11 trace minerals

growing, garden varieties are recommended, with selection based on type (determinate versus indeterminate), fruit type (beefsteak, small fruited, cherry), and adaptation to light and temperature conditions. Seed sources for garden tomato varieties are given in Table 11.22.

Disease and Insect Control

This topic is covered in greater detail in Chapter 14. Those diseases that commonly infest tomato plants are listed in Table 11.23, and color plates of these diseases can be found in the book edited by Jones et al. (1991). The primary disease problems in tomato are *Botrytis* and *Phythium*. Many tomato cultivars (varieties) have some degree of disease resistance to the more

Table 11.21 Instructions for Preparing Organic Fertilizers

Organic fertilizers need not be expensive and can be made on your own. This recipe, to the best of my knowledge, was created by Steve Solomon, founder of Territorial Seed Company. All measurements are shown in terms of volume, not weight.

4 parts seed meal
1 part dolomite lime
1/2 part bone meal or 1 part soft rock phosphate
1/2 part kelp meal

1. Seed meal provides N and smaller amounts of P and K. Some states prohibit its use in certified organic operations (not something a home grower needs to be concerned about). Other options are afalfa meal, or rape/canola meal. The NPK value of cottonseed meal is about 6-2-1. Bloodmeal can be substituted in place of some seed meal, since it acts more quickly. Use three parts seed meal and one part bloodmeal. Seed meals tend to be acidic, so lime is included to balance that. Dolomite limestone is roughly half magnesium carbonate ($MgCO_3$) and half calcium carbonate ($CaCO_3$). Calcitic limestone is pure calcium carbonate. Plants usually need more Ca than Mg, therefore a mix of 2/3 dolomite lime and 2/3 calcitic lime is recommended.
2. Bone meal and rock phosphate provide the bulk of the P component. Less bone meal (NPK 0-10-0) is required since it releases its P more readily. The advantage of using rock phosphate (NPK 0-3-0) is that it continues to contribute P to the soil over many years. Bone meal is produced as a byproduct of the beef industry while rock phosphate is mined.
3. Kelp meal (NPK 0-0-10) contributes K and micronutrients. It tends to be more expensive than the other components. Another possible K source is Jersey greensand. It has the same advantages and liabilities as rock phosphate (very slow release) but does not supply micronutrients.

Formulas for Balanced, All-Purpose Organic Fertilizer, Fertilizer Ratio

Fertilizer Ratio (N-P_2O_5-K_2O)	*Ingredients*
2-3.5-2.5	1 part bone meal
	3 parts alfalfa hay
	2 parts greensand
2.5-2.5-4	3 parts granite dust
	1 part dried blood
	1 part bone meal
	5 parts seaweed
4-5-4	2 parts dried blood
	l part phosphate rock
	4 parts wood ashes
3.5-5.5-3.5	2 parts cotton seed meal
	1 part colloidal phosphate
	2 parts granite dust
0-5-4	1 part phosphate rock
	3 parts greensand
	2 parts wood ashes
2-8-3	3 parts greensand
	2 parts seaweed
	1 part dried blood
	2 parts phosphate rock

Table 11.22 Tomato Seed Sources for Garden Types

Fedco, PO Box 520, Waterville, ME 04903; 207-873-7333

Johnny's Selected Seeds, 310 Foss Hill Road, Albion, ME 04619; tel: 207-437-4301; fax: 207-437-2165

Vesey's Seeds, Box 9000, Calais, ME 04619; fax: 207-566-1620

Pinetree Garden Seeds, PO Box 300, Gloucester, ME 04260; tel: 207-926-3400; fax: 207-926-3886

J.L. Hudson, Seedman, PO Box 1058, Redwood City, CA 94064

Peters Seed and Research, 407 Maranatha Lane, Myrtle Creek, OR 97457

W. Atlee Burpee Co., 300 Park Ave., Warminister, PA 18974, tel: 800-888-1447; fax: 215-674-4170

Seed Savers International, 3076 N. Winn Road, Decorah, IA 52101; tel: 319-382-5990; fax: 319-3 82-5 872

Park Seed Company, 1 Parkton Ave., Greenwood, SC 29647-0001

Territorial Seed Company, PO Box 157, Cottage Grove, OR 97424-0061; tel: 541-942-9547

Catalog Descriptions: variety, type of fruit (beefsteak, medium to large, small to medium, cherry, or paste), fruit color (red, yellow, orange), growth habit (determinate or indeterminate), days to fruiting [early (40 to 60 days), midseason (70 to 80 days) or late (85 to 95 days)], resistance to disease (V — verticillium wilt, F — fusarium wilt, FF — fusarium races 1 and 2, N — nematodes, T — tobacco mosaic virus, A — alternatia stem canker, St — stemphylium gray leaf spot) and other pests, adaptation to varying climatic conditions, and number or weight of seeds.

commonly occurring diseases, and therefore are preferred for use in most instances.

It is essential that disease symptoms visible on the plant and insects found on the foliage or in the greenhouse be properly identified by relying on the skill of professional pathologists and entomologists, respectively. The best means of handling these pests is to anticipate their presence by taking effective preventative measures (Peckenpaugh, 2003a). Good sanitation practices that keep the growing area clean and prevent the entrance of pests into the growing area (or greenhouse) can do much to reduce the introduction and multiplication of disease organisms and insects (Chandler, 2003). Knowing when an infestation reaches that level that will significantly damage the tomato plant is critical for determining when control measures need be applied.

Insects that commonly attack the tomato plant are listed in Table 11.24; the most common is the whitefly (*Bemisia tabaci*), whose control measures range from chemical treatment to the use of predictor insects (McGrath, 2002b). The other major insect infesting the tomato plant is spider mites. In order to monitor for types and populations of insects in the greenhouse, sticky strips (both yellow and blue colored) and ribbons should be placed about the greenhouse and examined periodically. From the types and numbers being trapped on these strips and ribbons, the determination as to treatment control measures can be taken. Drawings of most of the insects affecting tomato as

Table 11.23 Diseases That Affect Tomato

Anthracnose
Bacterial wilt, brown spot (*Pseudomonas solunuceurum* bacterium)
Curly top, western yellow blight (virus)
Early blight (*Alternaria solani* bacterium)
Fusarium wilt (*Fusarium oxysporium* bacterium)
Late blight, buckeye rot (*Phytophthora infestans* and other *Phytophthora* bacteria)
Septoria leaf spot (*Septoria lycopersici* bacterium)
Tobacco (tomato) mosaic virus (virus)
Tomato spotted wilt (virus)
Verticillium wilt (*Verticillium ulbo-atrum* and *V. duhliae* bacteria)

Table 11.24 Insects That Affect Tomato

Whitefly (*Trialeurodes vaporariorum*)
Two-spotted spider mite (*Tetranychus urticae*)
Aphids (*Myzus persicae*, *Alacorthum solani*, *Macrosiphum euphorbiae*)
Tomato leaf miner (*Liriomyza bryoniae*, *Liriomyza bryaniae*)
Thrips (*Heliothrips haemorrhoidalis*, *Frankliniella tritici*, *F. accidentalis*)
Caterpillars
Cutworms
Fungus gnats (*Bradysia* species and *Sciara* species)

well as other crops may be found in the Knott's Handbook for Vegetable Growers Fourth Edition, pages 345 to 356 (Maynard and Hochmuth, 1997).

Summary

There is no universal system applicable for the successful commercial production of tomato in greenhouses that applies to all climatic conditions. Greenhouse design and function, growing medium, nutrient solution formulation and method of application, cultivar selection, cultural procedures, and disease and insect control measures vary with climatic conditions. Management skill adds another varying factor. For example, crop management procedures suited for a low-light cold climatic region will not work in high-light warm climates. Daily attention to details is essential, from the simplest task to the most complex. For example, a grower constantly complained about poor yield and quality, although he was not always daily suckering and tying plants to the support line. His failure to do these two relatively simple tasks in a timely manner was taking away nutrients from the developing fruit and not keeping the upward developing plant in an upright position on the support line.

Changing the nutrient solution formulation based on the changing nutritional status of the plants is important. Irrigating when not needed or not changing the irrigation schedule when the atmospheric demand is high are common management errors. The secret of success is based on maintaining a consistent growing environment, where adjustments, if and when needed, are gradual, adapted to the changing environment, both inside and outside the greenhouse.

Cucumber (*Cucumis sativus* L.)

It is generally believed that the cucumber originated in India or possibly Burma and has been cultivated for at least 3000 years. It has been cultivated in China, and by the ancient Greeks and Romans. The cucumber fruit most commonly accepted and consumed is field grown or is pickled for direct consumption or made into relish. The typical field-grown cucumbers are not grown in the greenhouse, but the European seedless type is. The financial return for cucumber is less than that for tomato, although the crop is easier to manage.

The cucumber grown today in the greenhouse is the European seedless type, which is parthenocarpic (produces fruit without pollination). Only gynoecious types or predominantly gynoecious types (with few male flowers) are acceptable since they are less vigorous, come into production earlier, produce more, and can be grown at lower temperatures than the monoecious types. Cultivar selection, suggested by Papadopoulos (1994), should be based on overall productivity, plant habit and vigor, fruit quality (i.e., length, diameter, shape, and smoothness), fruit shelf life, disease resistance, and energy requirement. For greenhouse production, the cucumber is second to tomato, and is generally grown in similar media, perlite in either bags [2 ft^3 (0.18 m^3)] (Figure 11.27) or

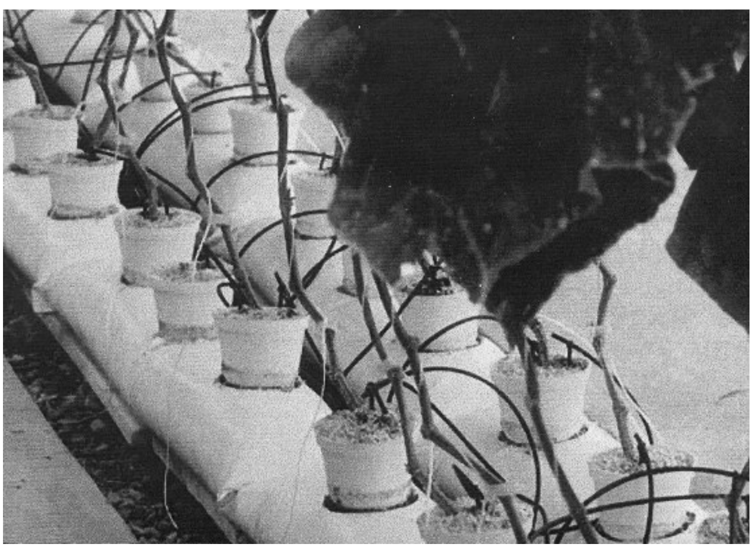

Figure 11.27 Cucumber plants rooted in perlite-filled cups set in perlite-containing bags. The black tubes are the drip lines that deliver nutrient solution to each cup.

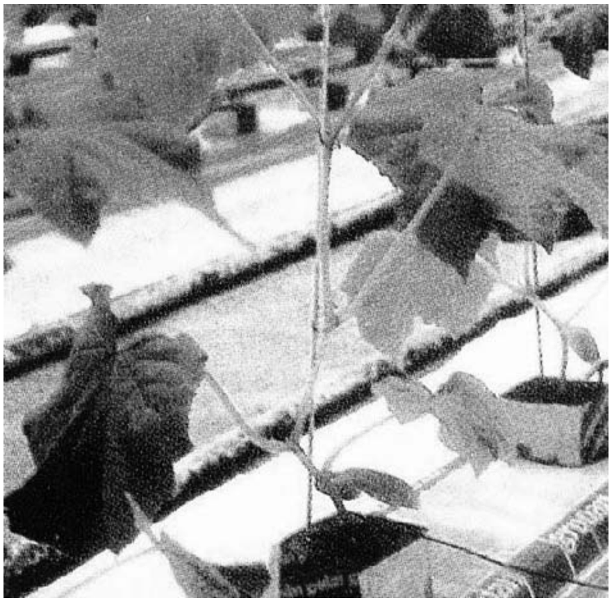

Figure 11.28 Cucumber plants rooted in rockwool cubes set in rockwool slabs. *Source:* Papadopoulos, A.P., 1994, Growing Greenhouse Seedless Cucumbers in Soil and in Soilless Media, Agricultural Canada Publication 1902/E, Communications Branch, Agricultural and Agri-Food Canada, Ottawa, Canada.

BATO buckets (see Figure 11.15), or in rockwool cubes on rockwool slabs (Figure 11.28), the nutrient solution applied by means of drip irrigation. The NFT hydroponic method is not recommended for cucumber (Papadopoulos, 1994). Papadopoulos (1994) describes other growing systems for cucumber, such as a trough system, in peat bags, sawdust, and straw bales.

Seasonal scheduling will depend on climatic location. For example, a grower in Ontario, Canada follows a staggered cropping schedule, a fall crop from November to May, and a summer crop from May/June to September/October (Spillane, 2004). Papadopoulos (1994) suggests three cropping schedules, Early Spring Crop from November seeding through July, late Spring Crop from December seeding through July, and Fall Crop from June seeding through December (Table 11.25).

Cucumber grows best under high air temperature [50 to 55°F (26.6 to 29.4°C)], humidity, and light intensity conditions and when there is a continuous supply of water and nutrient elements. However, the cucumber plant is equally sensitive to adverse growing conditions, particularly high air temperature [greater than 56°F (30°C)] combined with high light intensity as well as high EC of the nutrient solution (Morgan, 2002a). Morgan (2002a) recommends that the nutrient solution temperature should not exceed 71.6°F (22°C); that is more likely to occur using the NFT hydroponic growing technique. When

Table 11.25 Crop Schedule for Greenhouse Cucumber

Early Spring Crop
Sow seed 15 November to 15 December
Set plants in permanent bed 20 December to 20 January
Harvest February to July
Remove plants 1 July to 20 July

Late Spring Crop
Sow seed 15 December to 30 January
Set plants in permanent bed 20 January to 1 March
Harvest March to July
Remove plants 1 July to 20 July

Fall Crop
Sow seed 20 June to 15 July
Set plants in permanent bed 15 July to 15 August
Harvest 15 August to 15 December

Source: Papadopoulos, A.P, 1994, Growing Greenhouse Seedless Cucumbers in Soil and in Soilless Media, Agricultural Canada Publication 1902/E, Communications Branch, Agricultural and Agri-Food Canada, Ottawa, Canada.

the air temperature reaches l04°F (40°C), significant air movement in the canopy is essential (Spillane, 2004).

Cucumber seeds are very expensive and therefore should be carefully handled. Seeds germinate in 2 to 3 days; the optimum germinating temperature is 54°F (28.8°C). Once germinated, the optimum temperature for seedling growth is 77°F (25°C). Bottomley (2000) reported on Australian growers who germinate seed at 70°F (21°C) and once germinated, the temperature is dropped to 59°F (15°C). Manrique (1993) recommends a seed germination temperature of 52 to 59°F (11 to 15°C). Papadopoulos (1994) recommended light conditions and air and rooting temperatures for seeding and seedling growth. During seedling growth, both water and nutrient stress should be avoided. When the seedling has three to four true leaves, it is ready for transplanting into the growing medium. During the first 2 months of plant growth, Manique (1993) recommends a daytime temperature of 70°F (21°C), nighttime of 66°F (19°C), and for the remaining growth period, a daytime temperature of 66°F (19°C) and a nighttime temperature of 62.6°F (17°C) as the optima.

Grafting to disease-resistant root stocks is done when the growing medium cannot be sufficiently sterilized; the main root disease is black root rot. However, grafting is not easily performed by inexperienced individuals. Grafting procedures are described by Papadopoulos (1994). Grafting is not the usual procedure when the crop is grown hydroponically.

For a single-row growing system, space between rows should be 4 to 5 ft (1.2 to 1.5 m) with plants spaced 12 to 18 in. (30 to 45 cm) in the row. For a double-row growing system, space between the double row should be 2 ft (0.6 m) with 5 to 6 ft (1.5 to 1.8 m) between the centers of the double rows, and plants spaced within the row at 18 to 24 in. (45 to 61 cm). In-row and between-

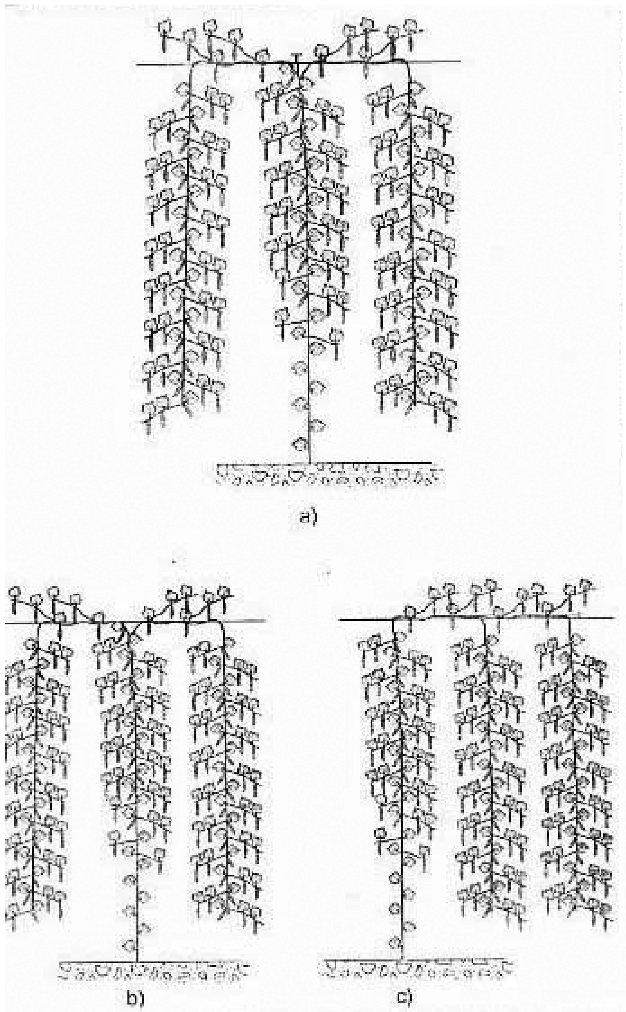

Figure 11.29 Pruning cucumber plants using the original umbrella system. a: standard form, b: first variation, c: second variation. *Source:* Papadopoulos, A.P., 1994, Growing Greenhouse Seedless Cucumbers in Soil and in Soilless Media, Agricultural Canada Publication 1902/E, Communications Branch, Agricultural and Agri-Food Canada, Ottawa, Canada.

row spacing can be altered based on light conditions; greater spacing is required at low light, tighter spacing when light conditions are high. In addition, the plant training system used will set the spacing required. Generally, high plant density will reduce fruit set and size and increase the potential for disease infestation.

Prompt attention to the cultural requirements of the cucumber plant is essential to maintain its status in a highly productive condition. Pruning is to a single stem using two pruning systems, original umbrella or modified umbrella (stem fruit) (Figure 11.29 and Figure 11.30), respectively. The cucumber plant can be trained to a support wire in four different configurations: canopy, vertical cordon, inclined cordon (V-cordon, V-training), and guernsey

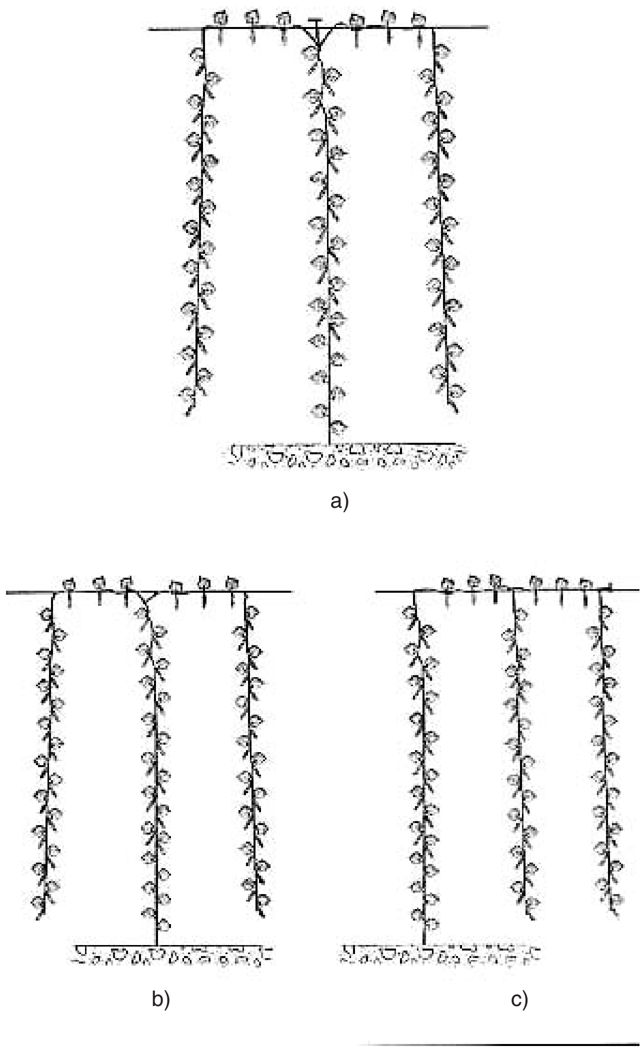

Figure 11.30 Pruning cucumber plants using the modified umbrella system. a: standard form, b: first variation, c: second variation. *Source:* Papadopoulos, A.P., 1994, Growing Greenhouse Seedless Cucumbers in Soil and in Soilless Media, Agricultural Canada Publication 1902/E, Communications Branch, Agricultural and Agri-Food Canada, Ottawa, Canada.

arch system (Papadopoulos, 1994). These various plant training procedures are also described by Morgan (2002a). Pruning and training create conditions by establishing and maintaining optimum fruit load, complete leaf coverage (i.e., no light reaching the ground), and uniform exposure of all foliage for efficient light absorption (Papadopoulos, 1994). Removal of dead, diseased, or insect-damaged foliage should be done as soon as identified as such.

The plant grows rapidly, and fruit production can be high under good growing conditions. For example, fruit yields can vary from a low of 2.5 fruits per plant per week to a high of seven depending on light conditions. In order to maintain plant strength and fruit size development, selective fruit thinning may be needed. If the fruit load is too heavy, plant vigor is reduced, and maturing fruit may be stunted, misshapen, curved, or discolored. 1t is also important to remove from the plant fruit that when mature will be unmarketable at harvest, a determination that should be made as quickly as possible.

However, this rapid development can lead to fruit quality problems unless the growing conditions are carefully set and maintained. Curvature of the fruit, known as "crooking," can occur early in the fruit development stage, and such fruit should be removed from the plant. However, some minor degree of curvature can occur without affecting marketability. Crooking occurs due to a variety of factors, temperature and moisture stress being most common, physical factors that would impair fruit elongation, and nutritional insufficiencies. Fruit bitterness also occurs when the cucumber plant is under stress, similar to that causing crooking.

Depending on the growing season, 20 to 40 fruit can be harvested per plant. Mature fruit will be ready for harvest normally within 2 weeks after fruit set (Figure 11.31), and therefore, fruit should be harvested (every day to every other day depending on growing conditions) as soon as it reaches marketable maturity. Once cooled to 53°F (12°C), the fruit must be shrink-wrapped in order to maintain its turgidity since the fruit will quickly lose

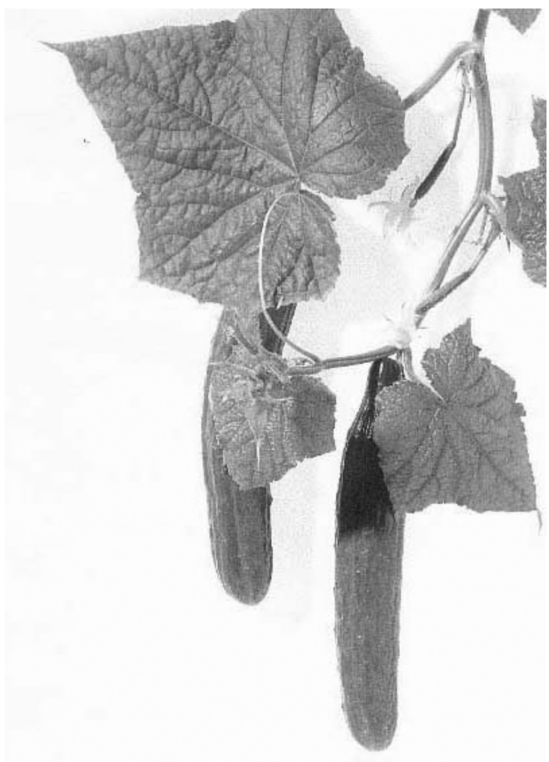

Figure 11.31 Mature European cucumber fruit.

water due to its thin skin. Once harvested, fruit quality can only be maintained, not enhanced. The fruit is best stored at 50 to 55°F (10 to 13°C) at 90 to 95% relative humidity with a shelf life from 10 to 14 days. Fruits should be stored away from other fruits, such as apples and bananas, that emit ethylene.

The fruit is unusual-looking [up to 24 in. (61 cm) in length) and it is seedless. Its consumer acceptance has been found to be limited in the marketplace and therefore requires unique marketing strategies. The fruit is a good source of vitamin C and provides some vitamin A and the elements Ca and Fe.

Carbon dioxide enhancement of the greenhouse atmosphere from 1000 to 1500 ppm during the daylight hours can improve fruit development and yield when ventilation is not needed during the winter months (Morgan, 2002a; 2003c). It is important to keep air moving through the plant canopy to keep leaf surfaces cool while keeping the CO_2 content within the canopy at least at the ambient level. Relative humidity, either high or low, can significantly affect the cucumber plant and the incidence of insect and disease infestations.

The nutritional requirement of the cucumber plant is such that a 1:1 balance between the elements N and K is required. The availability of water and the required essential nutrient elements can significantly impact the plant in determining its vegetative versus fruiting habit. The plant is sensitive to changing EC of the nutrient solution, as increasing EC can result in slow plant growth and poor fruit set. The response of the cucumber plant to both the macro- and micro-nutrients is discussed in detail by Papadopoulus (1994). Nutrient solution formulations are given in Table 9.3 and Table 9.10 in Chapter 9. The cucumber is also considered Mg sensitive, and visual symptoms of Mg deficiency have been observed by the author in many cucumber crops. In addition, the cucumber plant is responsive to Mn, moderately so to Cu, and not sensitive to B. The elemental contents in a nutrient solution for cucumber as recommended by Morgan (2002a) are given in Table 11.26. The nutrient element content of the cucumber plant defining sufficiency is given in Table 11.27. Color pictures of visual symptoms of nutrient disorders in cucumber can be found in the book by Roorda van Eysinga and Smilde (1981). Molybdenum deficiency symptoms are shown in the book by Bould et al. (1984)

Morgan (2002a) considers silicon (Si) an important element essential to ensure good growth, recommending that its nutrient solution concentration be between 75 and 140 ppm.

The most commonly occurring fungal disease in cucumber is powdery mildew (*Pseudoperonospora cubensis*), which first appears as white or gray spots on older leaves and will quickly spread if the environmental infestation conditions are favorable (moderate air temperature and high relative humidity). In addition, the author has observed that powdery mildew seems to be most aggressive when the plants begin to fruit heavily. There are few chemical control measures, and some cultivars have some degree of mildew resistance. The best control is to keep the infestation from occurring by controlling the greenhouse environment. Other diseases that will affect the cucumber are damping off (caused by either *Pythium* spp. or *Rhizoctonia solani* — normally occurs at transplanting), pythium root rot (*Pythium uphuniderrnuturn*), sclerotinia stem rot (*Sclerotinia sclerotiorum*), and cucumber mosaic virus. Iden-

Table 11.26 Recommended Elemental Contents of a Nutrient Solution for Cucumber

Element	*Concentration (ppm)*
Major Elements	
Nitrogen (N)	216
Phosphorus (P)	58
Potassium (K)	286
Calcium (Ca)	185
Magnesium (Mg)	185
Sulfur (S)	43
Micronutrients	
Boron (B)	0.70
Copper (Cu)	0.07
Iron (Fe)	6.85
Manganese (Mn)	1.97
Molybdenum (Mo)	0.05

Source: Morgan, L., 2002, *The Growing Edge* 13(3):32–43.

Table 11.27 Content of Nutrient Elements in Dry Matter of Leaves from Healthy Plants or Plants with Deficiency or Toxicity Symptoms

Nutrient Element	*Healthy Range*
Major Elements	**mol/kg**
Nitrogen	
Total	1.8 to 3.6
Nitrate-N	0.07 to 1.0
Phosphorus	0.11 to 0.25
Potassium	0.5 to 1.5
Magnesium	0.2 to 0.8
Calcium	0.5 to 2.5
Sulfur	
Total S	0.13 to 0.30
Sulfate-S	0.05 to 0.28
Micronutrients	**mmol/kg**
Boron	
Copper	0.03 to 0.35
Iron	1.7 to 5.4

tification of these diseases and control procedures should be determined by an experienced plant pathologist.

Aphids and thrips are the common cucumber insect pests and their control should be based on approved control measures.

Schneider (2001) discusses his outdoor experience growing European cucumber using a home-designed NFT hydroponic growing system. From seven plants, he harvested 178 cucumbers weighing over 200 lb (91 kg), harvesting from mid-July to the end of September.

Pepper, Bell Types (*Capsicum annum* L.)

Pepper is native to Mexico and Central America. The species was brought into cultivation between 5000 and 3000 B.C., although seeds of pepper have been found in archeological sites in Mexico dating back to 7000 B.C. Spanish and Portugese traders were largely responsible for carrying and distributing peppers worldwide. This tropical herbaceous perennial plant becomes woody at the stem base and becomes shrublike. Plants are erect and highly branched.

The *Capsicum* genus includes all peppers; they vary widely in size, shape, flavor, and sensory heat. Today, it is the sweet or bell pepper that is primarily grown in greenhouses in Northern Europe. The financial return for greenhouse hydroponically grown peppers is not as high as that for either tomato or cucumber, and its marketability will depend on consumer needs and tastes. Peppers (known as chiles) were introduced into southern Europe around A.D. 1500 by Columbus and became a part of the world spice trade. Chile peppers are used for food seasoning in tropical areas, particularly in India and tropical America. The book by Morgan and Lennard (2000) gives details on the production of this crop.

Bell pepper fruits are normally green during their initial development, and as fruit matures (ripens), the color changes from green to bright red (most common), or orange or yellow. It is the breakdown of chlorophyll (green color pigment) that exposes the underlying fruit color. Fruit whose initial color is either white or pale yellow, lilac, purple, or black when immature will also ripen to red. The fruit can be eaten raw or cooked. The commonly grown greenhouse bell pepper cultivars and their characteristics are given in Table 11.28. Seed sources for bell peppers are given in Table 11.29.

Bell pepper is grown in similar hydroponic systems as tomato (see pages 187–204), in perlite-containing bags or buckets (such as BATO) or on rockwool slabs. If the NFT hydroponic method is used, Morgan and Lennard (2000) recommend that the maximum length of the gully be no more than 25 m at a gradient of 1:40, and the nutrient solution flow rate be 1 L per minute with a capillary mat placed in the base of the gully.

Pepper seed germinates at temperatures between 70 and 75°F (21 and 23.8°C). Seedling growth is slow; the optimum temperature range is 77 to 81°F (25 to 27°C) during the day and 64 to 68°F (18 to 20°C) at night. Later, optimum growth of young plants requires daytime air temperatures between 65 and 70°F (18.3 and 21°C), and a nighttime temperature of 65°F (18°C). Plant growth essentially stops when the air temperature is 50°F (10°C) or below. When the air temperature is cool, warming the rooting medium to 75 to 86°F (24 to 30°C) can improve fruit yield. When nighttime air temperatures are greater than 70°F (21°C), flower and fruit buds will drop from the plant. Air temperatures above 86°F (30°C) can result in poor fruit set. Morgan (1999d) suggests that when plants are in flower, good ventilation should keep the air temper-

Table 11.28 Commonly Grown Greenhouse Bell Pepper Cultivars and Their Characteristics

Cultivar	*Days to Maturity*[a]	*Characteristics*
Ripen to Red		
Ace	50 to 55	Small- to medium-size elongated bells ripen in 7 days, very heat resistant
Aji Duice	90 to 95	Small, semisweet, semihot fruits
Big Berta PS	70 to 75	Huge (7-inch long), thick-walled bells
Blushing Beauty	70 to 75	Large bells ripen from ivory to pink to orange-red to bright red, disease resistant
Jalapeno TAM	70 to 75	Small plump fruits are mildly sweet
Jiggle Bells	55 to 60	Small bells ripen in 70 days, bitter when green
King Arthur	60 to 65	Medium-size bells ripen in 75 days, disease resistant
Lipstick	55 to 60	Blunt, cone-shaped pimientos ripen in 75 days, heavy yields, prone to cracking in rainy climates
Sweet Banana	65 to 70	Six-inch-long, Hungarian wax type, bright yellow when unripe
Ripen to Yellow		
Early Sunsation	70 to 75	Blocky bells ripen to golden yellow 2 weeks after reaching mature size
Gypsy	55 to 60	Elongated bells, very productive, disease resistant
Ripen to Orange		
Gourmet	65 to 70	Medium-size bells turn bright orange in 85 days
Ripen to White		
Ivory	65 to 70	Medium-size bells ripen to a rare creamy color, resists sun scald
Ripen to Brown		
Miniature Chocolate Bell	55 to 60	Heavy yields of small fruit, earliest-to-mature "chocolate"
Sweet Chocolate	60 to 65	Medium-size bells ripen to brown in 75 to 80 days

[a] From transplant to first mature green pepper.

ature below 80°F (27°C). At high air temperatures [86°F (30°C)], the plant will set many flowers, although, depending on light conditions, may not be able to bring fruit to full size. Fruit abscission occurs under low light conditions. Under high light conditions, particularly during the summer months, shading of the greenhouse is necessary to avoid damage to developing fruit.

From 12 to 15 fruits per square meter can be supported by the pepper plant under low light conditions and up to 24 fruits per square meter under high light. Controlling the number of fruit per plant is necessary to ensure good-sized marketable fruit. Harvesting when the fruit is dark green and glossy, rather than waiting until the fruit turns red, will keep the plants in a higher state of fruit production. Relative humidity can influence fruit size but will not

Table 11.29 Seed Sources for Bell and Chile Peppers

Burpee, 300 Park Ave., Warminster, PA 18974; 800-888-1447; www.burpee.com
Cross Country Nurseries, PO Box 170, 199 Kingwood-Locktown Rd., Rosemont, NJ 08556; 908-996-4646; www.chileplants.com
Harris Seeds, 355 Paul Road, PO Box 24966, Rochester, NY 14624; 800-514-4441; www.harrisseeds.com
Johnny's Selected Seeds, 955 Benton Ave., Winslow, ME 04901; 207-861-3901; www.johnnyseeds.com
Nichols Garden Nursery, 1190 Old Salem Road, NE, Albany, OR 97321; 800-422-3985; www. nicholsgardennursey.com
Territorial Seed Company, PO Box 158, Cottage Grove, OR 97424; 541-942-9547; www.tertitorial-seed.com
Tomato Growers Supply Company, PO Box 2237, Fort Myers, Fl 33902; 888-478-7333; www.tomatogrowers.com

significantly reduce total fruit yield over the normal range that would occur in the greenhouse.

Plant spacing varies with light conditions — under high light 3 to 4 plants per square meter, at low light, 2 plants per square meter (Morgan and Lennard, 2000). However, there are some who would recommend a denser population, up to 8 plants to square meter. Plant spacing can also be based on the number of stems per square meter depending on how the plant is trained to the support line. Pepper plants can be trained to a single-, double-, or even triple-stemmed plant as the pepper plants will naturally begin to branch early. However, it is best to train to a two-stem system that keeps the plant architecture open for best fruit set and development, open to good light penetration and air movement, and, in addition, minimizes the potential for disease (such as *Botrytis*) development (Morgan, 1999d). Kapuler (2000) found that survivorship of the pepper plant has to do with the way the plant is built; beneficial developmental characteristics are:

1. Types that develop woody stems with age
2. Branches that are stout and arranged so that they hold the fruits out from the plants
3. Plants that develop fruits that are small to medium size—this indicates balanced growth
4. Plants that easily make meristems from old growth — important for filling out under fruiting conditions

Pepper flowers are self-pollinated, and fruit should form easily; however, the flower can be pollinated using a hand-operated vibrator (see Figure 11.22-1), or bumblebees introduced into the greenhouse can enhance fruit set. Misshapen fruit is the result of poor pollination. Other fruit disorders, such as cracking occurs due to high air temperature, while sunburn and sunscald appear as a patch of sunken gray tissue on the fruit surface. Blossom-end rot occurs due to Ca deficiency, induced by either high temperature [86°F (30°C)] and/or moisture stress or lack of sufficient Ca in the rooting medium and/or nutrient solution (Morgan, 1999d; Taylor and Locascio, 2004). The pepper plant is sensitive to Mg and is moderate in its requirement for N, P, and K. Visual leaf symptoms for B, Cu, and Fe deficiency are shown in the book by Bould et al. (1984).

Carbon dioxide enrichment to 800 to 1000 ppm can be beneficial under low light conditions, although even at low CO_2 levels (200 ppm), fruit set can be high. The response of pepper to CO_2 enrichment in terms of photosynthetic rate is greater than that of tomato (Morgan and Lennard, 2000).

Fungus diseases, such as *Botrytis, Sclerotinia*, and various viruses, are the commonly occurring disease problems in pepper, with the fungus diseases easily controlled by fungicides. White flies, red spider mites, thrips, and aphids are the insects that can infest the pepper plant — insects that can be controlled by both biological and chemical means. Disease and insect chemical control measures should conform to those based on current pest management regulations.

The author has successfully grown bell pepper in either GroTroughs or GroBoxes, with the growing medium either pure perlite or a 50:50 mixture of perlite and composted milled pine bark (see Figure 11.9-1 and Figure 11.10-1, respectively).

Pepper, Chiles

The explorer Christopher Columbus sailed west attempting to reach the Indies by a new route. Arriving in the Americas, he was introduced to a new fruit, called aji by the locals, which he called pepper. It was very spicy, so the name chile pepper. Portuguese and Spanish traders took the chile pepper to Europe and to their colonies throughout the world. The first chiles were thought to have originated from Bolivia and then were spread throughout South and North America. Chile pepper Web sites and seed sources are given in Table 11.30 and Table 11.29, respectively.

The hot pepper types are *Capsicum baccututum, Capsicum chinense*, and *Capsicum frutescens*. Capsaicin is the principal source of the pungency in the chile fruit, which is a many-seeded berry. Actually, the pungency is due to a mixture of seven homologous branded-chain alkyl vanillylamides, of which capsaicin is the most prevalent.

These compounds are found mainly in the placenta or membrane of the chile fruit, and they increase in content with fruit maturity and when the plant is exposed to hot, semiarid conditions. Plant characteristics vary among types in terms of degree of hotness, pod form, and color (Waterman, 1995).

Seeds will germinate in 8 to 20 days depending on the temperature; the optimum range is 65 to 85°F (18 to 29°C). Morgan (1999c) identifies the best germination temperature range as between 72 and 82°F (22 and 28°C). Seeds do not easily germinate, so care should be used to ensure that the temperature and moisture conditions are optimally maintained (Spillane, 1999; Peckenpaugh, 2002c). Germination and seedling procedures given by Morgan (1999d)

TABLE 11.30 Chile pepper resources and websites

The Chile Pepper Institute (http://www.chilepepperinstitute.org)
Chile Pepper Magazine (http:hwww.chilepepper.com)
The Chile Seed Company (http://www.chileseeds.co.uk)
The Chile Seeds and Plant Ring (http://www.ushotstuff/HotSeeds.htm)
The Chile Woman (http://www.thechilewoman.com)
Cross Country Nurseries (http://www.chileplants.com)
FireGirl (http://www.firegirl.com)
The Great Chilli Farm ((http://www.chillifarm.com)
Johnny Pepper Seed (http://www.johnnypepperseed.com)
Pepper Fool (http://www.pepperfool.com)
Pepper Joe's (http:hwww.pepperjoe.com)
The Ring of Fire (http://www. ringoffire.nein)
Seeds of Change (http://www.yahoo. com/seedsofchange/chiles.htm)
Tough Love Chile Company (http://www.tough-love.com)

Source: Peckenpaugh D.J., 2002c, *The Growing Edge* 13(5):61–73.

should be followed. For best seedling growth, the air temperature should be 75°F (24°C) during the day and at night 64°F (18°C). Seedling plants should be handled by the leaves and not by their stems, which are tender and can be easily damaged.

During plant growth and development, chile pepper plants grow best at daytime temperatures of 65 to 85°F (18 to 29°C), and nighttime temperatures of 60 to 75°F (16 to 24°C). Hot pepper plants require high temperatures while the fruits are developing. Poor fruit set occurs at low air temperature. For some chilies, it may take as many as 120 days from the seedling stage to harvestable fruit.

The chile pepper plant requires high light conditions but not excessive light for best growth. The relative humidity should range between 50 and 70% and be no lower than 65%. Flowers will self-pollinate, although movement of the plant and insects can assist in pollination. Early flowers should be removed to encourage vegetative growth for young plants. As fruit begins to mature on the plant, the day length should not exceed 10 to 12 hours. A nutrient solution formula for hot pepper is given in Table 11.31.

The common diseases that can affect chile pepper plants are anthracnose, bacterial spot, and tobacco mosaic virus (TMV). Their control should conform to current disease control procedures as outlined in Chapter 14. Blossom-end rot, a breakdown of the developing end of the fruit, occurs when plants are subjected to moisture stress and/or insufficient Ca in the growing medium or nutrient solution (Taylor and Locascio, 2004).

The common insect pests that can infest chile pepper plants are aphids, cutworms, European corn borers, flea beetles, leaf miners, tomato hornworm, and weevils; their control should conform to recommended pest management procedures as given in Chapter 14.

Table 11.31 Nutrient Solution Formula for Hot Pepper

Reagents	*Ounces/10 gallons*
Part A	
Calcium nitrate	160
Potassium nitrate	17
Iron EDTA	6.7
Part B	
Potassium nitrate	17
Monopotassium phosphate	47
Magnesium sulfate	96
Potassium sulfate	35
Manganese sulfate	1.08
Zinc sulfate	0.15
Boric acid	0.53
Copper sulfate	0.04
Ammonium molybdate	0.01

To use: Dilute 1:100 of Part A and B, cf. = 25, (EC = 2.5), pH 5.9

Source: Morgan, L. and Lennard, S., 2000, *Hydroponic Capsicum Production: A Comprehensive, Practical and Scientific Guide to Commercial Hydroponic Capsicum Production*, Casper Publications Pty Ltd, Narrabeen, Australia.

Chile pepper fruits are rich in Vitamins A, B, C, and E and are a good source of K and niacin.

Lettuce (*Lacturia*)

Lettuce is the world's most used salad crop. It is native to the eastern Mediterranean basin and was cultivated by the Egyptians as early as 4500 B.C. The domestication of the species was undertaken to remove the spines, make plants slow bolting, and to make them contain less latex and less tissue bitterness. The four generally recognized morphological forms are crisphead, butterhead, cos, and loose leaf; the butterhead and loose leaf varieties are more commonly grown in the greenhouse. Seed sources are given in Table 11.32.

Lettuces are relatively easy to grow hydroponically, requiring less skill on the part of grower than for most of the other commonly hydroponically grown crops, and are a crop widely grown commercially in greenhouses and outdoors (Morgan 1999f; Ryder, 1999). The nutrient flow technique (NFT) is that commonly selected (see pages 127–141) (Christian, 1996, 1997; Fox, 1997; Schneider, 1999a; Furukawa, 2000; Morgan, 2000c; Kubiac, 2000; Alexander, 2001a; Meade, 2002a; Smith, 2002c,d). Examples of NFT systems used commercially were given at the NFT Lettuce & Herb Grower Conference and Workshop held in October 2000. High water quality and nutrient solution

Table 11.32 Lettuce Seed Sources

Abbott and Cobb, Feasterville, PA; 800-345-7333; www.acseed.com
R.H. Shumway Seeds, Randolph, WI; 800-342-9461; www.rhshumway.com
Seeds of Change, Santa Fe, NM; 888-762-7333; www.seedsofchange.com
Seeds West Garden Seeds, Albuquerque, NM; 505-843-9713; www.seedswestgardenseeds.com
Southern Exposure Seed Exchange, Mineral, VA; 540-894-9480; www.southernexposure.com
Stokes Seeds, Buffalo, NY; 800-396-9238; www.stokesseeds.com
Territorial Seed Company, Cottage Grove, OR; 541-942-9547; www.territorial-seed.com

maintenance are essential for success in NFT lettuce production (Alexander, 2001a).

Lettuce and salad greens are being grown in an organic NFT system as part of a NOVA Private Industry Council program (Schoenstein, 2001). Seedlings are placed in 12-foot (3.6-meter) long gullies, plants spaced 4 in. (10 cm) apart, with the slope of the NFT gully greater than that for a nonorganic based nutrient solution. More details on the growing system are given by Schoenstein (2001).

Since lettuce as well as most salad greens are cool season crops, it is essential to keep the air temperature between 46 and 75°F (8 and 24°C). Bolting, tipburn, loss of color, and poor germination occur if the air temperature is above 77°F (25°C). A list of slow-bolting lettuce cultivars is given in Table 11.33. During periods of high air temperatures and/or high light intensity conditions, lettuce as well as other cool-season crops (spinach and broccoli) tend to either bolt, go to seed, or turn bitter in taste. Tipburn, death of the leaf margins (a Ca-deficiency symptom), is another problem that is primarily associated with high temperature that stimulates rapid growth and slow water movement into the plant. Increasing the Ca content in the nutrient solution, reducing the K:Ca ratio, and keeping the EC low will minimize the occurrence of tipburn. Some cultivars are more susceptible to tipburn than others and should not be selected if the environmental conditions are likely to induce its occurrence.

Keeping the crop cool by shading [can reduce the air temperature by as much as 10–15°F (5–8°C)] and misting (Fox, 1997) can keep lettuce plants productive through periods of high temperature and light intensity. However, high humidity can adversely affect the crop by reducing transpiration, which

Table 11.33 Slow-Bolting Lettuce Cultivars

Bronze Mignonette: loose-leaf butterhead with green-and-bronze color
Buttercrunch: easy-to-grow butterhead, compact head of tender, juicy green leaves
New Red Fire: crisp, sweet, ruby-red loose-leaf
Sierra: open-heanded, upright crisphead with glossy green, red-tinted leaves
Sloboit: large rosette of bright green, ruffled leaves

cools leaf surfaces, reduces the uptake of essential nutrient elements, and increases the potential for fungus disease (such as *Botrytis* and mildew) infestations.

Seeds are usually planted in germination cubes (rockwool is preferred) and, upon germination, the cubes containing the emerging seedlings are set in the NFT trough. Seeds can also be planted in cups of growing medium, and once roots are visible from the bottom of the cup, are set into the NFT trough. The rooting medium can be either a mixture of various organic (such as coconut fiber) or inorganic (perlite) substrates or inorganic alone, such as rockwool, or a mix of inorganic/organic (perlite and composted milled pinebark), or a mix of two inorganic substances (composted milled perlite and vermiculite) (Fox, 1997; Morgan, 2003f). The author uses a 50:50 mixture of perlite and composted milled pinebark as the growing medium. Smith (2002b) found a grower who used a mixture of 20% pumice and 80% vermiculite as the rooting medium. Fox (1997) found a large lettuce grower in Perth, Australia who uses a 50/50 mixture of perlite and vermiculite as the rooting medium.

The design of the NFT growing system, such as trough width (2 to 4 in.), depth (1.5 to 3.5 in.), and length (10 to 30 ft), is normally within these parameters. Troughs are set on a slope of 1 to 2%. Smith (2004) and Morgan (1999c) give instructions for the design and fabrication of NFT gullies suitable for hydroponic lettuce production. NFT gullies 59 ft (18 m) long with a depth of 11.8 in. (30 cm) and a nutrient solution flow rate of 0.13 gallons (0.5 L) per minute are the system used by a grower in Perth, Australia (Fox, 1997).

Spacing of plants within the trough must be sufficient to avoid overlapping of leaves prior to harvest. Spacing between troughs may be fixed, sufficient to avoid leaf overlapping prior to harvest, or troughs can be set on an adjustable track so they can be moved apart as the plants increase in size. Trough spacing movement occurs every 4 to 8 days.

Recommended formulations for the nutrient solution, their use and reconstitution, if recirculated, can vary considerably. Since the roots are not in a rooting medium in the NFT trough, the frequency of nutrient solution flow must be sufficient to keep the roots moist and the plants adequately supplied with water. Morgan (2000b) gives considerable details on the growing of many types of salad greens and herbs using the NFT method. Included are details on greenhouse environmental conditions — optimum air temperature range [46 to 75°F (8 to 24°C)], relative humidity control, and shading during high temperature periods, water quality, and nutrient solution management, including the range in nutrient element concentration used by growers (Table 11.34). Smith (2002b) found a grower who raised the temperature of the nutrient solution 4 to 5 degrees above the ambient air temperature when climatic conditions are cool in order to improve plant growth.

A vertical NFT system developed by Cornell University is described by DeKorne (1992–93) (Figures 11.32-1 and 11.32-2). The growing medium is either gravel or perlite, although other substrates can be used, such as vermiculite or a mixture of perlite with an organic substrate. The nutrient solution is introduced at the top of the column, with the flow rate sufficient

Table 11.34 Concentration Range of Elements in Nutrient Solutions Used by Different Growers for Growing Lettuce and Other Greens

Element	*Concentration, mg/L, ppm*
Major Elements	
Nitrogen (N)	100 to 200
Phosphorus (P)	15 to 90
Potassium (K)	80 to 350
Calcium (Ca)	122 to 220
Magnesium (Mg)	26 to 96
Micronutrients	
Boron (B)	0.14 to 1.5
Copper (Cu)	0.07 to 0.1
Iron (Fe)	4 to 10
Manganese (Mn)	0.5 to 1.0
Molybdenum (Mo)	0.05 to 0.06
Zinc (Zn)	0.5 to 2.5

Source: Morgan, L., 2000b, *The Growing Edge* 11(5):12–27.

to keep all the plants from top to bottom supplied with water and the essential elements. A catch basin is usually placed under the base to the column to catch the outflow. Although not commonly done, the outflow can be collected and added back to the nutrient solution reservoir. Periodic observation of the catch basin as to accumulation amount can be used as a means for determining the sufficiency of flow of nutrient solution through the column. Depending on placement and surrounding columns, it may be necessary to continuously and/or periodically rotate the columns so that all the plants, irrespective of position (what side or top and bottom), will receive sufficient solar radiation required for good growth.

Another vertical system employs an array of buckets set at 90 degrees from each other to form a column, with the exposed corners of each bucket being the plant container (Figure 11.33), a growing system commercially available from Verti-Gro, Inc.[1] The buckets can be filled with perlite (preferred) or other rooting medium (see Figures 11.3-1 and 11.3-2). The nutrient solution is applied at the top of the array, and a catch basin placed below the column will collect the effluent, which may or may not be recirculated. A description of the Verti-Gro system is given by Docauer (2004).

Styrofoam sheets floated on an aerated nutrient solution are another method for growing lettuce, called the "raft system" as plants, rooted in rockwool cubes or cups of medium, are set in openings on the sheet (see Figure 11.4), a method described by Spillane (2001) and Morgan (2002f). A hydroponic nutrient solution formula for the lettuce/raft system is in Table 11.35. A video entitled "Building a Hydroponic Floating Garden" can be obtained from the University of Florida (IFAS), Live Oak, FL 2000 ($15 VHS).

[1] Verti-Gro, Inc., 15000 SE U.S. Highway 441, SummerField, FL 34991 (www.vertigro.com).

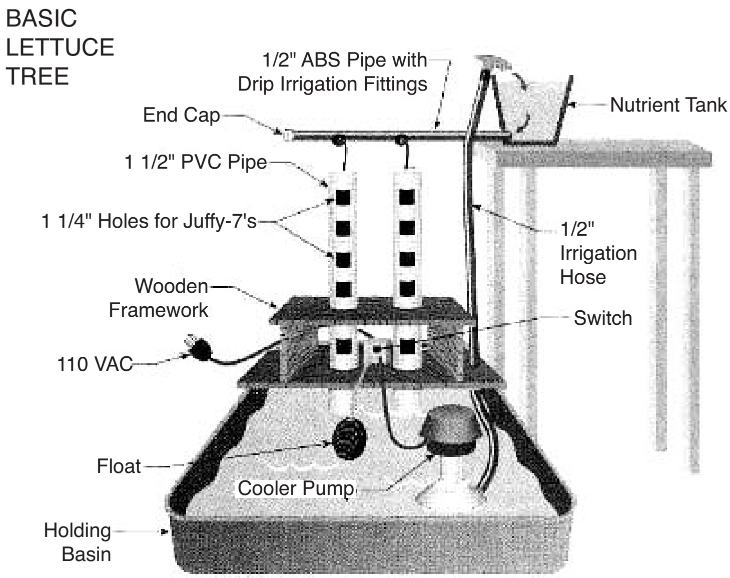

Figure 11.32–1 Design of the vertical NFT system developed by Cornell University for growing lettuce. ***Source*****: DeKorne, J.B., 1992–93. An orchard of lettuce trees: vertical NET system,** ***The Growing Edge*** **4(2):52–55.**

Figure 11.32–2 Photograph on the left shows initial seedling placement, and photograph on the right shows mature lettuce plants ready for harvest. ***Source*****: DeKorne, J.B., 1992–93. An orchard of lettuce trees: vertical NET system,** ***The Growing Edge*** **4(2):52–55.**

In the raft system, the depth of nutrient solution can range between 3 and 10 in. (7.6 and 25 cm), although some recent research found that nutrient solution depths greater than 3 in. (7.6 cm) did not improve growth or yield. However, a 5-in. (12.7-cm) depth of nutrient solution tends to result in more consistent growth. Morgan (2002d) lists the advantages of the raft system as: does not require electrical power, provides maximum use of the growing area, moderates the temperature conditions due to the larger volume of nutrient

Figure 11.33 Series of vertical styrofoam bucket arrays with lettuce in various stages of maturity.

solution as well as its buffering capacity, ease of examining root development, and sterilizing the growing system between crops. The disadvantages are lack of ease for reaching and servicing the crop, the pond must be level and leak proof, a substantial volume of water is initially needed, and the introduction of a root disease, such as *Pythium*, can quickly destroy a crop and require that the water and the entire growing system be sterilized. Morgan (2002f) found that oxygenation of the nutrient solution increased yield and reduced the incidence of tipburn. The temperature of the nutrient solution, its depth (volume), and the degree of agitation (aeration) will determine the O_2 level in solution. Lettuce growth is significantly reduced if the dissolved O_2 level in the nutrient solution drops below 3 ppm.

Source water quality requirements for lettuce as well as all greens are greater than for most other crops. For example, if the water contains more than 35 ppm Na, which would also include the element Cl, such source water quality can have a significant detrimental effect on lettuce growth and quality (Alexander, 2001a).

Table 11.35 Hydroponic Nutrient Solution Formula for Lettuce in a Raft System

Reagent	*Grams/26 gallons*
Part A	
Calcium nitrate	6254
Potassium nitrate	729
Iron chelate	500
Part B	
Potassium nitrate	729
Monopotassium phosphate	992
Magnesium sulfate	2127
Manganese sulfate	80
Zinc sulfate	11
Boric acid	39
Copper sulfate	3
Ammonium molybdate	1

To use: 1:100 dilution

The 1:100 dilution rate will give the following elemental levels (ppm): N = 116, P = 21, K= 82, Ca = 125, Mg = 21, S = 28, Fe = 6.8, Mn = 1.97, Zn = 0.25, B = 0.70, Cu = 0.07, Mo = 0.05; EC = 1.0 mS/cm and TDS = 700

Source: Morgan, L., 2002f, *The Growing Edge* 14(2):46–60.

Both top and root growth is not affected when the nutrient solution pH ranges between 5.0 to 6.0. Lettuce is not sensitive to Mg but has a high requirement for the micronutrients Mn, Mo, and Cu and a medium requirement for B and Zn. Color pictures of visual symptoms of nutrient disorders in lettuce can be found in the books by Roorda van Eysinga and Smilde (1981) and Scaife and Turner (1984). Visual symptoms of Mo deficiency are shown in the book by Bould et al. (1984).

It is also possible to grow lettuce in a rooting medium, although this method of growing is not in common use. The author has successfully grown lettuce using the subirrigation GroSystems trough (see Figure 11.10). Those looking for simple hydroponic techniques for growing lettuce will find useful descriptive instructions given by Bradley (2003).

The intensity of the red color in red-leaf lettuce will increase at lower air temperatures. It should be remembered that plant growth ceases when air temperatures are less than about 52–54°F (10–12°C).

Morgan (2000b) gives instructions for growing a wide variety of salad greens in the crop families of Asteraceae, Brassicaceae, Chenopodiaceae, and Amamthus, as well as edible flowers and herbs.

Manique (1993) found that much of the growth variation in lettuce is related to the daytime temperature (81%) and solar radiation (65%), expressed in the equation: yield = 7.03 (log daytime temperature × log solar radiation). Lettuce is photosynthetically saturated at 11 Mj/m²/day while growth is inhibited if the radiation intensity exceeds 19 Mj/m²/day (Manique, 1993). Manique (1993) found that head yield and marketable yield are responsive to CO_2 level at low irradiance levels.

The diseases that commonly affect lettuce are astor yellows, big vein, bottom rot, downy mildew, drop, and mosaic (Maynard and Hochmuth, 1997). The common insect pests are leafhopper, leaf miner, and looper. Professional assistance should be obtained for identifying the type of disease or insect affecting lettuce; growers should then follow those pest management procedures acceptable for this crop (see Chapter 14).

Herbs

There are some who jokingly refer to herbs as "weeds" since they are relatively easy to grow and will grow rapidly under optimum conditions. Herbs that have been grown hydroponically are:

Basil (*Ocimum busilicum*)
Oregano (*Origanum vulgare*)
Sweet marjoram (*Marjorana hortensis*)
Chive (*Allium schoenoprasom*)
Thyme (*Thymus vulgaris*)
Sage (*Solvia officinalis*)
Watercress (*Nasturtium officinalis* R. Br.).
French sorrel (*Rumex scutatus*)
Rosemary (*Rosemary officinals*)
Dill (*Anethum gruveolens*)
Parsley (*Petroselinum crispum*)
French tarragon (*Artemesia dracunculus*)
Mint (*Mentha*)

Parker (1991) identifies 11 herbs that can be grown hydroponically, describing the cultural procedures for each herb as listed on the following page.

Spillane (1992) lists a wide range of medicinal plants, giving their characteristics and use, plants that can be easily grown hydroponically. Herb mint characteristics, its commercial, culinary, and medicinal uses as well as cultural requirements are described by Waterman (1994). Creaser (1997), using sloping trays containing coarse perlite, found that basil, mint, oregano, and marjoram grow rapidly in southern climates, slower in northern regions, and that basil had a 40% increase in flavor over that which was field-grown. Sage, its uses, hydroponic cultivation, and cultivars, was investigated by Knutson (1997a). The cultivation procedures for thyme and its uses have been described by Knutson (1997c); this herb is easy to grow and has a wide range of uses. Those interested in Chinese medicinal herbs and their uses will find the article by Waterman (1999) of interest, although no instructions are given for their

Herb	Characteristics
Basil (*Ocimum baslicum*)	Member of the mint family, annual, requires considerable light, will grow to 12 to 18 in. (30 to 46 cm)
Chives (*Allium schoenoprasum*)	Member of onion family, easiest of all herbs to grow, grown from seed, slender, grass-like, can be planted densely hydroponically
Dill (*Anethum graveolens*)	Annual herb, can grow to 3 ft (1 m) in height, should be started from seed, easy to germinate, requires pruning
Marjoram (*Origanum marjorana*)	Annual plant, can be grown as perennial indoors
Mint (*Mentha cordifolia, M. piperita*)	Most vigorous of all perennial herbs, grows very well hydroponically, propagate by runners, tolerant to low light levels, pinch off flowers when appearing
Oregano (*Origanum vulgare*)	Can be started from seed but best results from dividing mature plants, grows best in well-drained medium
Parsley (*Petroselinum crispum*)	Thrives best in cool, damp conditions, needs plenty of water, seeds are very slow germinating
Rosemary (*Rosemarinus officinallis*)	Can grow to a height of 5 ft (1.5 m), requires considerable space, propagate from stem cuttings, seed germination is very slow and young plants lack vigor, sensitive to overwatering, use well-drained medium, sensitive to overfertilization with N
Sage (*Salvia officinalis*)	Perennial herb, easy to maintain at a height of 12 to 16 in. (30 to 40 cm), seed germination is slow but seedlings are sturdy, very sensitive to overwatering and wet growing medium, requires high light
Tarragon (*Artemesia dracunculus*)	Perennial herb requiring adequate light and well-drained medium, requires regular pruning
Thyme (*Thymus vulgaris*)	Perennial herb, has high light and low water requirements, sensitive to high-acid growing conditions, usually propagated from cuttings

propagation and production. A similar review on medicinal herbs can be found in the article by Vyn (2000). The book by Duke (2002) “describes most herbs concisely and in an equally concise manner, evaluates the scientific research on their use.”

Morgan (2001f) gives considerable details on the characteristics and cultural requirements for cilantro (*Coriandrum sativum*) and sweet basil (*Ocimum basilicum* L.) which are easy to grow hydroponically using the NFT method. In a later article, she (Morgan, 2004a) describes the commercial production of 10 seed-grown herbs [basil (Nufar), chives, cilantro, dill, lemon balm, sweet marjoram, oregano, parsley (Italian), sage, and thyme and seven perennial cutting-grown crops (lemon, mint, oregano, rosemary, sage, tarragon, and thyme). The two primary hydroponic growing systems are NFT and media-based, although the raft system, aeroponics, flood-and-drain, and bag, pot,

Table 11.36 Elemental Concentration of a Nutrient Solution for Watercress

Elements	*mg/L, ppm*
Major	
Nitrogen (N)	161
Phosphorus (P)	63
Potassium (K)	248
Magnesium (Mg)	34
Sulfur (S)	72
Micronutrients	
Iron (Fe)	6.90
Manganese (Mn)	1.97
Boron (B)	0.70
Zinc (Zn)	0.25
Copper (Cu)	0.07
Molybdenum (Mo)	0.07

Source: Smith, B., 2003a, *The Growing Edge* 14(3):81–87.

and capillary-based systems are alternatives for some applications. Morgan (2004a) provides details on how each growing system is designed and used. Morgan (2004b) continues her discussion on the hydroponic production of exotic and familiar herbs (thyme, oregano, marjoram, arugula, dill, sorrel, recao, epazote. lemongrass, kaffir, bay, and hot chilies).

Smith (2003a) visited with a New Zealand grower who is growing watercress (*Nasturtium officinale*) outdoors in sloping ground troughs continuously supplied with nutrient solution that flows beneath the root mass. The composition of nutrient solution for watercress is given in Table 11.36 and for temperate climates in Table 11.37. Those looking for simple hydroponic techniques for growing basil and watercress will find useful the descriptive instructions given by Bradley (2003).

As with lettuce, herbs are relatively easy to grow hydroponically, requiring less skill on the part of the grower than for most other crops, and are widely grown commercially in greenhouses and outdoors (Morgan, 2000b). The NFT method is commonly selected for herbs. Descriptive information on the NFT method was given at the NFT Lettuce & Herb Grower Conference and Workshop (Alexander, 2001a). The requirement for high-quality water and the maintenance of the nutrient solution were major topics discussed. Examples were given for growing and marketing herbs commercially.

Morgan (2000b) provides details on the requirements to produce high quality herbs in the greenhouse and using the NFT hydroponic growing method. Basil has been grown hydroponically under high-tensity discharge (HID) lighting (Christian, 1990a), with plant performance increasing when the grower switched from ebb-and-flow to NFT (Christian, 1990b). Christian (2002) provides details on a NFT basil greenhouse operation located in Pennsylvania

Table 11.37 Typical Hydroponic Nutrient Formula for Watercress (Temperature Climate)

Reagents	*Concentration (g/100 L)*
Part A	
Calcium nitrate, $Ca(NO_3)_2 \cdot 4H_2O$	6704
Potassium nitrate, KNO_3	2210
Iron chelate (EDTA)	500
Part B	
Potassium nitrate, KNO_3	3210
Monopotassium phosphate, KH_2PO_4	3007
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	5523
Manganese sulfate, $MnSO_4$	80
Boric acid, H_3BO_3/Solubor	39
Zinc sulfate, $ZnSO_4 \cdot 7H_2O$	11
Copper sulfate, $CuSO_4 \cdot 5H_2O$	3
Ammonium molybdate	1

To use: Dilution rate: 1:100

Source: Smith, B., 2003, *The Growing Edge* 14(3):81–87.

that has been producing 18,000 to 20,000 bunches of basil a week. The Nutri-Gardens, whose greenhouse operation in the desert is described by Peckenpaugh (2002h), grows basil as well as other herbs in 20-ft (6-m) long NFT gullies suited for high-temperature growing. The greenhouse temperature is maintained at 75°F (24°C) with the use of cooling fans and shading. During the winter months, the nutrient solution is heated to 72°F (22°C).

In most instances, seeds are planted in germination cubes (rockwool is preferred) and upon germination, the cubes containing the emerging seedlings are set in the medium in the NFT trough. The design of the NFT growing system, trough width (2 to 4 in.), depth (1.5 to 3.5 in.), and length (10 to 30 ft) are normally within these parameters. Troughs are set on a slope of l to 2%. Since the roots are not in a rooting medium in the NFT trough, the frequency of nutrient solution flow must be sufficient to keep the roots moist and the plants adequately supplied with water. The design of troughs is discussed by Morgan (1999c) and Smith (2004).

The spacing of plants within the trough must be sufficient to avoid overlapping of leaves prior to harvest. Spacing between troughs may be fixed, sufficient to avoid leaf overlapping prior to harvest, or the troughs set on an adjustable track so they can be moved apart as the plants increase in size.

The vertical NFT system developed by Cornell University as described by DeKorne (1992–93) for lettuce, as well as the Verti-Gro system (see pages 247–249), can equally used for herbs.

Those interested in a windowsill herb garden will find Goulant's (1994) article of interest; it describes propagation procedures, how to move from outside to indoors, and pest prevention. The top ten herbs for the windowsill are rosemary (*Rosemarinus*), sage (*Saliva officibalis*), tarragon (*Artemisia dracunculus*), basil (*Ocimum basilicum*), bay (*Laurus nobilis*), chervil (*Anthriscus cerefolium*), chives (*Allium schoenoprasum*), oregano (*Origanun*), parsley (*Petroselinum crispum*), and thyme (*Thymus vulgaris*).

The formulation of the nutrient solution, its use, and its reconstitution if recirculated can vary considerably. It is also possible to grow herbs in a rooting medium, although this method of growing is not in common use. The author has successfully grown herbs using the subirrigation GroSystems trough (see Figure 11.10).

Microgreens

A relatively new innovation in salad green production is "microgreens," the growing and harvesting of seedlings of various types of plants (lettuce, spinach, watercress, celery, radish, mustard, herbs, etc.) to make a green salad mix. Currently, microgreen seedlings are being produced on a soil mix, harvesting in 6 to 8 days from seedling. Hydroponic cultivation using a nutrient solution wetted fiber mat has a number of distinct advantages, including better control of the nutrient element supply and the harvest of soil-free product. Since this is a specialty item, the growing of microgreens is not the challenge, but its marketing may be.

Strawberry (*Fragaria x ananassa*)

The strawberry (originally named "strew-berry," which refers to the way the runners and berries are strewn across the ground) is a small perennial plant, which can be grown as either an annual or longer-term crop. Strawberry is widely grown over many climatic zones, although 98% is grown in the northern hemisphere. The United States accounts for over 20% of the world production, which is currently greater than 2.5 million metric tons. California accounts for nearly 80% and Florida 10% of the total production in the United States. Per capita consumption in the United States of both fresh and frozen strawberries is 5.2 lb (2.35 kg). Most strawberries are soil grown in various configurations, under plasticulture (Pitts et al., 1998) or straw mulch. Relatively few are grown hydroponically in greenhouses unless to satisfy a local market for off-season locally grown fruit. Morgan (2003b) states that "successful growers will understand the need to select the correct cultivar, the type of planting material, hydroponic media and system, and other important aspects of cultivation." The strawberry plant is relatively easy to grow and can adapt to most hydroponic growing systems (Donnan, 1997; Morgan, 1997b; Morgan, 2003b).

It should be remembered that hydroponic growing does not invalidate the cultural requirements of the strawberry in terms of chilling requirement, plant nutrition, pollination, and disease and insect pest control (Hancock, 1999; Childers, 2003). Morgan (1997b) lists six steps for producing your own hydro-

Table 11.38 Steps for Producing Your Own Hydroponic Strawberries

1. Obtain your plants in spring (they should have already initiated flower buds) for immediate planting and a summer fruiting crop. For out-of-season production (using day-neutral cultivars), obtain plants in late spring and chill for 3 to 4 months in the refrigerator, then plant in a heated greenhouse in autumn for a winter crop. Make sure the plants obtained are from a reputable source so that they are not infected with viruses. You can cut your own runners from the best plants.
2. Trim back any old dead leaves and roots and dip in a fungicide before planting or cool storage to ensure that any pathogens are killed.
3. Plant your strawberry crown three-quarters above the free-draining media in your bed or pot. Clean, sterilized, or fresh medium has the advantage of not harboring any disease pathogens from previous crops.
4. Make sure the plants receive full sunlight. Good air flow around and under the leaves will help reduce humidity. Temperatures between 64 and 77°F (18 and 25°C) produce the best results, so beware of excessive heating in the greenhouse situation [above 86°F (30°C)].
5. Leaf growth should occur rapidly once planted, followed by the first flower truss after four weeks. Flowers open after four weeks. Once flowers open, allow bees and other flying insects into the greenhouse to assist with cross-pollination.
6. Once fruitlets begin to form, you can isolate these from sitting on the damp me with a white plastic mulch (white reflects the light back onto the plants' leaves for photosynthesis and helps maintain temperature). Ripening fruit sitting on damp media may rot if disease pathogens are present.

Source: Morgan, L., 1997b, *The Growing Edge* 9(1):18–23.

ponic strawberries (Table 11.38). In her later article, Morgan (2003b) gives instructions to the hydroponic grower on "out-of season plant preparation and establishment" procedures. There is no recommended cultivar for growing strawberries hydroponically, as cultivar selection would be based on its adaptation to the climatic environment (Morgan, 1997b, 2003b).

Several hydroponic systems have been used for strawberry; the NFT is one. The requirements for the successful use of this technique have been given by Donnan (1997). The channel width must be at least 6 in. (150 mm) and the length and slope of the channel sufficient to ensure a consistent flow of nutrient solution, which is not significantly altered by the time it reaches the end of the channel. Donnan (1997) also describes other hydroponic growing procedures, including vertical pipes (Figure 11.34), flood-and-drain in gravel in pipes, rockwool pieces in pipes, and hanging vertical bags [strawberry trees, Morgan (1997b)].

Strawberry plants can also be planted in the Verti-Gro (see page 247) hydroponic system. In a vertical bag system in Australia, a strawberry fruit yield of 3.45 kg/m^2 was obtained, which is about 11% higher than that obtained with traditional ground growing. An average fruit yield of 6 oz (170 g) per plant would be considered an unacceptable commercial fruit yield. In her research, Morgan (2003b) found that hydroponic medium systems were generally more productive than the NFT growing method, the main criterion being that the rooting medium remain constantly aerobic. No matter what hydroponic

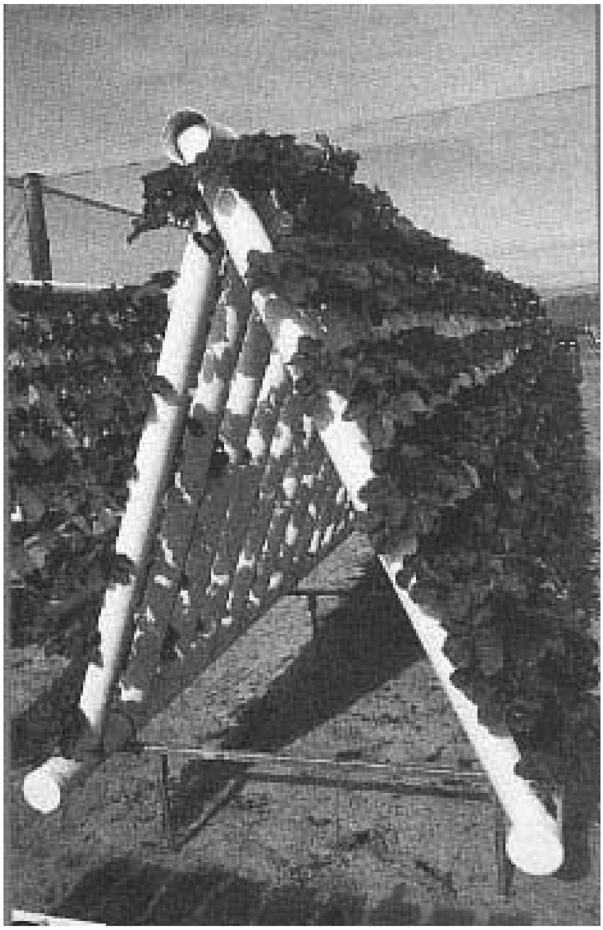

Figure 11.34 Strawberries growing in vertical pipes. ***Source*****: Donnan, R., 1997. Hydroponic Strawberries,** ***Practical Hydroponics & Greenhouse Issue*** **34:54–64.**

system is used, it is important that the crown of the strawberry plant be not kept wet, which would lead to crown rot. In addition, if the growing environment is kept wet (poorly drained conditions), fungus diseases are likely to occur; the primary one is *Phytopphthora fragariae* (red core).

Donnan (1997) also warns against high root temperature greater than 86°F (30°C) that can occur in some hydroponic growing systems as well as due to close plant spacing; both factors can lead to poor fruit production.

The strawberry plant should be planted in full sunlight for best growth and fruit production with good airflow around and under the leaves. The strawberry plant becomes light saturated at around 800 to 1200 mmol/m²/sec photosynthetic photon flux at ambient CO_2 levels (325 to 350 ppm) and at an air temperature of 77°F (25°C). Below 700 mmol/cm²/sec, the photosynthetic rate begins to decrease rapidly (Morgan, 2003b). The optimum air temperature for best growth is between 64 and 77°F (18 and 25°C), while air temperatures above 86°F (30°C) in both the root zone and aerial environment tend to severely reduce plant growth and fruit production. The strawberry plant is sensitive to day length, both long and short days, and varieties are available that are day-neutral, frequently referred to as "ever-bearing." Short-day varieties do best in mild winter areas, where the air temperature averages 55°F (13°C) and in warm summer areas averaging 82°F (28°C), while the day-neutral varieties do best in long cold winters and mild summer temperatures of 75°F (24°C). The strawberry plant needs to pass through a chilling period for normal flowering and fruit production to occur.

Strawberry flowers are mostly self-pollinated, although insects (mainly bees) assist in the transfer of pollen. In the greenhouse, bumblebees must be introduced to ensure adequate pollination; one hive (50 bumblebees) can pollinate 4000 strawberry plants (Morgan, 2003b). In the field as well as the greenhouse, wind movement of the flower itself can assist in pollination. Insufficient and uneven pollination will result in misshapen and undersized fruit. Once pollinated, the white stage is usually reached in 21 days and the red stage by 30 to 40 days. Fruit ripening occurs in a 5- to 10-day period, when the fruit turns from white to red.

Morgan (1997b) suggests that for optimum growth and fruit production, the major element content of the nutrient solution and EC adjustment with season should conform to those given in Table 11.39. In a more recent article, Morgan (2003b), the composition of the nutrient solution recommended for fruiting plants is as given in (Table 11.40).

In addition, Morgan (2003b) suggests that a portion of the N in the nutrient solution be in the NH_4 form, particularly under low light conditions. High levels of available K are required for large berry size, high flavor and yield, and sustained keeping quality. A K to N ratio of l to 4 or above in the nutrient solution is recommended by Morgan (1997b).

Visual symptoms of nutrient element insufficiencies for both the plant and fruit are shown in the atlas published by Ulrich et al. (1980).

Common strawberry plant diseases that occur in wet humid conditions are *Phytophthora fragariae,* gray mold or *Botrytis cinerea* — diseases that can be controlled by providing a warm, dry environment and/or with the use of selective fungicides. The common diseases that affect the strawberry plant are given in the compendium by Maas (1998).

The North American Strawberry Growers Association (Thompson, 2002) recently reported that there are 35 breeding programs worldwide and that at least 150 cultivars have been released during the past 5 years. Of the 150 available, only six cultivars dominate the world market — "Camarosa," "Diamante," "Selva," "Chandler," "Elsanta," and "Senga Sengana." The largest strawberry breeding program is being conducted at the University of California. Some of the specific culitvar niches are given in Table 11.41.

The author has successfully grown strawberries in both the GroBox (see Figures 11.9-1 and 11.9-2) and GroTrough (see Figures 11.10-1 and 11.10-2) in the garden, selecting day-neutral plants for planting in the spring. I have

Table 11.39 Elemental Content of Nutrient Solution Recommended for Optimum Growth and Fruit Production of Strawberry[a]

Element	*Content, ppm (mg/L)*
Nitrogen (N)	207
Phosphorus (P)	55
Potassium (K)	289
Calcium (Ca)	155
Magnesium (Mg)	38
Sulfur (S)	51

[a] And standard levels of trace elements.

Source: Morgan, L., 1997b, *The Growing Edge* 9(1):18–23.

Table 11.40 Recommended Nutrient Solution Elemental Content for Fruiting Strawberry Plants

	Content (ppm; mg/L)
Major Elements	
Nitrogen (N)	128
Phosphorus (P)	58
Potassium (K)	211
Calcium (Ca)	104
Magnesium (Mg)	40
Sulfur (S)	54
Micronutrients	
Iron (Fe)	5
Manganese (Mn)	2
Zinc (Zn)	0.25
Boron (B)	0.70
Copper (Cu)	0.07
Molybdenum (Mo)	0.05

Source: Morgan, L., 2003b, *The Growing Edge* 14(4):46–60.

also had good results by replanting runners in the late fall into either grow system. Morgan's (2003b) "out-of-season" plant preparation and establishment recommendations are another way of using runners as production plants. Plants will overwinter in both growing systems here in South Carolina, although I am uncertain if these runner plants will survive a hard winter freeze. I have had some success in growing plants in the greenhouse using these same growing systems, although fruit set is not very high since the plants have not been properly treated as is specified in Table 11.38. In addition, without insect pollination (the use of bumblebees, for example), low fruit set and misshapen fruit are common occurrences.

Table 11.41 Strawberry Cultivar Niches by Location and Use

Cultivar	Location and Use
Totem, Hood	NW North America for processing
Florence, Everest	Regional U.K. sales
Cigoulette et al.	French markets
Sweet Charlie, Strawberry Festival	Early, fresh east coast North American markets
Allstar, Honeoye, Jewel, Earliglow	Pick-your-own and roadside markets east North America
Chandler	Annual production in southeastern North America
Tethis, Pajaro	Southern Italy
Tudla	Sicily
Seascape	Germany

Source: Thompson, G., 2002, *North American Strawberry Growers Association Newsletter* 27(4):1–2. State College, PA.

Green Bean (Snap Bean) (*Phaseolus vulgaris* L.)

This crop (green bean and snap bean are the commonly used names) is not a suitable crop for commercial production in the greenhouse, although it can be greenhouse grown. The author has grown this crop outdoors as a garden crop in GroSystem troughs containing a growing medium of either pure perlite or a 50-50 mixture of perlite and composted milled pinebark (Figure 11.35). Green bean is very easy to grow hydroponically, and pod production can be high as the plants will continue to produce as the edible pods are harvested when fully elongated.

There are over 300 varieties of green beans to choose from; the selection is based on pod color, adaptation to climatic conditions, and plant type (bush

Figure 11.35 Green bean plants growing in a GroSystem GroTrough.

versus pole). Bush-type green beans are recommended for hydroponic growing unless a trellis system is mounted over the hydroponic growing vessel. Some of the more common green bean varieties and their characteristics are given in Table 11.42. Seed sources for bush and pole bean varieties are given in Table 11.43.

By not coming in contact with soil, the lower leaves of the plant will remain green and actively photosynthesizing, contributing to sustained pod set and growth. The same cultural procedures applicable for soil growing are equally applicable hydroponically.

Seeds are directly placed into the growing medium and watered with nutrient solution from above until the plant cotyledons break the surface. Seeds will germinate in 16 days at 59°F (15°C) and in 8 days at 77°F (25°C). Plant spacing in the row is between 2 in. (5 cm) and 4 in. (10 cm). The nutrient solution formula suitable for this crop is similar to that for other crops; therefore, no special formulation is needed. For the micronutrients, the green bean plant has high requirements for Fe, Mn, and Zn; moderate for Mo; and a low requirement for B and Cu (Maynard and Hochmuth, 1997). Visual symptoms of S, B, and Mn deficiency are shown in the book by Bould et al. (1984).

Table 11.42 Green Bean Varieties and Their Characteristics

Variety	*Characteristics*
Blue Lake	High yielding with round pods
Garden of Eden	Heirloom with broad, flat, sweet-flavored green pods, brown seeds, with dark brown strips
Kentucky Wonder	Old standard heirloom since 1850s
Marvel of Venice	Heirloom yellow Romano bean with white (rather than black) seeds
Purple Peacock	Dark purple pods and stems, light purple flowers, and dark leaves, handles cool conditions well
Rattlesnake Snap	Dark green pods that are streaked with purple, resistant to drought
Romano	Delicate-flavored Italian heirloom with flat wide pods and meaty beans

Table 11.43 Bush and Pole Bean Seed Sources

Bountiful Gardens, Willis, CA; tel: 707-459-6410; www.bountifulgardens.org
Henry Field’s Seed & Nursery Co., Aurora, IN; tel: 513-354-1494; www.henryflelds.com
Johnny’s Selected Seeds, Winslow, ME; tel: 207-861-3901; www.johnnyseeds.com
Seed Savers Exchange, Decorah, IA; tel: 563-382-5990; www.seedsavers.org
West Coast Seeds Ltd., Delta, BC, Canada; tel: 604-952-8820

Sweet Corn (*Zea mays* L. subsp. *mays*)

Sweet corn is being successfully grown hydroponically outdoors by the author in GroTroughs containing a growing medium of either pure perlite or a 50/50 mixture of perlite and composted milled pinebark (Figure 11.36). The same cultural procedures as those applicable for soil growing are equally applicable hydroponically. In small plantings, two requirements for success involve the number of plants and their spacing, which will determine the effectiveness of pollination for the emerging ears. Incomplete pollination will result in poor ear development due to missing kernels. No fewer than 20 plants should be grown, planting in double rows rather than in one continuous row. If subjected to high winds, the plants will require bracing since the root mass is not sufficient to hold the plants upright under such conditions.

The number of days before harvestable ears are present will depend on the maturity of the variety selected: 64 days for early varieties to 96 days for late varieties. Seed is directly placed into the growing medium and watered with nutrient solution from above until the plants begin to emerge. The author has found that corn seeds need to be placed 3 in. (7.6 cm) below the surface of the rooting medium to ensure that the emerging plant is well anchored. Plant spacing within the row is from 8 to 12 in. (20 to 30 cm), and space between the rows of 12 to 18 in. (30 to 46 cm). Seed will germinate in 22 days at 55°F (13°C) and 4 days at 77°F (25°C).

The corn plant is very sensitive to changing moisture and aeration conditions within the rooting medium; therefore, it is essential that for whatever hydroponic growing method is employed, the rooting medium be constantly supplied with nutrient solution (or water) and maintained in a high aerobic status.

Figure 11.36 Sweet corn growing in a GroSystem GroTrough.

Some evidence of N deficiency (firing of the lower leaves) has been evident in some years suggesting that the N level in the nutrient solution should be increased about 20 to 25% over that recommended for other crops. For the micronutrients, the relative response to Mn and Zn is high; moderate to B, Cu, and Fe; and low for Mo (Maynard and Hochmuth, 1997). Color plates of visual deficiency symptoms for the macro- and micronutrients may be found in the book by Scaife and Turner (1984). A video (Nutrient Deficiencies in Corn) showing the visual nutrient element deficiencies is available (GroSystems, Inc., 109 Concord Road, Anderson, SC 29621).

Okra [*Abelmoschus esculentus* (L.) Moench]

Okra has been successfully grown hydroponically outdoors by the author in GroTroughs (see Figure 11.10) containing a growing medium of either pure perlite or a 50-50 mixture of perlite and composted milled pinebark. The same cultural procedures as those applicable for soil growing are equally so hydroponically. Seeds are planted directly into the rooting medium, which is kept moist by periodic applications of nutrient solution on the surface until the plants emerge. The optimum row spacing is between 8 and 12 in. (20 and 30 cm) within the row. The speed of seed germination is dependent on temperature: 6 days at 95˚F (35˚C) to 13 days at 70˚F (21˚C). Okra does best in warm climates; the optimum range for good growth is between 70˚F (21˚C) and 90˚F (32˚C), with immature fruit ready for harvest in 50 (early varieties) to 60 (late varieties) days.

The plant grows extremely well, probably partially due to the fact that water and nutrient elements are being continuously supplied by this growing technique. The proper management of the crop can keep the plants in a continuously fruiting condition. The edible plant part is the immature fruit. After the plants reach a height of about 5 feet, remove the growing point, and new fruit will appear at the lower nodes. The same nutrient solution formulation used for other crops is adequate for okra, a crop with moderate nutrient element requirements.

Melons

Both watermelon [*Citrullus lanatus* (Thunb.) Matsum and Nakai] and cantaloupe (*Cucumis melo* L. Cantaloupensis group) grow very well hydroponically outdoors using either the author's GroBox (see Figures 11.9-1 and 11.9-2) or GroTrough (see Figures 11.10-1 and 11.10-2) containing a growing medium of either pure perlite or a 50-50 mixture of perlite and composted milled pinebark. It is best to germinate seed in a germination cube, and when the roots begin to emerge from the cube, transplant the seedling into the hydroponic growing medium. The same cultural procedures as those applicable for soil growing are equally applicable hydroponically. A flat trellis is attached to the growing vessel so that the plants and setting fruit will be kept off the ground. The same nutrient solution formulation used for other crops is adequate for both melons, which have a moderate nutrient element requirement.

Other Types of Plants

Although vegetables and related crops are those primarily grown hydroponically, other crops are being grown either hydroponically or in soilless mixes. Earlier in this chapter, the author reported on a visit made to a grower who had successfully switched from tomatoes to chrysanthemum flower production using the tomato hydroponic growing system and nutrient solution management procedures (see pages 167–168). Others have either switched from hydroponic vegetable growing to other crops, such as flowers, banana, and various fruit crops, or they have gone from soil-growing their crop to hydroponics.

Nakazawa (1990) found a psychologist who is growing banana in a soilless medium (two parts of a mix of sawdust, sludge, and sewage and one part pumice) in a greenhouse. Banana has been successfully grown in a Gro Box medium combined with a top feed hydroponic system as described by Taggart and Randolph (1996). Wally and Barb Thomas (1996–97) wrote about a orchard grower who found perlite to be the perfect rooting medium due to its ease of petting, free draining characteristic, total fertilizer control, simplicity of management, and excellent aeration as compared to that of bark, peat, or rockwool. Water chestnuts were easily grown hydroponically in a watertight gravel-sand mix-filled bed 3.9 in. (10 cm) in depth using a tomato-based nutrient solution formulation (Morgan, 2003e). The primary requirements are to keep the growing medium at the proper pH and EC levels plus at a high O_2 content. Keeping the growing medium moderate in temperature [less than 77˚F (25˚C)] is also essential for high production.

Cut roses are being grown hydroponically as described by Horst (1997) and Johnson (1998a), who also state that at least 60% of all the cut roses grown in the United States are being grown hydroponically. The preferred growing medium is coconut hulls (best suited for maintaining the proper pH). The timing of water and/or nutrient solution application is controlled by a system that integrates solar integration, a set timer schedule, and evaporation or humidity level. Water quality, control of the nutrient elements, amount of O_2 available to the roots, and heating of the nutrient solution slightly higher than the greenhouse air temperature are considered important factors in the successful production of cut roses (Smith, 2002e). The production of cut roses in plastic bags of “very good grade pumice — a volcanic, open structured natural media” proved to be an inexpensive medium system, with water and a nutrient solution being supplied through a drip irrigation system (Smith, 2002e). Only water of high quality and sterilized is used to make the nutrient solution whose application is carefully controlled. Water use per plant is about 1 l a day. The temperature range within the greenhouse is carefully maintained at a minimum nighttime temperature of 64°F (18°C), and during the day the maximum is 70°F (20°C). "The benefit of being able to control the nutrition and water accurately" is the reason why the Thiessen Greenhouse Flowers, Ltd. switched to hydroponics for the production of roses (Spillane, 2003b). The growing medium is coconut fiber in raised beds, with the nutrient solution applied by means of a drip irrigation system. The nutrient solution is not recirculated. All of the basic greenhouse functions [heating, venting, airflow, humidity control (maintained between 60 to 70%), watering, lighting, etc. are computer controlled.

Another flower that is being grown hydroponically is Gerbera (Emamuel, 2003). Comparisons were made of three growth media: sawdust in bags, coconut coir in crates, and rockwool slabs. The best plant growth and quality were obtained when the rooting medium was rockwool, the poorest with the sawdust bags. A modified lettuce-formula nutrient solution is used, delivered to the plants by means of a drip irrigation system. Frequent checks of the medium pH are made to keep it at 5.7; the EC of the nutrient solution should be kept at 1.8 mS/cm. Daytime greenhouse temperature is 70°F (21°C), with the nighttime temperature at 60°F (15°C).

Carnations are being grown in pumice (volcanic material) using a drip irrigation system; the frequency of irrigation is determined by the amount of light (intensity and duration) entering the greenhouse (Smith, 2003b). The pumice is placed in 20 × 12 in. (51 × 30 cm) polyethylene trays. The pH of the nutrient solution is adjusted to maintain the medium at pH 5.8. For the production of high-quality stems, the greenhouse temperature is maintained between 54 and 64°F (12 and 18°C). During the summer, if the greenhouse temperature reaches 95°F (35°C), stem quality decreases significantly.

Morgan (2001c) has written about the hydroponic production of red raspberries in the greenhouse for out-of-season production. Cane selection, dormancy, environmental conditions, pruning and training, nutrition, flowering, pollination, fruit set, and fruit quality and yield are the topics discussed. The plants can be grown in either modified NFT gullies or in various media (sand, peat, perlite, and vermiculite) systems as long as the substrate does not easily become waterlogged (i.e., free-draining).

Babaco (also known as "highland papaya") and passionfruit are two tropical fruits that can be grown hydroponically in the greenhouse (Morgan, 2002b). Babaco will grow successfully in any of three different hydroponic systems, flood-and-drain, NFT, and medium (sawdust, peat, and perlite mixtures)-filled pots, although it grows best in 6.5 to 9 gal (25 to 35 L) pots filled with a sawdust, peat, perlite mixture. The nutrient requirements are about the same as for beefsteak tomato, although the N requirement is higher during early vegetative growth and the K requirement is high during fruiting. For good fruit production, minimum greenhouse temperature at night is 50°F (10°C), and a daytime temperature range of 53 to 64°F (12 to 18°C). Passionfruit is best grown in medium (sawdust, composted milled pinebark, sand, perlite, vermiculite, expanded clay, pumice)-filled 5 to 6 gal (20 to 25 L) pots. The plants have high nutrient element requirements for both N and K and grow best when the greenhouse temperature is kept between 60 and 82°F (16 and

28°C). Both plants have unique cultural requirements for successful fruit production in their propagation, pruning and training, nutrition, flowering and fruit set, and insect and disease control. Fruit from both plants have specific postharvest requirements.

The Scottish Highland Hydroponicum is filled with a wide range of plants, including tomatoes, soft figs, and banana as well as other fruits, vegetables, and flowers being grown within three climatic zones (Farquhar, 2003). All these plants are being grown in the specially designed Pyramid Pots (see Figure 4.1), in which the nutrient solution is supplied by a passive Wick System, both developed by Robert Irvine (Savage, 1995).

Although root crops do not grow well in hydroponic systems, Smith (2001) describes a hydroponic system for growing potatoes. In a large drum [22-gal (100-L)] half filled with expanded clay (Hydroton) as the substrate, several seed potatoes (red-skin potatoes recommended) are set on the substrate and just covered with Hydroton. The drum should have a large drainage hole in the base so that the added nutrient solution will easily flow out of the drum. As the plants emerge, the base of the new growth is covered with Hydroton, allowing several inches of new growth uncovered, and then continuing to add Hydroton as the plant grows. A drip irrigation system is put in place that continuously applies nutrient solution (Dr. Allen Cooper's two-part starter nutrient solution formula, see Table 9.3 in Chapter 9) during the daylight hours. After plant growth reaches the top of the drum, the top growth is allowed to continue to expand until it "starts to age." At this point, the crop is harvested by emptying the drum.

Summary for Hydroponically Grown Crops

Tomato (see pages 187–204)

a. Most widely grown crop hydroponically
b. Offers the highest financial return compared to all other crops
c. Has high input requirements in terms of cultural management and skilled labor

Most common hydroponic growing systems: On rockwool slabs or in buckets (bags were in the past in wide use) of perlite.

Potential yield: 35 to 45 lb (16 to 20 kg) of vine-ripe fruit per plant per season; ~330,000 lb/A; best fruit yields at weekly fruit yields between 2 and 2.5 lb (0.9 and 1.1 kg) per plant.

Optimum growing temperatures: 75 to 80°F (24 to 26°C) day; 70 to 75°F (21 to 24°C) night (will vary with light intensity).

Pollination: Hand pollination using a vibrator or with the use of bumblebees.

Nutritional requirements: N and P are frequently in excess in plants due to high concentrations of N and P in the nutrient solution, imbalances between K and Ca + Mg due to lack of balance among these three elements in the nutrient solution, and deficiency of Mg due to imbalance and low Mg in the nutrient solution and low Zn due to either high P, use of chelated Fe, and/or low Zn concentration in the nutrient solution.

Insects: Most insects can be effectively controlled using beneficial insects, or as a last resort, chemical control; whitefly is the most common insect pest.

Diseases: Controlled by good management practices and fungicides when required.

Common fruit physiological disorder: Blossom-end rot.

Fruit quality factors: Misshapen fruit and fruit cracking.

Cucumber (European) (see pages 232-240)

a. Specialty crop with limited consumer demand
b. Fruit is long with thin skin that requires special packaging (shrink wrap)
c. Plants are easy to grow; less labor required than for tomato
d. Growing systems the same as for tomato
e. Yield and growing requirements about the same as for tomato

Fruit quality: Major problem is crooking due mainly to stress.

Nutritional requirements: Mg is a common deficiency, occurring when fruit begins to set on the plant.

Insects: Most insects can be effectively controlled using beneficial insects when needed; major insect: whitefly.

Diseases: controlled by good management practices and fungicides when required; major disease: powdery mildew.

Pepper (Green Bell) (see pages 240-243)

a. Specialty crop with limited market appeal
b. Financial return low; may not be a profitable crop
c. Various varieties grown for unique market demands
d. Growing systems the same as for tomato
e. Relatively easy to grow with considerably less labor required than for tomato
f. Less subject to insect attack and diseases as compared to tomato

Yield: 2 1b (0.95 kg)/plant; 185,000 lb/A

Lettuce (see pages 245–252)

a. Relatively easy to grow with few problems, but requires factory-type production and harvesting system to maintain the flow of product while maximizing growing space.
b. A crop can be produced about every 28 to 35 days.
c. Need to have a system of seeding, transplanting, and growing to maintain continuous supply of product, therefore lighted facilities needed for seeding and early growth.
d. Range of plant types can be grown (head and leaf types, etc.), which also can be mixed with herbs.
e. Best grown in a NFT hydroponic system.
f. Vertical columns or pots can be used in order to reduce the growing space required.

Yield: About 25,000 to 30,000 heads per acre per month, can be more or less depending on the design of the growing system and variety grown.
Nutritional r equir ements: No special requirements, grows well under low nutrient element levels
Common disor ders: Tipburn and bolting at high temperatures.

Strawberry (see pages 256–261)

a. Plants grow very well hydroponically, but new crop for possible winter (January-February) greenhouse production; yield and fruit quality factors have yet to be thoroughly investigated as well as selection of varieties that will produce well in the greenhouse.
b. Insect and disease problems can frequently occur, making greenhouse production difficult.
c. Unique vertical growing systems can be used for this crop, thereby increasing space utilization in the greenhouse or under a shelter.
d. Requires transplants for fall planting (requires a cold period) with spring fruit production or cold-storage plants for winter fruit production.
e. Flowers need to be pollinated by high air movement or by the use of bumblebees.
f. Outdoor hydroponic growing system could make production possible in an urban setting.

Gar den vegetables

a. Many garden vegetables, except the root crops, can be grown in most hydroponic systems, although many of these crops are seldom grown hydroponically.
b. Perlite bag/bucket and rockwool slab growing systems are not well adapted to general vegetable production and not suitable for outdoor growing.

Commonly Used Growing Systems

Perlite Bag Culture System

Design: Seed is germinated in a rockwool cube and when the plant is of sufficient size, the cube is set into the perlite through an opening in the bag; nutrient solution is delivered at the base of the plant by means of a drip-irrigation system; plant roots grow out of the rockwool cube into the bag of perlite; a system of growing which was in wide use for the production of tomato, cucumber, and pepper; perlite-filled bags are being replaced by perlite in buckets (BATO).
Advantages: The system is relatively simple and low cost in terms of growing material (perlite); the perlite bags can be discarded or used an additional time if disease organisms are not present and/or much of the root mass can be removed prior to planting the next crop.

Disadvantages : The method requires a carefully designed system for delivering the nutrient solution from a storage tank to the plant and a means of disposing the unused nutrient solution that flows from the bag, roots may grow out of the bag drain holes, a major problem that occurs with the long-term growth of crops, such as tomato; the perlite will require periodic leaching to remove accumulated salts in order to prevent a soluble salt buildup, a determination based on an electrical conductivity (EC) measurement made on a sample of liquid drawn from the perlite in the bag.

Perlite Bucket Culture System

Design: Seed is germinated in a rockwool cube, and when the plant is of sufficient size, the cube is set into the perlite in the BATO bucket; nutrient solution is delivered at the base of the plant by means of a drip-irrigation system; plant roots grow out of the rockwool cube into the bucket of perlite; a system of growing that is in wide use for the production of tomato, cucumber, and pepper.
Advantages: The system is relatively simple and low cost in terms of growing material (perlite) after the investment in buckets is made; the perlite can be discarded or used an additional time if disease organisms are not present and/or much of the root mass can be removed prior to planting the next crop; effluent from the BATO bucket can be easily collected as the buckets are fitted at the base with an outlet that can be connected to a PVC pipe drainage system, the BATO bucket has a small reservoir in its base.
Disadvantages: Requires a carefully designed system for delivering the nutrient solution from a storage tank to the plant and a means of disposing the unused nutrient solution that flows from the BATO bucket and a means of controlling the time and rate of flow through the drip-irrigation system; root growth may not fill the bucket, particularly directly under the dripper due to lack of O_2, and roots may grow primarily between the outer edge of the perlite and bucket wall, a major problem that occurs with the long-term growth of crops, such as tomato; the perlite in the buckets will require periodic leaching to remove accumulated salts in order to prevent a soluble salt buildup, a determination based on an electrical conductivity (EC) measurement made on a drawn liquid sample from the perlite.

Rockwool Slab Culture System

Design: Seed is germinated in a rockwool cube and when the plant is of sufficient size, the cube is set in an opening cut in the sleeve that encases the rockwool slab, with the nutrient solution being delivered to the base of the plant by means of a drip-irrigation system; plant roots grow out of the rockwool cube down into the rockwool slab.
Advantages: Rockwool is an inert material that has excellent water holding and aeration properties in which plant roots grow very well.

Disadvantages: Fairly expensive system that requires a carefully designed program for delivering the nutrient solution from a storage tank to the plant and then a means of disposing of the unused nutrient solution plus a means of controlling the time and rate of flow of the nutrient solution through the drip-irrigation system; there is a substantial loss of unused water and nutrient elements when the nutrient solution flows from the slab. Root growth may become so massive as to fill the slab leading to root death (O_2 starvation) and roots may grow out of the drain holes in the base of the sleeve enclosing the slab, a major problem that occurs for the long-term growth of crops, such as tomato; the slab will require periodic leaching to remove accumulated salts in order to prevent a soluble salt buildup, a determination based on an electrical conductivity (EC) measurement made on a drawn liquid sample from the slab or effluent from the slab; the rockwool slab may be used one additional time or discarded; however, the disposal of the slabs poses a significant problem.

The Ideal Hydroponic Growing System

There is no "ideal" hydroponic growing system, although aeroponics comes close since in this growing system, plant roots have no effect on the composition of the applied nutrient solution, and the application rate can be precisely controlled. Unfortunately, this system of hydroponic growing has not proven to be economically feasible. What most do not realize is that with the current hydroponic growing methods, the plant has three sources from which to draw essential elements:

1. That being applied by the nutrient solution
2. That which has remained in solution in the rooting mass or medium from previous nutrient solution applications
3. That which has precipitated (see pages 223–224) in the rooting medium but can be partially solubilized by the acidification property of contacting plant roots.

In a way, what is now considered "hydroponic" is actually functioning as a modification of what occurs in soil (see Chapter 3). The requirement for an ideal hydroponic growing system becomes impossible unless some control over these three sources of essential elements can be controlled.

The fact that with time there is an accumulation of ions in the rooting medium, which requires periodic water leaching for their removal, and that in addition the formation of precipitates is taking place indicates that greater-than-needed nutrient elements are being applied, i.e., most nutrient solution formulations are too concentrated. In addition, the rate of precipitation is determined to some degree by plant water use. As water is drawn from the nutrient solution remaining in the rooting medium, the solution is concentrated, and precipitate formation is enhanced.

The most efficient system of nutrient solution delivery would be one in which water and the nutrient solution can be applied separately. For example, a dose of nutrient solution would be applied at the beginning of the day, and then water applied during the day as needed based on atmospheric demand. The nutrient solution formulation would be based on actual plant need and the application rate (combined concentration and volume applied). For example, a fairly concentrated nutrient solution could be initially applied, sufficient to meet the crop requirement for a specified time period, and then water applied as needed until the next dose of nutrient solution is applied (once daily would be best). One important objective would be the elimination of the need to water-leach the rooting medium periodically to remove accumulated nutrient elements, an accumulation that is an indication of excessive rate application.

One of the demands that will significantly impact hydroponic systems is the need to better utilize water, a precious commodity in most parts of the world. If water treatment is required, then significant savings can be obtained if water utilization is maximized. If any water (nutrient solution) flow from the rooting medium occurs, and if periodic water leaching is required to reduce the accumulation of unused nutrient elements, then that system of nutrient solution management is out of control.

Therefore, the ideal hydroponic growing system would be one in which there is near total utilization of both nutrient elements and water by plants — a goal worthy of investigation.

Commonly Used Nutrient Solutions

There are numerous hydroponic formulations, although most are modifications based on the Hoalgand/Arnon nutrient solution (see Table 7.11). The Steiner Nutrient Solution formulations (see page) are based on the concept that if the cations and anions are in their proper balanced ratios, the plant will use less energy for ion uptake. Steiner's concept has yet to be verified.

The primary factor missing in most nutrient solution formulations is the use factor, i.e., volume applied at each application and frequency of application. In general, the more frequently a nutrient solution is applied, the lower should be the concentration of the elements in solution. Another factor that is not generally taken into consideration is the ease of uptake of certain ions (see pages 21–24), such as K^+, NO_3^-, and Cl^-, which are easily taken up by plant roots, while the ions Ca^{2+} and Mg^{2+} are less so, which can lead to overfertilization of the former ions and deficiency of the latter. In general, the micronutrient contents of most nutrient solutions are higher than needed except for the element Zn.

In general, most nutrient solutions are more concentrated than needed. The author recommends that when the Hoagland/Arnon nutrient solutions (see Table 7.10 in Chapter 7) are used, the dilution of the aliquots recommended be not in 1 L but in 1 gallon (3.78 L) of water. The P rate should be half that recommended in the Hoagland/Arnon nutrient solutions (see Table 7.10) and the Zn concentration should be doubled so that the Zn in the nutrient solution is 1 mg/L, ppm, particularly if the P in the nutrient solution is high (>30 mg/L, ppm) and chelated (EDTA or DTPA) forms of Fe are used in the formulation.

There is some question whether nutrient solution formulations should be altered to fit the crop or changed with changing plant development. Using EC to regulate elemental uptake is also a questionable practice.

Chapter 12

The Hydroponic Greenhouse

This discussion is primarily limited to greenhouse structures that are less than 0.5 acre (0.2 hectare) in size, with particular reference to a stand-alone greenhouse, measuring 3000 to 3600 ft^2 (279 to 334 m^2), or multiple-bay units consisting of two to five bays of units of the stand-alone size. Large greenhouse facilities exist, consisting of 20-acre (8-hectare) units that may be in a complex that includes two to six units. Large greenhouse complexes have some similarity to what might be called the “single-owner/operator” greenhouse, but there are significant differences in design and operational requirements that are beyond the scope of this discussion.

For the single-owner/operator, economic and market considerations will determine what size unit(s) best fits. Once that decision is made, what follows in this chapter applies.

There is nothing unique about hydroponics that would significantly alter the basic structure or operating characteristics of a greenhouse, characteristics that can be found in the books by Aldrich and Bartok (1994), Hanan (1998), Nelson (2002), Betyes (2003), and Taylor (2003) and in articles by Goldberg (1985) and Beytes (2003). The primary requirements are based on what plant(s) are to be grown (Nelson, 2002). The only aspect within the greenhouse that might be different will depend on the hydroponic growing system, whether in pots, ground beds, or troughs, or in troughs placed on the greenhouse floor or benches. Also, the delivery of the nutrient solution and water to plants may require specialized equipment. For example, an ebb-and-flow or NFT system would require a different means of nutrient solution storage and delivery than that for a drip irrigation system. In an ebb-and-flow hydroponic system, the nutrient solution tank is normally placed in the ground below the level of the growing beds. The size of nutrient element tanks, for example, could determine their placement either within or outside the greenhouse.

Placement may also require some means of temperature control in order to ensure that the temperature of the nutrient solution delivered to the rooting medium is near or equal to that of the greenhouse air temperature. The flow of effluent from pots, slabs, and troughs, if recovered, would require a collecting, pumping, and storage system, but if discharged, would require a floor design to accommodate such drainage. Today, such nutrient solution discharges are coming under water quality regulations, thereby requiring storage and treatment prior to discharge (Johnson, 2002c). The NRAES-56 publication (Anon., 1996) covers requirements for effective nutrient solution management, principles of root zone management, water quality and delivery, and related subjects that can affect the operation of a hydroponic greenhouse. Savage (1985b, 1989) has two publications on the financial aspects of constructing and managing a hydroponic greenhouse.

Greenhouse Defined

A term early used to identify a greenhouse was "hothouse," a term that is not in wide use today. In the *Merriam-Webster Dictionary,* hothouse is defined as "a greenhouse maintained at a high temperature esp. for the culture of tropical plants." This identification derives from the fact that a greenhouse will collect solar radiant energy that heats the interior. Jensen and Malter (1995) defined a greenhouse as "a framed or inflated structure, covered by a transparent or translucent material that permits optimum light transmission for plant production and protected against adverse climatic conditions." Hanan (1998) states that "greenhouses are a means of overcoming climatic adversity using a free energy source, the sun." Beytes (2003) defined a greenhouse as "a building having glass walls and roof for the production of plants." That definition would not fit since the glazing (cover) materials in use today include many different types of material other than glass. According to *Webster's New World College Dictionary,* a greenhouse is "a building made mainly of glass, in which the temperature and humidity can be regulated for the cultivation of delicate or out-of-season plants," a definition that would fit the concept of design and use in this discussion. The term "glasshouse" "is a European term for an artificially heated structure used for growing plants" (Gough, 1993).

Beytes (2003a) identifies three basic greenhouse designs, single-bay freestanding as the low-cost entrance into the greenhouse business (Figure 12.1) (Thompson, 2003); multiple-bay gutter-connected as the most efficient functional greenhouse (Figure 12.2) (Grosser, 2003), although it lacks flexibility; and retractable roof, which can be the best of two worlds, providing plenty of ventilation (Figure 12.3) (Vollebrecht, 2003). The greenhouse type selected may also be that which best matches the crop to be grown and the local climatic conditions, such as light intensity and duration, temperature extremes, wind, and incidence of hail and snow events. Morgan (2003a) has written an excellent review on greenhouse design and function for both the commercial and hobby grower. She describes how the selection of structural materials and design, glazing materials, and systems for heating and cooling and humidity and pest

Figure 12.1 Single-bay greenhouse. The greenhouse is a freestanding house that can be of varying width, length, and style and covered with various types of glazing materials.

Figure 12.2 Gutter-connected multiple-bay greenhouse. The number of bays can be many depending on the designed use, with each bay gutter-connected.

control are to be made based on the climatic region and intended use. Automated operational systems driven by computerized sensors that Morgan (2003a) describes, "have resulted in the production of totally controlled growing environments that are achieving yields higher than thought possible 10 years ago."

Past climatic records should be examined to determine what extremes have occurred and their frequency of occurrence. High (Morgan 2001a) and low (Morgan, 200lb) temperature extremes, and light duration and intensity will determine the size and capacity for the heating and cooling systems and

Figure 12.3 Greenhouse with removable roof. The roof here is polyethylene sheeting that is pulled into gathered sections. Other materials and design features can be used to move the roof off and back into place.

determine whether shading or thermal blankets will be needed. If the climatic air temperature during much of the growing season is above 32°F (0°C), the primary requirement for environmental control within the greenhouse will be cooling (ventilation). If the climatic air temperature during much of the growing season is below 32°F (0°C), the primary requirement for environmental control within the greenhouse will be heating. In either instance, a totally different greenhouse design may be required to cope with exterior climatic extremes (Morgan 2003a).

Location Factors

In earlier periods (prior to 1970), greenhouses devoted to vegetable production were located near large population centers, but with the ability to move produce rapidly from one region of the country to another, and even from bordering countries, site selection can be based on factors other than closeness to markets. Jensen (1997) reported on the demise of the greenhouse vegetable industry that once existed around large population centers in the central United States. He states that "today … light is considered the most important factor for greenhouse vegetable production, rather than locating close to a population center." Some would dispute this contention, as many single-operator greenhouse vegetable growers are successfully growing and marketing their produce in local markets, which frequently are large population centers.

Other than economic considerations, the location and positioning of the greenhouse can determine how well the enclosed crop performs. Resh (1995) lists the following site requirements:

1. Full east, south, west exposure to sunlight with windbreak on north
2. Level area or one that can be easily leveled
3. Good internal drainage with minimum percolation rate of 1-in./h
4. Have natural gas, three-phase electricity, telephone, and good-quality water capable of supplying at least one-half gallon of water per plant per day
5. On a good road close to a population center for wholesale market and retail market at greenhouses if you choose to sell retail
6. Close to residence for ease of checking the greenhouse during extremes of weather
7. North-south oriented greenhouses with rows also north-south
8. A region which has a maximum amount of sunlight
9. Not located in an area with excessively strong winds

In addition, the greenhouse should be placed so that features in the immediate area will not shade the greenhouse. Exposure to wind can significantly impact the heating and cooling requirements; therefore, having a windbreak can prove to be highly desirable. In rolling terrain, placement on hill peaks would expose the greenhouse to uncontrollable wind and in the valleys to cool air drainage, fog, and stagnant air.

Determining what exists upwind, even several miles away, is important to avoid either dust deposition on the greenhouse or the possible intake of substances that would cause damage to the enclosed crop. If the greenhouse is to be placed in an actively cropped area, what crops are being grown and what chemicals are being applied to these crops must be known. Some crops, such as soybeans for example, are excellent insect hosts; insects can be brought into the greenhouse through the ventilation system, thereby adding to pest control requirements. Herbicides and other pesticides applied aerially to nearby field and fruit crops can be carried by drift into the greenhouse through the ventilation system. Having a windbreak can minimize the deposition of suspended material that might accumulate on the greenhouse surface or the immediate surrounding area. The author visited a large greenhouse complex that was located in an isolated area where there was little human activity within miles. Selecting such an isolated location would minimize what might be brought into the structures from surrounding human activity.

In addition, the immediate area around a greenhouse must be kept as inert as possible, with the minimum of activity from operations that might stir up aerial particles, such as having nearby service buildings bringing vehicular traffic close to greenhouse entrances.

At one time, the author was responsible for a series of research field plots at various locations. At one location, a site east of a heavily traveled highway, the yield results were consistently different from those obtained at the other locations. It was not until I measured the amount of ammonia (NH_3) in the atmosphere above the plots that I understood why the yield results at this site were always higher. The NH_3 that was coming from truck and automobile exhaust was being deposited on this field plot as ammonium-nitrogen (NH_4-N), which contributed sufficient N to the crops being grown on these plots to significantly influence yield.

The author was curious why a large greenhouse operator selected a certain area in the southeast for the production of foliage plants. Besides the availability of an educated work force and a desirable living area, the specific location was determined based on long-term weather records that showed the number of cloudless days during the year for that area was high. A similar greenhouse location in upstate New York was selected since the daily light conditions based on long-term sunshine data records were higher for that particular site than that for the surrounding area. Based on solar photosynthetically active radiation (PAR), Table 12.1 being the "most important factor for greenhouse vegetable production," Jensen (1997) suggests that the southwestern desert regions of the United States would be an ideal location, and indeed such placement and growth in acreage has occurred in that area.

Basic Structural Design

The structural design of a greenhouse is critical as the size and spacing of framing material can affect the extent of light shadowing, while some types of structural materials can act as thermal accumulators, adding either desired or undesired heat to the greenhouse atmosphere. The ability to withstand wind and snow loads will determine the strength required for the structure, an important consideration in some areas. A common error made in greenhouse design is to underestimate the impact of extreme climatic events (wind, hail, and snow) on the structural integrity and maintenance of the interior environment. Commonly used structural materials are treated wood, galvanized steel, aluminum tubing, and PVC tubing.

Greenhouse structures vary from just a loose covering over the top of the crop (Wells, 1996), with or without moveable side curtains designed to protect plants from rain or from the extremes of outside temperatures, to a relatively airtight structure so that the interior environment can be precisely controlled. Polyethylene film–covered greenhouses normally have rigid clean plastic (polycarbonate) end walls. Quonset (trademark for prefabricated shelter set on a foundation of bolted steel trusses and semicircular arching roof) is the common design for polyethylene film–covered structures (Figure 12.4).

Table 12.1 Solar Photosynthetically Active Radiation (PAR) by Location in the United States, PAR (mol/m^2)

Location	*December*	*June*	*October-March*
Tucson, AZ	23	63	195
Miami, FL	25	44	187
San Diego, CA	21	48	172
Denver, CO	17	58	153
Philadelphia, PA	10	46	100
Cleveland, OH	8	48	92
New York, NY	6	44	78

Figure 12.4 Quonset-style greenhouse (common design for most single-bay greenhouses primarily for use by an owner/grower operator).

A single-bay commercial greenhouse structure can vary considerably as to physical size: length 90 to 130 ft (27.4 to 39.6 m), width 24 to 40 ft (7.3 to 12 m), and height 8 to over 12 ft (2.4 to 1.6 m) to the gutter.

The height of the greenhouse can have a significant effect on the ability of the heating and cooling systems to maintain a uniform air temperature within the structure. The larger the volume of air to be conditioned tends to minimize significant shifts in the interior air temperature, humidity, and CO_2 concentration.

Freestanding (see Figure 12.1) and gutter-connected greenhouses (see Figure 12.2) have different design requirements. Gutter-connected greenhouses offer economy in construction and space utilization but add additional requirements to control the interior environment. Large open areas pose challenges for disease and insect control as well as special equipment to maintain uniform atmospheric conditions throughout the structure.

The design of entrances and the placement of screen coverings over air vents and other openings will determine how well insect and disease organisms can be kept from entering the greenhouse (Jacobsen, 2003). The main door entrance into the greenhouse should be housed in a doored attachment, similar to entrances into most business buildings. Entering the attachment, workers can change clothes, walk into a disinfectant bath, etc., and then enter the greenhouse without a blast of air being injected into the greenhouse if the ventilation fans are operating.

How well the various sections of the greenhouse fit together will determine how "tight" the structure will be, a desirable feature to keep unwanted air and insects out, but if it is too "tight," uneven air pressure from inside or out may result in cracks and breakage of joined sections.

For glass- or rigid plastic–covered greenhouses, such structures frequently have moveable vent panels at the rigid line, or large moveable vents that can

Figure 12.5 Greenhouse showing movable vent panels at the ridge line. Open vent panels allow hot air to escape, which pulls air from below, thereby ventilating the entire greenhouse.

open the entire top of the greenhouse (Figure 12.5). For most plastic film–covered greenhouses, the common design is to place an exhaust fan(s) at one end of the greenhouse (Figure 12.6) and an adjustable opening, with or without a cooling pad (Figure 12.7), at the other end so that air can be pulled through the length of the greenhouse. Air baffles may be placed at various positions in the gable so that air being pulled through the greenhouse by an exhaust fan(s) will be periodically directed downward, ensuring air mixing throughout the entire depth and length of the greenhouse. A very effective way of ventilating a greenhouse is to place the ventilation fans and cooling pads on opposite sides along the length of the greenhouse so that air is pulled across the shortest distance. Unfortunately, few greenhouses are so designed.

Flooring

A range of materials can be used as flooring in the greenhouse; the best choice is concrete, and the least desirable choice is compacted soil or sand. For initial cost considerations, the walkways may be concrete, while the crop rows consist of sand or gravel or other similar materials. The crop rows and, if the entire floor consists of these materials, other than concrete, plastic ground cover should be placed over the crop rows or the entire floor to serve as a barrier. Crop trash, a source of disease and other problems, that falls on an open floor cannot be taken up if the floor is not firm. The lack of firmness of the flooring can cause problems with use, affecting foot traffic movement in the greenhouse as well as interfering with the floor drainage system. With a smooth and firm flooring material in place, keeping the floor clean and free of trash is greatly enhanced. Experience has shown that the initial investment

Figure 12.6 Placement of exhaust fans at the end of greenhouse (normal arrangement for pulling air into the greenhouse from openings in the opposite end of the greenhouse). Normally, exhaust fan placement is at the base of the greenhouse. For cross-flow ventilation, fans may be placed higher on the side walls, as in Figure 12.16.

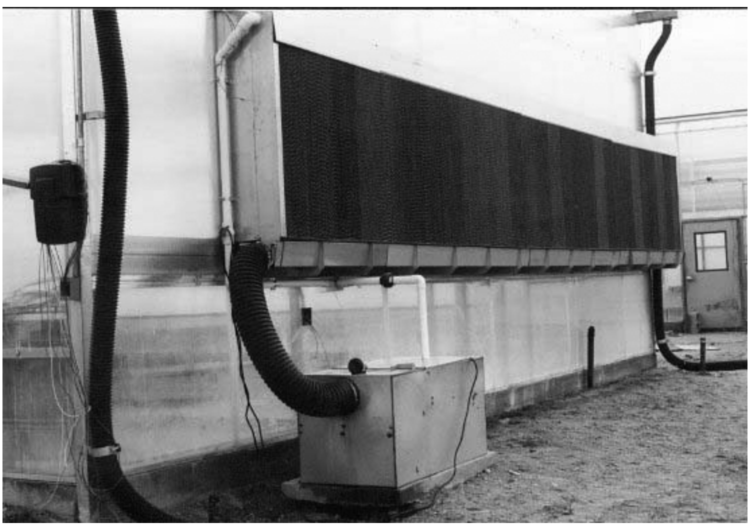

Figure 12.7 Cooling pad placed at one end of the greenhouse. Air is pulled through the cooling pad by exhaust fans placed at the opposite end of the greenhouse — see Figure 12.6. Water is passed over the cooling pad. As shown here, the large box set on the ground contains water, which is pumped to the top of the cooling pad and allowed to flow down the pad and then is collected and flows back into the water storage box.

in concrete over the entire greenhouse floor pays dividends. The floor of the greenhouse should have a 1 to 2% slope.

Glazing Materials

Glazing simply refers to the type of material covering or attached to the greenhouse frame. Another term that is found in the literature for glazing is cladding (something that covers or overlays, according to the Merriam-Webster dictionary). The commonly used glazing materials are glass, polyethylene film (high or low density, linear low density), ethylene vinyl acetate, and coextruded films. At one time, fiberglass was frequently used, but its flammability has almost totally eliminated its use today.

Coene (1995) lists five important considerations when selecting the greenhouse covering:

1. Material integrity in direct sun without losing clarity
2. Guaranteed lifespan (Table 12.2)
3. Fire resistance
4. Transmission of photosynthetic radiation (PAR) (Table 12.1 and Table 12.3)
5. Energy efficiency properties (Table 12.4)

Another characteristic is the diffusion of light passing through the covering. Light diffusion will distribute light more evenly in the greenhouse, resulting "in more even light distribution without defined shadows" (Coene, 1995). Fiberglass has a high diffusion property as well as structural strength; for these reasons it was, at one time, in wide use as a glazing material.

Some types of coverings will not transmit equally all the wavelengths of light striking their surface, thereby filtering the light and changing its spectral characteristics (Morgan 2003a). The characteristics of various types of glazing materials including glass, polyethylene film, polycarbonate, fiberglass, and

Table 12.2 Life Expectancy and Transmission of Greenhouse Cladding (Glazing) Material

Cladding (Glazing)	*Material Life Expectancy (years)*	*Transmission (%PAR[a])*
Glass	25	90
Polythene	1 to 2	89
Ethylene vinyl acetate (EVA)	2 to 3	88
Fiberglass	10+	82
Polycarbonate	12+	80
Rigid PVC	10+	70

[a]Photosynthetically active radiation.

Source: Morgan, L., 2003a, *The Growing Edge* 14(3):26–35.

Table 12.3 Cladding (Glazing) Transmission Coefficients

Cladding (Glazing) Material	*Transmission Coefficient*
Single layer of glass	1.1
Single layer of plastic film	1.2
Single layer of fiberglass	1.2
Double layer of plastic film	0.7
Double layer of acrylic or polycarbonate extrusion	0.5

Source: Morgan, L., 2003a, *The Growing Edge* 14(3): 26–35.

Table 12.4 Calculated Greenhouse Collector Efficiencies

		Greenhouse Collector,%			
		Greenhouse Temperature			
		22°C		*27°C*	
Ambient Air Temperature	*Solar Radiation*	*Single Glazing*	*Double Glazing*	*Single Glazing*	*Double Glazing*
°C	w/m^2				
	100	0	0	0	0
0	200	0	1.6	0	0
	350	0	9.3	0	3.9
	250	0	14.6	0	4.9
5	300	0	20.2	0	12.0
	450	0	29.4	0	23.9
	300	0	25.3	0	18.0
10	450	4.9	32.8	0	27.9
	600	17.4	36.5	1.8	32.9
	450	24.6	37.9	4.9	31.8
15	600	32.2	40.3	17.4	35.8
	750	36.7	41.8	24.9	38.2

Source: Garzoli, K, 2001, *Practical Hydroponics*, Issue 60:64–76.

acrylic are discussed in the book edited by Beytes (2003a). All these materials have varying transmission characteristics that will significantly affect radiation input and output from the greenhouse. The selection of which glazing material is best will be determined by cost, durability, and external environmental factors (i.e., wind, snow load, hail resistance, etc.). The so-called "greenhouse effect" is a phenomenon due to a shift in wavelength. Radiation entering the greenhouse adds heat to the interior environment due to a wavelength shift, as radiation reflected back from the interior surfaces is of a longer wavelength than that entering and is therefore trapped within the greenhouse as heat.

The effect of light filtering and diffusion on plant color and architecture was illustrated to the author in a greenhouse tomato experiment conducted in two greenhouses that were located just a few miles apart. One greenhouse was covered with fiberglass, the other glass. Those plants in the glass-covered house were dull green in color and had long internodes, while those in the fiberglass-covered house were dark green in color with short internodes. Interestingly, only small differences in fruit yield occurred, but the tomato plants in the glass-covered greenhouse required more frequent adjustment due to their longer internodes.

Heating and Cooling

Heating and cooling requirements will vary depending on the location, type of structure, and crop to be grown (Anon., 1994; Ball, 2003; Rearden, 2003; Morgan, 2003a,b). In general, it is better to oversize these systems in order to ensure that the environment inside can be easily maintained. The positioning of ventilation fans, cooling pads, and heating devices will determine how well the inside air temperature and humidity can be controlled. For some crops, such as tomato and cucumber, air movement up through the plant canopy is preferred. Floor heating, particularly in cooler climatic areas, can be beneficial to a crop, keeping the rooting medium at or near the ambient air temperature in the greenhouse. The warming of the nutrient solution/water to that of the current air temperature in the greenhouse, or even 4 to 5 degrees F above the ambient air temperature (Smith, 2002b), will minimize possible plant wilting due to reduced water uptake. The rate of water uptake by plant roots is correlated to temperature, decreasing with decreasing temperature (Nielson, 1974; Harssema, 1977).

Heating

There are primarily two systems for heating the greenhouse atmosphere, forced hot air or radiant heat. The most commonly used is either a natural gas- or propane-fired jet fan heater placed in the gable of the greenhouse on the ventilation fan end (Figure 12.8). Heated air is pushed through a gable-placed large plastic-holed tube running the entire length of the greenhouse (Figure 12.9). The heated air is distributed through the holes in the tube, the force of the discharge being sufficient to push heated air into the greenhouse cavity. The burning of fuel in the greenhouse adds humidity to the atmosphere. When the outside temperature cools the supporting greenhouse structure, the moisture will condense, making the walls and interior structures wet, including the plants, which is highly undesirable.

The other heating method is by the passage of either boiler-generated hot water or steam in pipes that are placed down the sides of the greenhouse at floor level, and in some instances, pipes are placed between crop rows. This

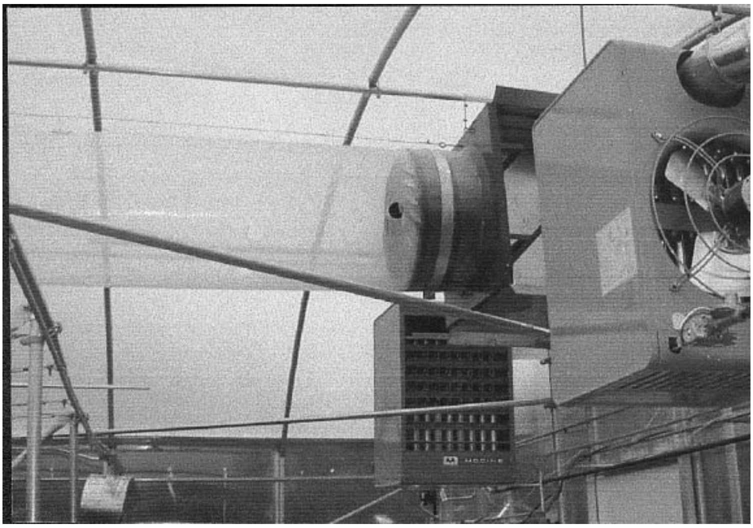

Figure 12.8 Natural gas- or propane-fired jet fan heater placed in the gable at the ventilation fan end of the greenhouse (common method of heating and dispersing hot air into a greenhouse).

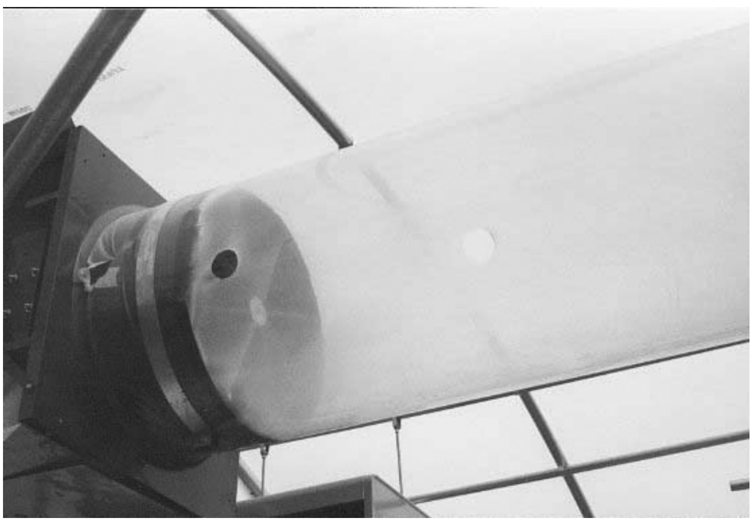

Figure 12.9 Fan-driven (see the fan in Figure 12.8) heated air is delivered through a large plastic-holed tube that runs the entire length of the greenhouse in the gable.

type of heating system is referred to as "hydronic heating"; it provides even heating of the greenhouse atmosphere by radiation from the heated pipes. With hydronic heating, the greenhouse and canopy atmospheres are kept dry as heated air moves from floor-level pipes through the plant canopy into the gable. Using a small gable-placed fan, this moisture-laden air can then be exhausted out of the greenhouse.

Heat loss from the greenhouse occurs by three processes: conduction (heat loss conducted through solid materials), convection (removal of heat by air currents), and radiation (heat loss by short or long wavelength radiation through the glazing material). In addition, heat loss can occur through infiltration of cool air and loss of heated air through cracks and openings in the greenhouse. Based on the average of the coldest days of the year, a winter design temperature can be determined. In very cold climates, the use of thermal blankets, either on the outside or placed at the base of the gable as well as along the sides of the greenhouse, can significantly reduce back radiation at night, or when the greenhouse is exposed to cold winds. The winter design temperature map for estimating heat loss for greenhouses located in the continental United States is shown in Figure 12.10 (Bartok, 2000).

Morgan (2001b) describes greenhouse design and operating procedures needed to minimize the effects of low temperatures on plant growth and greenhouse functions. She focuses on the selection of glazing materials, the design of heating systems, and air distribution procedures that can have a significant effect on the maintenance of the interior environment within parameters essential for sustaining plant growth. For plastic polyethylene film–covered greenhouses, double layers separated by continuously introduced air minimize the loss of heat by both conduction and back radiation. Similarly, twinwall panels of polycarbonate are commonly used as end walls, although they can be used as side walls as well as the covering glazing material; the double-walled material is more energy-efficient as compared to single-walled panels.

In some climatic regions floor heating can be beneficial. This is provided by placing either hot water–heated pipes or electrical heating cables on the surface or in the greenhouse floor itself. For the most efficient floor heating effect, a thermal barrier is placed under the greenhouse floor.

The temperature range in which plant enzymes are active is between 50 and 104°F (10–40°C). The optimum air temperature for most greenhouse-grown plants ranges between 55°F (13°C) and 77°F (25°C). At low temperatures, plants may show signs of a P deficiency, a purple pigmentation of the new leaves and under, some situations, Fe deficiency symptoms — symptoms that will disappear when the air temperature in the greenhouse is brought into the normal range for best plant growth. Low air and medium temperatures can result in pathogen development (particularly Botrytus), as well as reduced root uptake of water and/or nutrient solution.

Alternative sources of both fuel and heat have been used for heating greenhouses. For example, waste oil (Anon., 1977b) and methane released from a landfill (Simon, 2003) have been used as fuel sources, and hot water condensate from a nearby steam-powered electrical plant, introduced into a radiant heating system, has been used to heat a greenhouse (Peckenpaugh, 2004b). Kleemann (1996) describes how wind-powered generators can be used to supply electrical power to a greenhouse.

Johnson (2003) describes a unique hot water storage system in which water is heated during the day to 200°F (93°C) by a gas-fired boiler and the CO_2 generated from the combustion, after passing through a exhaust gas separator,

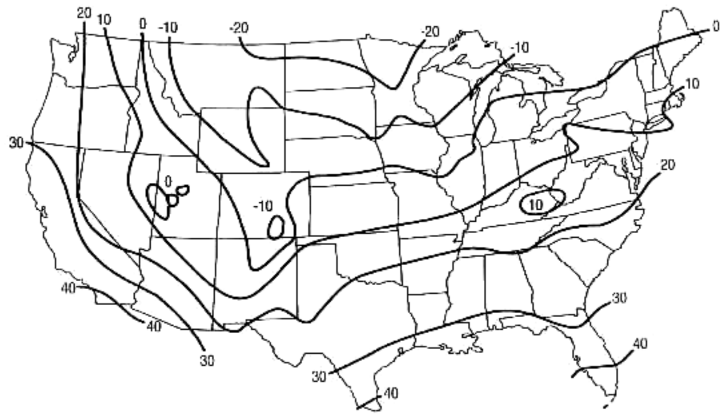

Figure 12.10 Winter design temperature map for estimating heat loss for the United States. Heat gain is indicated by the positive numbers for the year in the southern regions, and heat loss by negative numbers in the northern latitudes. *Source:* Bartok, J.W., Jr., 2000, Greenhouses for Homeowners and Gardeners, Cooperative Extension NRAES-137, Natural Resource, Agriculture, and Engineering Service (NRAES), Ithaca, NY.

is introduced into the greenhouse (see the section on CO_2 enhancement). At night the stored hot water is used to heat the greenhouse.

In some climatic regions during the winter months (December through February in the northern hemisphere, June through August in the southern hemisphere) when light intensity is low and daily maximum daytime air temperatures are usually less than 32˚F (0˚C), few attempt to grow under these conditions.

Cooling

It should be remembered that a greenhouse, once referred to as a “hothouse,” is a very efficient solar collector (thermal accumulator), a possibly desirable characteristic in cool/cold low-light climatic conditions but an undesirable characteristic in high-light warm/hot climatic conditions (Morgan 2001a; Jones and Gibson, 2001). The so-called “greenhouse effect” is due to the trapping of incoming radiation within the greenhouse as heat — heat that is not readily reradiated back out through the glazing material. In addition, incoming radiation striking the objects within the greenhouse acts as heat sinks, adding significantly to the heat load that can be either beneficial or detrimental for controlling the interior environment. Buntyn-Maples (1994–95) talks about “Greenhouse Growing — Southern Style, where plants face detrimental 40˚F (4˚C) temperature days and even colder nights without interior supplemental heating methods or the solar warmth of a greenhouse.” Most growers in the southern regions will not grow in the middle of summer months (June–August) due to high temperatures. Jones and Gibson (2001) related poor tomato growth

Figure 12.11 Ventilation vents at the roof ridge line open to allow hot air to be exhausted from the greenhouse gable.

and fruit yield to the amount of radiation (measured as minutes of sunshine per month) entering greenhouses located in the southeastern United States. They found that months with more than 10,000 minutes of accumulated sunshine negatively impacted tomato plant performance.

Removing warm/hot air from the greenhouse by natural means may be as simple as raising side curtains or opening ventilation vents at the roof ridge line if the greenhouse is so designed (Figure 12.11). For structures without such features, cooling is primarily obtained by pulling outside air into the greenhouse by ventilation fans (Figure 12.12) (Ball, 2003). The fans are placed at one end of the greenhouse or along its sides, and air is pulled through openings on the opposite end or side. Those openings may be fitted with a cooling pad that is kept wet by water passing over or through it (Figure 12.13). The effectiveness of the cooling pad in reducing the incoming air temperature will depend on the relative humidity of the outside air; the higher the humidity, the less reduction in air temperature occurs. The approximate air temperature drop across a Carolina Cooler[1] (6 inch medium) during July with a properly sized ventilation system is shown in Figure 12.14. The design and effectiveness of cooling pads can be calculated based on pad size and the volume of air pulled through the pad (Short, 2003). Each gallon of water evaporated from the movement of air through a cooling pad will absorb 8100 BTUs of heat energy.

The author believes pulling cool air across (the shortest distance) the greenhouse is much more efficient in cooling the interior than pulling air through the longest distance. However, few greenhouses are designed with side ventilation systems. Depending on the climatic conditions, 60 air changes

[1]A product of Jaderloon, Burlseon, Texas.

Figure 12.12 Large ventilation fans placed at the end of the greenhouse. The size and number of exhaust fans will determine the amount of air that will be exhausted from the greenhouse. In this situation, this greenhouse was located in a warm climatic region; therefore, a need for high capacity air movement existed.

Figure 12.13 The cooling pad in this greenhouse occupies the entire end of the greenhouse. The size of the cooling pad can significantly affect the cooling effect.

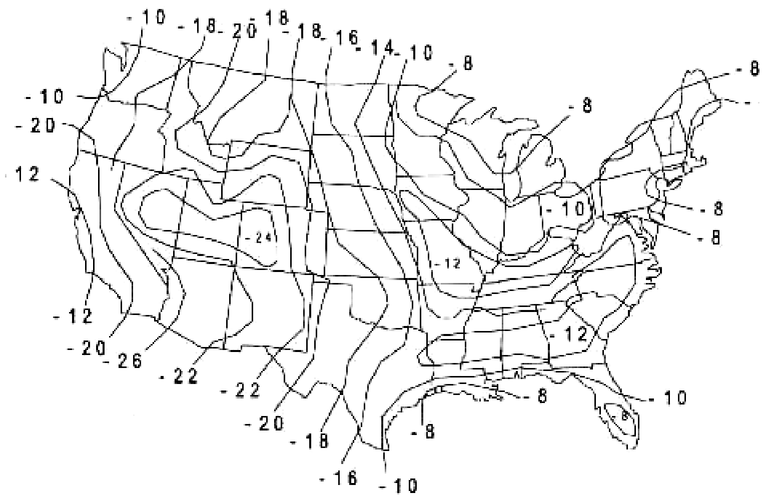

Figure 12.14 Approximate air temperature drop across Carolina Cooler (6-in. medium) during July with a properly sized ventilation system (product of Jaderloon, Burleson, Texas).

per hour may be necessary on high light intensity days in order to maintain an optimum air temperature within the greenhouse by bringing cooler air in from outside.

Opening the greenhouse to outside air either flowing into or out of the greenhouse will allow insects, disease organisms, and other pests to enter. In order to minimize entry, screens of various mesh size (below 500 micron mesh recommended for insect blocking) are needed. If the primary cooling system is by means of a cooling pad, a large screened plenum may be required to allow sufficient air to pass through (Jacobsen, 2003).

Shade cloth placed over the top of the greenhouse will reduce the amount of incident radiation passing through the glazing or, when placed at the bottom of the roof gable over the plant canopy, will decrease the air temperature within the greenhouse or plant canopy, respectively. When to shade and the amount of shade will depend on what crop is being grown and the intensity of radiation being received. For example, for tomato when the greenhouse temperature during the day exceeds 85°F (29°C), shade should be applied, and for lettuce and herbs, shade should be applied when the greenhouse temperature during the day is greater than 80 to 82°F (26.6 to 27.7°C).

Shade cloth pulled over the top of the greenhouse, as shown in Figure 12.15, is not easily placed or removed, which provides little control for intermittent use. More recently, greenhouses are being fitted with shade cloth inside the greenhouse at the gable base that can be drawn over a crop or pulled back with relative ease. The ability to place and remove shade can be of significant advantage for regulating the amount of radiation impacting the crop and for obtaining better control of the interior environment.

Figure 12.15 Shade cloth pulled over the top of a polyethylene-covered greenhouse.

The degree of radiation reduction will vary with the mesh characteristics of the shade material. Normally, 40% white shade material over a polyethylene-covered greenhouse is recommended, while 50% white shade material would be recommended for high altitudes and high light intensity light areas. In the past, glass-covered greenhouses were whitewashed to reduce incoming radiation, a procedure not in common use today.

Misting is another way that the plant canopy can be cooled. It is frequently used both to cool and to provide protection to newly rooted cuttings or emerging seedlings from the effect of high light intensity. The disadvantages of this technique are the potential for disease development when a cool and damp environment exists as well as the requirements for high pressure pumps, fine nozzles, and water free of suspended particles (Beytes, 2003). In some climates, misting or flowing water over the greenhouse roof can significantly reduce the amount of radiation entering the greenhouse.

Nyun (1997) has designed a unique side wall "squiggly cut" lath shading system for use with hobby-type greenhouses.

Morgan (2001a) discusses those procedures needed to minimize the effects of high temperatures on greenhouse operations. The effect of temperature on the enclosed greenhouse crop varies with species and how well the cooling system functions. The basic influencing factors are related to greenhouse design, such as increased roof heights and inclusion of roof vents, and the use of fans and aspirated screens to pull cool air through the greenhouse at various heights (Figure 12.16).

The effect of uneven cooling on a crop between the cooling pad and the exhaust fan can be easily seen in most greenhouses if the transporting air is being pulled at a considerable distance [>50 ft (15 m)] and there is little air mixing in between. The air temperature differential may be as much

Figure 12.16 Vent fans placed at the gable height on the side of a greenhouse to pull air across the greenhouse at the gable level (a ventilation system useful in warm climatic regions).

as 10 degrees Fahrenheit from the cooling pad end to the ventilation fan end. For example, if tomato is the crop and the canopy height is at the support wire, the cooled air being pulled through the cooling pad will tend to pass over the top of the canopy. Such a condition can have a significant effect on plant growth and fruit yield. The remedy would be to have a cross-flow pad-ventilation fan system (pulling air across the greenhouse rather than down its length), and/or to direct air up through the canopy from its base. If the cooling pad has an inside door closure, that closure should be hinged at the top so that air coming off the pad is being directed at the base of the plant canopy.

The plant cools itself through transpiration, the loss of water vapor from leaf surfaces, similar to the effect that evaporating perspiration has on the human body. The effectiveness of this cooling process requires a continuous movement of air over the leaf surfaces. Water movement into the plant roots can be impaired by inadequate O_2 and/or water in the rooting medium and low temperature (Nielsen, 1974; Harssema, 1977). The increasing electrical conductivity (EC) of the nutrient solution will also decrease the uptake of water (see page 106). Under any one of these water uptake restricting conditions, the plant may wilt when high atmospheric demand conditions exist. Upward movement of water in the conductive tissue (xylem) of the plant can be slowed by low air temperature and stagnant air, reducing the rate of water loss from leaf surfaces. Both conditions will affect the rate of photosynthesis, thereby slowing plant growth, and in turn result in decreased fruit yield. Therefore, sufficient air flow through the plant canopy is essential, particularly for certain crops, such as tomato and cucumber. This can be best obtained by introducing conditioned air at the bottom of the plant canopy.

Air Movement

Air movement throughout the greenhouse, and particularly within the plant canopy, can have a significant effect on plant performance. In an enclosed greenhouse, air movement created by the operation of heating and/or cooling equipment may not be sufficient to thoroughly mix the air in the entire greenhouse (Short, 2003). Even the placement of fans in the greenhouse gable directing air into the plant canopy can be ineffective. With a dense plant canopy created by tomato and cucumber plants, for example, it is very difficult to push air into the canopy, as the canopy acts like a "box," and air movement directed at the canopy either passes over the top or glances off of it. Therefore the air within the canopy has characteristics (temperature, humidity, CO_2 content) of its own which can be quite different than those of the air surrounding the canopy. The only way that sufficient air movement can be obtained is by the introduction of moving air from the base of the canopy so that air is constantly moving up through the canopy. This air may be conditioned, that is, either heated or cooled. If no air is being brought into the greenhouse from outside, it is very important that the entire mass of air within the structure be constantly mixed as plant growth and function can be impaired by standing in still air.

Plant Support System

For tomato, cucumber, and pepper greenhouse production, a plant support system must be installed. The system usually consists of a strand of strong wire stretched over the plant row with hanging string attached to the wire at each plant location. The plant is tied to the string. Various systems have been devised to ensure that sufficient string is present at each plant location to provide for lowering and tying over a full season of plant growth. The attachment of the support wire to a structural greenhouse member is not recommended since the plant weight on a support wire can be several tons. Most greenhouse structural members are not able to hold such weight. The support wire should be attached to sturdy-set stanchions placed about every 30 ft (9 m) down the plant row, or the stanchion can be placed in the middle of a double row with a cross piece at the top to hold each support wire in place.

Supplemental Lighting

There are two primary reasons for supplying supplemental light: photosynthetic, utilizing light sources to provide part or all that necessary for normal plant growth, and photoperiodic, that required for controlling flowering and plant shape (Yoemans, 1991; Sherrard, 2003). For many plants, the quantity of light for photosynthesis ranges from 100 to 1000 times that needed for photoperiodic lighting. If used for either application, the cost for supplemental lighting should either be equal to or less than the financial return gained by

Table 12.5 Plant Light Requirements

Plant	*Light Requirements*	*Comments*
Beans	Medium-high	Most require moderate light intensity over long season; flowering initiated high temperatures
Cucumber	High	Grows best under intense light and in warm temperatures; day-neutral; flowering initiated by high temperatures; provide supplemental lighting indoors and in winter greenhouses
Lettuce	Low	Grows best in partial shade or filtered light; may be grown in a sunny window indoors; long-day
Peppers	High	Prefers bright, warm conditions, but will survive periods of reduced light; day-neutral; flowering initiated by high temperatures
Tomato	High	Provide ample light and warm temperatures; day-neutral; flowering initiated by high temperatures; provide supplemental lighting indoors and in winter greenhouses

Source: Parker, D., 1994a, *The Growing Edge* 5(4):53–57, 66–67.

its use. For photosynthetic effect, supplemental lighting to extend the hours of daylight may be its only legitimate use for most crops. Supplemental lighting to increase light intensity during daylight hours is highly questionable in terms of significant benefit measured by increased yield and quality of produced product. The light level in the greenhouse to sustain growth for tomato and lettuce, for example, ranges between 800 and 1200 foot candles. The light requirement of plants varies considerably and those plants that are highly light responsive can benefit from supplemental lighting. Parker (1994a) has given the light requirements for some of the crops commonly grown in the greenhouse (Table 12.5). The light wavelength range in nanometers correlated to relative photosynthesis is shown in Figure 12.17. The relative energy of sunlight and three types of fluorescent lights by wavelength is shown in Figure 12.18. The response of plants to the light spectrum is more significantly expressed in terms of absolute energy measured in those portions of the spectrum where the plant response is greatest. The wavelength response of plants is given in Table 12.6 (Coene, 1995). This light energy is expressed in micromols per second per square meter (umol/sec/m^2) (Mplekas, 1989).

Parker (1994a,b), in a two-part article, describes light, its quality, intensity, and spectrum characteristics and its impact on plants. The spectral distribution for various lamps (standard fluorescent, mercury vapor, metal halide, and high pressure sodium) can be found in the second Parker (1994b) article. The suitability of a light source for supplementation depends on its spectral distribution (how closely the light emitted mimics sunlight) and its intensity. Also, the operational cost and life expectancy of lamps are equally important factors. In some instances, a combination of lamp types, such as incandescent and fluorescent, placed over a crop may provide the best spectral coverage

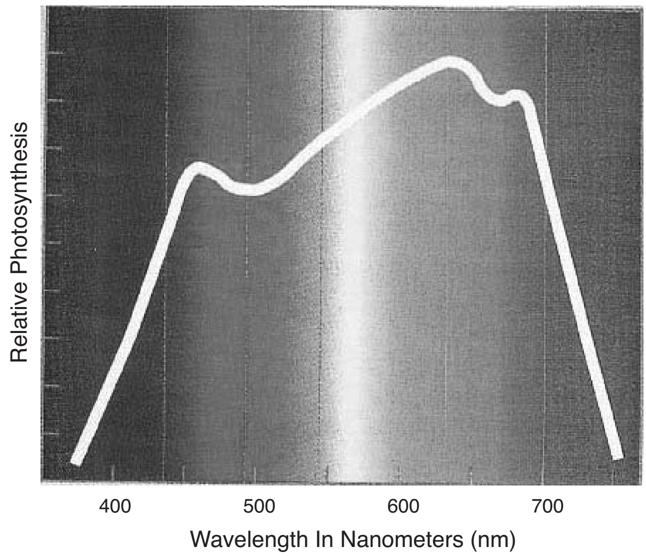

Figure 12.17 Relationship between wavelength and relative photosynthesis (Source: Parker, D., 1994a, *The Growing Edge* 5(4): 53–57, 66–67).

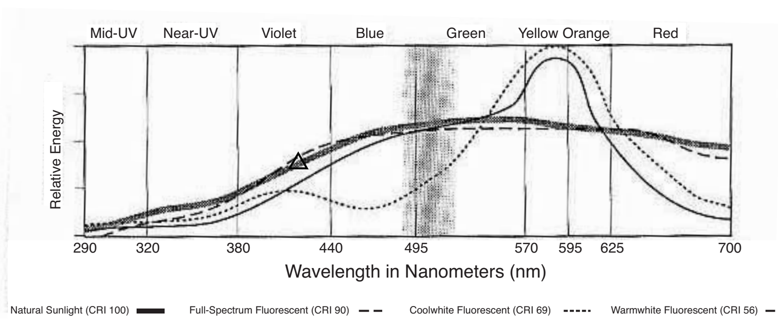

Figure 12.18–1 Relative energy of sunlight and three types of fluorescent lights by wavelength. *Source:* Parker, D., 1989, *The Growing Edge* 1(1):25–28, 51–52.

for maximum plant impact. Today, combination lamps that provide a wide spectrum of emitted light are available. Some lamps generate considerable heat, which can either be a benefit as a heat source or require that the unwanted heat be dissipated, which adds to their cost of operation. Supplemental light also has a "drying effect" that keeps plant foliage dry during low light periods.

The type of lamp, its emission intensity and spectrum (long versus short wavelength distribution), the use of reflectors, a mix of lamp types, and placement position over the plants will determine what crop effect occurs.

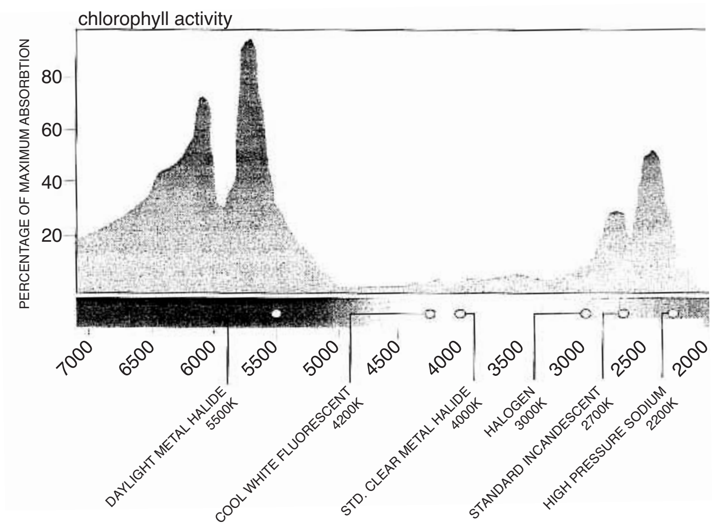

Figure 12.18–2. Chlorophyll activity as a percent of maximum absorption for various light sources. *Source:* Roberto, K., 2001, *How-To Hydroponics*, 3rd ed., Futuregarden, Inc., Farmingdale, NY.

Light quality (spectral distribution) and intensity are significant factors when selecting the lamp type. The types of lamps available for plant use are described by van Patten (1998), focusing on high intensity discharge (HID), metal halide (MH), and high-pressure-sodium (HPS) lamps. Metal halide lamps produce a complete spectrum similar to that of natural sunlight. One type of HID lamp is the sulfur lamp, light coming from a hot gas or plasma within a transparent envelope (Coene, 1996–97).

Those looking for a comprehensive review on the effect of light, both quantity and quality, including the effect of supplemental lighting techniques on plant growth and development, will find Mplekas's (1989) article of considerable value. Mplekas (1989) states "the increasing need for a scientific approach to horticultural lighting in order to increase plant production and to improve the economic return in an increasingly competitive market combine to emphasize to the commercial grower the importance of electric lights as a control tool in the field of horticulture."

A glossary of lighting terms is given in Table 12.7 and conversion constants in Table 12.8. To calculate the lumens per watt (LPW) for a bulb, divide the total initial lumens by the watts produced (1000 watts of light = 3700 BTUs = 1 kilowatt per hour).

Carbon Dioxide Enrichment

Carbon dioxide (CO_2) naturally exists in the ambient atmosphere at between 300 and 400 parts per million (ppm) and is considered by some an essential plant nutrient. Simply put, CO_2 diffuses through open stomata of chlorophyll-

Table 12.6 Breakdown of Wavelength Influence on Plant Physiology

Wavelength Range (nm)	*Plant Response*
280 to 315	Plant morphogenetic and physiological processes are influenced
315 to 400	Chlorophyll slightly absorbs this light; photoperiod is influenced holding back on cell elongation
400 to 520	Large absorption of light by chlorophyll and carotenoids; photosynthesis process greatly influenced
520 to 610	Low absorption by pigments
610 to 720	Low absorption by chlorophyll; photosynthesis and photoperiod are greatly influenced
720-1000 nm	Overall low absorption, cell elongation stimulated; flowering and germination influenced
Over 1,000	Absorption energy is converted to heat

Source: Coene, T., 1995, *The Growing Edge* 6(3):66–72.

containing leaves of a live plant and is combined with a split water (H_2O) molecule in the presence of light to form a carbohydrate; the whole process is called "photosynthesis" (see pages 14 and 383). The positive effects of CO_2 enrichment on plant growth have been known since the 1920s, although greenhouse CO_2 enrichment was not put into practice until the 1960s.

In an enclosed greenhouse, atmospheric CO_2 content will decline during the day due to photosynthetic activity (absorption of CO_2) and will increase at night as plants respire (release CO_2); the change in concentration is as much as 150 ppm. Frequent ventilation of the greenhouse and air mixing within the plant canopy can moderate this cycling of the CO_2 content. The rate of CO_2 depletion is directly correlated with the rate of photosynthesis, with the depletion occurring rapidly within a few hours after daylight. The author was surprised when he observed a 50 ppm drop in CO_2 content within a tomato plant canopy just a few minutes after direct sunlight at dawn entered the greenhouse (Harper et al., 1979). Plant photosynthetic activity can reduce the CO_2 content within the plant canopy to between 200 and 250 ppm.

The photosynthetic rate is positively correlated to the CO_2 concentration surrounding the plant; the extent of this concentration effect varies with plant species (whether C3- or C4-type plants, see pages 378–379) and light intensity (Carrathers, 1991–92). In addition, the positive enhancement effect can be markedly increased when the CO_2 concentration is three to four times that naturally existing in the atmosphere, while photosynthesis can be halted when the CO_2 concentration approaches 200 ppm. Excessively high CO_2 concentrations (2000+ ppm) can be toxic to plants, while concentrations of 5000 ppm can pose health dangers to those working in such an atmosphere (Morgan, 2003c).

The effect of CO_2 enhancement on plant growth for crops such as tomato, cucumber, bell peppers, flowers, lettuce and herbs, and ornamental and forage crops has been reviewed by Elber (1997) and Morgan (2003d). The extent of the enhancement effect varies with crop species and is not always beneficial.

Table 12.7 Glossary of Light Terms

Ballast
A device used with an electric discharge lamp such as fluorescent lamp, a high-pressure sodium lamp (example: Sylvania's Lumalux), or a metal halide lamp (example: Sylvania's Metalarc) to obtain the necessary circuit conditions for proper starting and operation of the lamp.

CU, Coefficient of Utilization
The ratio of the amount of energy (light) from a luminaire calculated as received on the planted area to the amount of energy emitted by the lamps alone.

EF, Equipment Factor
Since some lamps and luminaires do not operate at their published energy outputs, the equipment factor compensates for the reduction in output that may occur in actual usage. The EF is essentially a safety factor.

fc, Footcandle
The unit of illuminance when the foot is taken as the unit of length. It is the illumination on a surface, one square foot in area, on which there is a uniformly distributed energy level of one lumen. In SI terms the unit is "lux": 1 fc = 10.76 lx.

HID (High-Intensity Discharge) Lamp
A type of electric discharge lamp characterized by a high arc tube wall loading. Mercury, metal halide (examples Sylvania's Metalarc), and high-pressure sodium (example: Sylvania's Lumalux) are typical HID lamps used in plant growth areas.

Illuminance
The density of luminous energy on a surface.

Illuminant
A light source, such as fluorescent, incandescent, or HID.

LLD, Lamp Lumen Depreciation
The multiplier to be used in illumination calculations to relate the initial rated light output of the lamp to the anticipated minimum output based on the relamping program anticipated.

LL, Initial Lamp Lumens
The amount of light energy available from the selected light source.

Luminaire
A complete lighting unit consisting of the lamp or lamps together with the parts designed to distribute the light, position and protect the lamps, and connect the lamps to the power supply.

LDD, Luminaire Dirt Depreciation
The multiplier to be used in illuminance calculations to relate the initial illuminance provided by clean new luminaires to the reduced illumination they will provide due to dirt collection on the luminaires at the time when cleaning procedures will be instituted.

Mean Light Output
Average light output over lamp life.

Table 12.7 Glossary of Light Terms (continued)

The radiation in the wavelength range of 400 to 800 nm controlling the phytochrome reaction, which governs development and differentiation of growth responses (vegetative growth, flowering, reproduction, elongation, dormancy).

Photosynthesis
A process by which green plants take carbon dioxide from the air, and water and inorganic nutrients from the soil, in the presence of light energy, to form carbohydrates and to release oxygen as a byproduct.

PAR, Photosynthetically Active Radiation
The total radiation in the wavelength range of 400 to 700 nm contributing to photosynthetic productivity in relation to the relative quantum efficiency of the spectral quality of the radiation.

Radiation
The emission and propagation of electromagnetic waves or particles through space or matter.

RNCR, Room Capacity Ratio
A number indicating room cavity proportions calculated from length, width, and height.

Definitions
Footcandle = one lumen per square foot (fc = 1 Lm /ft^2)
Lux = one lumen per square meter (lux = 1 Lm /m^2)
One footcandle equals about 10.76 lux

Slake (1983) found that whole-day CO_2 enrichment maximizes tomato plant growth and fruit yield, but more important is keeping the CO_2 level constant at its ambient level within the plant canopy during the entire day in order to sustain plant growth and fruit yield. It should also be remembered that with sustained high CO_2 concentrations (1000 ppm), newly emerging leaves will have fewer stomata per leaf area, and it is through the stomata that photosynthesis occurs. Therefore, even though the CO_2 content of the atmosphere around the plant is high, the photosynthetic rate will decline due to the presence of fewer stomata on the leaves. In addition, some have observed a fairly large drop in plant photosynthetic response to elevated CO_2 with time, with initial increases ranging between 30 and 50% and then dropping to 5 to 15% (Wolfe, 1995).

There is also a significant relationship between light intensity and the CO_2 content of the air surrounding the plant (Mpelkas, 1989). Gaastra (1962) also observed a significant relationship between CO_2 concentration, light intensity, and leaf temperature and the rate of photosynthesis in cucumber. With increasing light intensity, the rate of photosynthesis reached a plateau due to either CO_2 concentration and/or leaf temperature. Such plateau events may limit the effectiveness of CO_2 enrichment with changing environmental conditions and plant characteristics.

Table 12.8 Conversion Constants[a]

Light Source	Conversion Factors	
	400 to 700 nm[b]	*400 to 850 nm[c]*
Daylight (sun and sky)	0.20	0.30
Blue sky only	0.21	0.26
High-pressure sodium	0.13	0.20
Metal halide	0.15	0.18
Mercury halide	0.13	0.18
Warm white fluorescent	0.14	0.15
Cool white fluorescent	0.15	0.15
Standard Gro-Lux fluorescent	0.33	0.35
Wide Spectrum Gro-Lux fluorescent	0.20	0.23
Incandescent	0.22	0.54
Low-pressure sodium	0.10	0.12

[a] To obtain μmol/sec/m² measurements, multiply footcandles by the given conversion factor depending on the lamp type.

[b] See Glossary: Photosynthetically active radiation (PAR).

[c] See Glossary: Photomorphogenic radiation.

Source: Mpelkas, C.C., 1989, in *Electrical Energy in Agriculture,* McFate, K.L. (ed.), Energy in World Agriculture 3, Elsevier, New York.

Elber (1997) describes the various ways CO_2 can be introduced into the greenhouse by either frequent ventilation, use of fuel-burning generators (which can also generate unwanted heat and water vapor), or use of bottled-gas emitters. If a combustion technique is used to generate CO_2, care must be taken to ensure that complete combustion occurs. Incomplete combustion will release gases, such as ethylene (C_2H_4) and carbon monoxide (CO), into the greenhouse that will be harmful to plants as well as greenhouse workers, particularly if CO is released. Closed loop systems of CO_2 generation and distribution to the crop have been devised for special applications, but require efficient heating and cooling systems plus the ability to remove unwanted released moisture generated by combustion.

Since CO_2 is heavier than air, it is normally introduced at the top of the plant canopy, being then distributed by downward diffusion. In tall greenhouses (30 ft or more) with roof vents open, CO_2 can be introduced at the base of the canopy as it will then be carried slowly by the upward-moving air from the base of the plant canopy to its top, thereby enhancing photosynthesis. If a greenhouse requires frequent ventilation by bringing in outside air for cooling, the benefits of CO_2 enrichment will be minimized and the cost of generation may exceed that gained from whatever increase in plant growth and fruit yield occurs.

Johnson (2003) describes how a rose grower during the day from the generation of hot water (200°F; 93°C) in a gas-fired boiler draws CO_2 from an exhaust gas separator that is then introduced into the greenhouse. The stored hot water is used to heat the greenhouse at night. Similarly, the PTO growers are generating CO_2 from their natural gas heating system for introduction into their tomato greenhouse (Smith, 2003c).

Climatic Control

In order to maintain the desired environmental conditions for the crop being grown, the interior greenhouse environment needs to be constantly monitored and controlled (Beytes, 2003b). Sensors needed to monitor the greenhouse environment vary considerably in performance characteristics and cost. Many greenhouse control systems are based on devices that monitor some factor, such as air temperature, and then activate either heating or cooling devices in order to bring the temperature back to the set range or point (Roberts, 1985; Gieling, 1985). The sensitivity of the measuring device, placement in the greenhouse, and its response time will frequently result in a wide cycling character of the interior environment that may not be best for the growing crop.

Significant advances have been made in sensing devices, resulting in improved performance. Sensors that are coupled with computer-activated devices can "sense" a change and then activate those devices needed to maintain the environment at the desired level, thereby minimizing the cyclic character of the greenhouse environment. Lubkeman (1998) reported that "computer technology is helping to bring better-quality plants to market because it provides total control of the greenhouse environment." In his article, he describes devices to measure temperature, relative humidity, air movement, CO_2, lighting and light intensity, timers, and master controllers, all needed to provide the control needed to properly maintain the greenhouse environment. Computer control of greenhouse operations and management decisions has been found to reduce material and labor costs, reductions that can range from 15 to 83% (Lubkeman, 1999). Johnson (2000a) states that "central computer control is definitely the path greenhouse management is traveling into the future; it has already proven to be today's most competitive labor-saving tool." Today, the greenhouse operator has many different control systems to choose from, and the decision as to what system will work best for the greenhouse operation will require professional input. The proceeding of the 1994 Greenhouse Systems International Conference (Anon., 1994) includes papers that relate to methods and procedures for controlling the interior greenhouse environment.

The placement of sensing devices outside the greenhouse for measuring air temperature, wind velocity, and light intensity, for example, can provide useful information to the control system in the greenhouse, thereby minimizing the effect of external conditions on the environment inside the greenhouse.

Backup Systems

Alarm systems to notify off-site greenhouse managers and automated backup equipment should be standard equipment in any greenhouse. Failures are not always convenient; they do not necessarily occur only when workers are in the greenhouse or nearby so that immediate action can be taken. Many crops have been lost or severely damaged due to the loss of electrical power or mechanical failures when no quick-acting backup systems were in place. It can take only a few hours of power or mechanical failure when temperature extremes exist (either cold or hot) to significantly damage a crop. An electrical power failure left a hydroponic tomato grower having to use city water under hydrostatic head pressure since he was not able to operate his water/nutrient solution delivery system as well as obtain water from his reverse osmosis system. He did not have a backup electrical generating system and had not stored sufficient treated water to meet the demand during the period of the power failure. Fortunately, little damage occurred in his plants due to water stress and quality of the water applied. When treated water is needed for making a nutrient solution and watering plants, that quantity of water sufficient to meet several days' demand should be in storage. Depending on the electrical demand, it may be necessary to compromise on what would be needed to survive short periods of power loss in terms of generating capacity. Placement of a greenhouse in an area where frequent power failures occur would not be a wise decision. The failure of heating and cooling systems is a greater challenge in terms of having access to immediate service personnel and/or having spare parts available to quickly fix a failed unit. Having a contingency plan for all possible failures and known by all the greenhouse workers is essential.

Sanitation

Greenhouse design requirements to keep insects and other pests out pose a problem in controlling entrances into the greenhouse as well as sanitation-conscious management of the surrounding area. Disease organisms and insects can be easily brought into the greenhouse on almost any item (clothing, shoes, tools, bags, boxes, etc.); therefore, a need exists for strict sanitation procedures. Keeping walkways and outer edges of the greenhouse clean; prompt removal of dead, diseased, and insect-infested plant tissue; and the limiting of other activities (such as fruit sorting, weighing, packaging, etc.), are some of the requirements that will keep the greenhouse free of damaging infestations. The type of greenhouse flooring and its ease of being kept clean can significantly affect the ability to keep falling plant debris from becoming a source of disease and insect infestations (see Chapter 14). Standing water on the greenhouse floor or water movement up through the flooring material can significantly contribute to atmospheric humidity.

Some managers restrict movement in and out of the greenhouse by having workers spend their whole working day in the greenhouse. Removing street clothes and working in sanitized uniforms is not an uncommon practice. Having workers walk through a chemical footbath prior to entering the greenhouse will sterilize footwear. Managers often have strict policies on visitation by nongreenhouse workers. All these procedures are designed to minimize the potential for introducing insects, disease organisms, and other substances in the greenhouse that might adversely impact the enclosed crop. The author was once a member of a group of research scientists that made periodic visits to tomato greenhouses in the Cleveland, Ohio area. We had to carefully select our tour schedule since some greenhouse managers would not let us visit if we had previously been in greenhouses where a disease, tobacco mosaic virus, was suspected to exist.

The inside of the greenhouse provides an ideal environment for animals (mainly rodents) and ants, which are common invaders. Their presence may not pose an immediate danger to the crop itself, but they can do considerable damage to the greenhouse structure as well as damage electric cables, piping, and control equipment. They can also bring disease organisms, insects, and weed seeds into the greenhouse from outside.

Proactive Management

Being proactive in responding to changing conditions in the greenhouse rather than attempting to control a problem after it appears can save a crop. This is particularly important when dealing with pests by daily observation and monitoring. In addition, the periodic application of pest-control chemicals can protect the crop from possible infestation. As seasonal light and external temperature conditions change, timely adjustments in scheduling crop management procedures will ensure minimum crop effects due to these changes. Being timely and following a preplanned schedule of procedures is far better than "winging it" day by day.

Winter Greenhouse Preparation

Richerson (2002) gives specific instructions for preparing the greenhouse for winter production by climatic zones. The three main requirements are scrubbing in order to disinfect the interior, caulking and repairing the glazing materials, and closing the greenhouse for a few hours to "cook" at a temperature level just below 100°F (37°C). Specific instructions are given for each climatic zone [1–4, 5–7, 8–9, and 10–11 (Figure 12.19)] in which the greenhouse may be located in order to prepare it for the growing season.

Controlled Environment Agriculture (CEA)

Controlled environment agriculture (CEA) is a science that describes systems of protected agriculture for the ultimate in environmental control at both the aerial and root levels. Such systems are found in many greenhouses and for all totally enclosed structures. The range of control includes air and root temperature; atmospheric humidity; atmospheric gas composition; light intensity, wavelength composition and duration; water supply and quality; growing

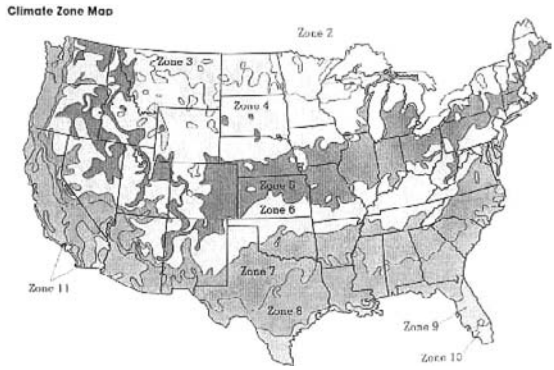

Figure 12.19 Climatic zones for the continental United States.

medium; and plant nutrition. In the Foreword of a Protected Agriculture World Bank technical paper by Jensen and Malter (1995), it was stated that the success of CEA "is very much dependent on the level and quality of applied technology." The NRAES-72 publication (Anon., 1994a) includes chapters on the design and fundamental operational procedures for CEA greenhouses. Jensen (1997) states that there are many types of controlled environment hydroponic systems, and "if improper attention is given to the greenhouse structure and its environment, no hydroponic system will prove economically viable."

Wignarajah (1995) listed six major advantages of crop production in controlled environments:

- The ability to increase photosynthetic productivity through the use of increased light supply and high CO_2 supply
- Minimization of water use by condensing the transpired water and reusing it in the production of the nutrient media for the plant
- Use of smaller space for production
- Production of consistently predictable high yields with time
- Uniform, high-quality product — an important factor in the modern consumer market
- A cleaner environment ensured through effective control of input and output requirements

He also stated two disadvantages: relatively high production costs and areas of lack of sufficient knowledge and technology for crop production in controlled environmental systems.

Another objective of CEA systems is to remove the grower from having to make decisions based on past experiences and current judgment, instead relying on computer-based instructions that have been programmed from designed models based on experimental research and long-term practical results.

The Greenhouse and Processing Crops Research Centre (GPCRC) in Harrow, Ontario, Canada is active in developing "computerized environmental, irrigation, and fertilization control systems, combined with advanced research into biological control and disease management for growing of tomato and cucumber" (Spillane, 2002). The Cornell Controlled Environment Agriculture (CEA) Center is "engaged in state-of-the-art agricultural technology, innovative greenhouse design, and computerized efficiency to create a perfect demonstration and learning model for high-tech hydroponics" (Alexander, 2001b; Meade, 2002b). In the Cornell CEA Center, the crop under study is lettuce being grown using a styrofoam raft system, a growing method described in some detail by Morgan (2002f) and used to produce lettuce and salad greens in a Quebec, Canada greenhouse (Spillane, 2001).

The University of Arizona's CEA Center was established in 1999 to "fill an urgent need for fundamental information in this rapidly advancing technology — the heart of hydroponics and other controlled environments applications" (Jensen and Silberstein, 2000). The Center's activities include educational training for college students as well as those in community colleges and high schools as well as sponsoring a national hydroponics conference called "Science Alive" (Brentlinger, 2001; Alexander, 2002; 2003).

Advances made in CEA are best illustrated in the developments that are occurring in the greenhouse/hydroponic industry in the Netherlands, where computerization of the entire production system is employed (Nederhoff, 2001). The designed system will allow the grower to enter the desired goals and the computer, using predetermined models, will regulate all phases of the production program. Nederhoff (2001) describes an installed Path registration computer system that records crop data in specified areas of the greenhouse, enabling the grower to pinpoint weak spots by continuous recording of plant growth and fruit yield as well as data on pests and diseases. Problems occurring in any section of the greenhouse or production system can be quickly identified for corrective application to the current crop. In addition, the obtained data and observations can be added to computer models that generate production management instructions.

In a recently published interview (Peckenpaugh, 2004), Dr. Otmar Silberstein, a founding member of the Hydroponic Society of America, stated that "ultra-modern greenhouses embody the latest technologies of controlled environments and new plant varieties take full advantage of these controls to optimize yield and quality. Hydroponics is emerging fully from age-old, traditional agriculture in which change, though dramatic in some cases, was slow." He concluded with "hydroponics is indeed a multifaceted, ever changing wave that's breaking on an increasing number of shores around the world. And the future is going to arrive in the present sooner than many of us think."

The Hobby Greenhouse

For the hobby grower, having a greenhouse structure for use in the cool or cold seasons of the year provides enjoyment as well as the ability to grow plants either for beauty or to provide a supply of off-season vegetables. For some, the greenhouse may only be used to start plants for summer growing or to extend the growing season for potted plants. The author knew an Ohio resident who wanted a fresh rose on her breakfast table every morning, a feat that required considerable skill and the requirement of a greenhouse for flower production during the winter months. Beginning with a small greenhouse, hobbyists can determine whether they have the desire and skill to enter into the commercial production of plants at some future time.

There are many structural choices in the design, size, glazing, and control features available for hobby greenhouses (Knutson, 1997). The greenhouse may be attached to another building (home, garage, or outbuilding) (Johnson 2002a) or be a window greenhouse or a stand-alone structure. Depending on the size and type, the greenhouse may be a solar house (Kubiac, 1999b; Johnson, 2000b; Garzoli, 2001), or one with heating and cooling capabilities in order to precisely control the interior environment. Bartok (2000) has written an excellent manual to guide users in determining what type of structure will best meet their need and then provides instructions on how to successfully manage a greenhouse. Bartok (2000) describes six greenhouse styles:

Gable (sloping, flat roof panels and vertical sides)
Slant-leg (flat, sloped roof panels attached to a sloping side wall)
A-frame (easy-to-build style)
Hoop (formed by covering bent pipe or tubing with a flexible plastic cover)
Gothic (roof and walls form a continuous shape)
Dome (made by connecting triangles together)

As was stated earlier, there is nothing unique about hydroponics that would require a specially designed hobby greenhouse other than size to accommodate the hydroponic system selected and if control of the interior environment is essential for successful plant production.

Bridgewood (2001) grows tomatoes and other plants in a geodesic greenhouse that is 10 ft 2 in (3.05 m) in diameter with automatic vents at the top, a "solar dome greenhouse that is designed to maximize available solar radiation; its unique design means that one or more panes of glass are always facing the sun."

CropKing's Sanctuary Hobby Greenhouse (Simon, 2004) is an excellent example of a greenhouse that offers the hobby grower a complete package of options that can be chosen depending on its use (for general or specific plant production) and location (warm or cool climates) (Figure 12.20).

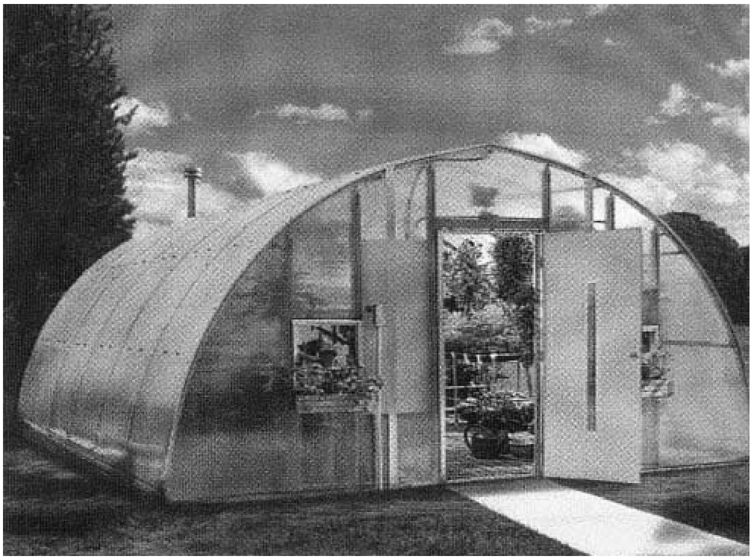

Figure 12.20 The CropKing Sanctuary Greenhouse.

Solar Greenhouse

A greenhouse is an excellent solar collector as entering radiation energy will warm the interior, giving rise to the term "hothouse" as a definition. Therefore, any greenhouse structure could be termed as being "solar." However, the term "solar greenhouse" normally refers to a structure that is entirely heated by solar means. For the solar greenhouse, its climatic location (solar energy input) and placement, glazing, and sun angle and the use of heat-storage devices can determine how efficiently the house will perform (Bartok, 2000). The books by Yanda and Fisher (1980) and Fuller (1999) describe the design, construction, and operation of a solar greenhouse. Johnson (2002a) describes the requirements for building a passive solar greenhouse with "glazing oriented toward the southern exposure of the sun in the winter when the sun is low in the sky." The glazed wall should be oriented directly at the sun at noon on December 21. In a *Virginia Gardener Newsletter,* it was stated, "the area of glazing should collect enough heat during a clear winter day to keep both the greenhouse and adjoining space at an average temperature of 60 to 70°F (15 to 21°C) during the day." In colder climates, double glazing of the solar greenhouse is recommended, plus the use of thermal blankets.

Yanda and Fisher (1980) advise that "a side view of the greenhouse cut out of paper is helpful in determining light patterns through clear roof areas and sides" (Figure 12.21). "By repositioning the solid/clear areas in the model, one should be able to get maximum winter sunlight for your location and also obtain some summer shading." Garzoli (2001) describes various solar means of heating a greenhouse with the use of solar collectors to heat air or water, and then storing the heat generated for later use. Various passive systems are also described for collecting, storing, and using heat.

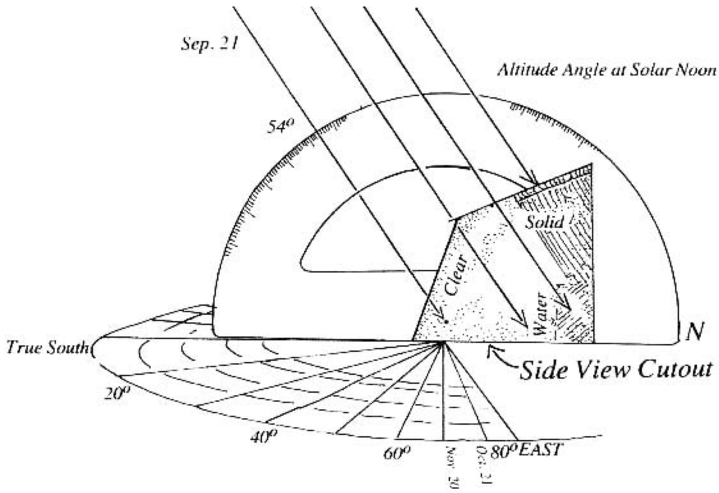

Figure 12.21 Side view of the greenhouse cut-out paper helpful in determining light patterns. ***Source:*** **Yanda, B. and Fisher, R., 1980,** ***Solar Greenhouse: Design, Construction and Operation,*** **John Muir Publications, Santa Fe, NM.**

An efficient solar greenhouse has sufficient thermal mass (water and rocks are the most commonly used primary collectors) to collect, store, and then release the collected passive solar heat at night. The darker the color of the thermal collector, the more efficient it becomes. In cool and cold climates, the nighttime temperature can drop to between 40 and 45°F (4.4 and 7.2°C); therefore, additional heat may be necessary to keep certain plants healthy and productive.

Since passive solar greenhouses will be warmer in the summer and cooler in winter than conventionally heated or cooled greenhouses are, crop selection must be confined to those crop species with wide temperature tolerance. During the day on bright sunny days, the air temperature may reach 85 to 90°F (29 to 32°C), while the nighttime temperatures may drop to 40 to 45°F (4.4 to 7.2°C). Johnson (2000b) lists from excellent to poor the suitability of crops for a solar greenhouse:

Excellent	*Good*	*Fair*	*Poor*
basil, celery, dill, fennel, kale, leaf lettuce, marijoram, mustard greens, oregano, parsley, spinach, Swiss chard	cabbage, collards, garlic, green onions	broccoli and edible pea pods, eggplant, leek	beans, carrots, corn, radishes, turnips

If air temperatures can be maintained away from the extremes given above, crops such as cherry and large fruit tomato, European cucumber, and pepper can be successfully grown in a passive solar greenhouse or if some degree of temperature control is used.

The Solviva Greenhouse

"By using the latest technologies — glazing, insulation, vapor barrier, fans, pumps — combined with age-old common-sense methods such as letting in the sun, protecting from the north, and using animal heat as well as natural aero- and thermo-dynamics, we have indeed created something new under the sun," stated Edey (1994) when describing the Solviva greenhouse. In addition, Edey (1994) said that, "over the years, the Solviva greenhouse has become widely acknowledged as being not only the most energy-efficient and least polluting greenhouse in the world, but also the most productive." Details on the design and operation of the Solviva greenhouse are given by Edey (1994).

The Ideal Greenhouse

No single style or size configuration would conform to what could be defined as the ideal greenhouse. The ideal greenhouse does not exist, as most structures and the devices and systems needed to control the greenhouse environment are the result of compromises based on a number of factors. Location and use determine most of the features found in a greenhouse. The structural and environmental control requirements for use in a cold climatic region (Morgan, 2001b) are quite different than those for a greenhouse located in a moderate winter climatic region, in which its primary period of use occurs during warm to hot days (Morgan 2001a). It should be remembered that a greenhouse is an excellent solar collector; its efficiency as a collector is determined to some degree by its glazing, which determines light transmission and spectral filtering (Coene, 1995; Morgan, 2003a). In a cold climatic region, the greenhouse design must be able to keep heated air in and cold air out. In a warm climatic region, the ability to efficiently ventilate the greenhouse is the primary factor. Little can be found in the literature on the design and operational requirements in those climatic regions that have extremes in both temperature and light intensity during the growing season.

In order to control out-radiation (keeping warm air inside and cold air outside), thermal blankets can be effectively used, while in order to keep excessive radiation from entering the greenhouse, shading is required. In both instances, being able to easily put in place or remove either thermal blankets and/or shade material becomes essential in order to best control the inside environment; this feature that is not commonly found in commercially available greenhouses.

The proper sizing of heating and/or cooling systems is critical in order to ensure adequate control of the inside air temperature. The ability to evenly heat and ventilate the entire mass of air in the greenhouse is a significant challenge. The best system of air movement and distribution would be to have conditioned air introduced up through the floor of the greenhouse and then vent stale hot air from the greenhouse either by openings in the roof or by air movement in the shortest distance possible by cross-flow ventilation.

Common Errors Made in the Design and Operation of a Greenhouse

1. Failure to take into consideration extremes in weather events (i.e., wind, snow, and hail) in the design and strength of the physical structure
2. Site selection that fails to take into consideration the surrounding environment
3. Failure to keep the area around the greenhouse free from substances that might enter the greenhouse and damage the enclosed crop
4. Undersizing heating and cooling systems
5. Failure to keep the greenhouse structure in a high state of repair
6. Inadequate control of the entrances, thereby allowing pests access to the greenhouse
7. Failure to adequately sanitize the greenhouse between crops
8. Inadequate control devices that do not respond quickly to changing conditions inside and outside the greenhouse
9. Lack of fail-safe or backup devices to maintain the greenhouse operation during periods of extreme weather conditions, power failures, mechanical failures, etc.
10. Lack of alarm systems to alert the greenhouse manager of a problem when off site
11. Not being proactive in the control of insect and disease infestations
12. Failure to utilize professional resources particularly for identifying and applying control measures for disease and insect infestations and nutritional problems
13. Failure to use strict criteria in the selection of greenhouse managers and workers
14. Lack of a continuous training and supervision program for greenhouse workers in the techniques of greenhouse operations and proper crop management procedures
15. Failure to adopt new technology promptly

Chapter 13

Diagnostic Testing Procedures

Success with any growing system is based to a considerable degree on the ability of the grower to effectively evaluate and diagnose the condition of the crop at all times (Roorda and Smilde, 1981; Paterson and Hall, 1981; 1993a). This is particularly true for the hydroponic/soilless culture and absolutely essential for the hydroponic grower, since all the essential elements except C, H, and O required by plants are being supplied by means of a nutrient solution. Errors in making and using the nutrient solution will affect plant growth, sometimes within a matter of a few days. Some growers possess a unique ability to sense when things are not right and take the proper corrective steps before significant crop damage is done. Most, however, must rely on more obvious and objective measures to assist them in determining how their growing system is working and how plants are responding to their management inputs. In the latter case, no substitute for systematic observations and testing exists. As the genetic growth and fruit yield potential of a crop is approached, every management decision becomes increasingly important. Small errors can have a significant impact; therefore, every task needs to be performed without error in timing or process. Under such conditions, nutritional management is absolutely essential.

Laboratory testing and diagnostic services are readily available in the United States and Canada (Anon., 1992) as well as other parts of the world. Samples can be quickly and easily sent to a laboratory from almost anywhere. Once the laboratory selection has been made, it is important to obtain from the laboratory its instructions for collecting and shipping samples before sending them. It also important that the laboratory selected to do the analytical work is familiar with the type of samples being submitted, and if an interpretation is to be made, that those making the interpretation are skilled analysts.

With the analytical capabilities available today, together with the ease of quickly transporting samples and analysis results, growers can almost monitor their plant growing system on a real-time basis. Although a routine of periodic testing is time consuming and costly, the application of the results obtained can more than cover the costs in terms of a saved crop and superior quality production. The grower should get into the habit of routinely analyzing the water source, nutrient solution, growing media, and crop. Interpretations and recommendations based on assay results are designed to assist the grower in order to avoid crop losses and product quality reductions.

Water Analysis

Water available for making a nutrient solution or for irrigation may not be of sufficient quality (i.e., free from inorganic as well as organic substances) to be suitable for use. Pure water is not essential, but the degree of impurity needs to be determined. Even domestic water supplies, although safe for drinking, may not be suitable for plant use. Water from surface ground water sources, ponds, lakes, and rivers is particularly suspect, while collected rainwater and deep-well water are less so.

For the elements, the presence of Ca and Mg could be considered complementary because both elements are essential, whereas the presence of B and Na, and the anions CO_3^{2-}, HCO_3^-, Cl^-, F^-, and S^- could be considered undesirable if levels are relatively high. The maximum concentrations of these elements and ions in irrigation water and water for making a nutrient solution have been established as presented in Chapter 7.

The only way to determine what is in the water is to have it assayed. Testing for the presence of organic constituents is a decision that is based on expected presence. Surface waters may contain disease organisms and algae, while in agricultural areas, various residues from the use of herbicides or other pesticides may be in the water. Tomato, for example, is quite sensitive to many types of organic chemicals; therefore, their presence in water could make its use undesirable, particularly for this crop.

Knowing what is in the water will determine whether it is acceptable with or without treatment and whether adjustments would be required to compensate for constituents that are present (see page 72–76).

Nutrient Solution Analysis

Errors in the preparation of a nutrient solution as well as in the functioning of dosers (Christian, 2001; Smith 2001f) are not uncommon; hence the requirement for an analysis to check on the final elemental concentrations prior to use. Since the elemental composition of the nutrient solution can be altered considerably in closed recirculating systems, it is equally important to monitor the composition of the solution as frequently as practical. A record of the analysis results should be kept and a track developed to determine how the concentration of each element changes with each passage through the rooting media. On the basis of such analyses, change schedules, replenishment needs, and crop utilization patterns can be determined.

The track establishes what adjustments in the composition of the nutrient solution are needed to compensate for the "crop effect," not only for the current crop but for future crops as well.

In addition, periodic analysis allows the grower to properly supplement the nutrient solution in order to maintain consistent elemental levels to ensure good crop growth as well as extend the useful life of the nutrient solution. Significant economy can be gained by extending the life of the nutrient solution in terms of both water and chemical use.

Water and Nutrient Solution Analysis Methods

It is now possible to continuously monitor the nutrient solution with devices such as specific ion (Figure 13.1), pH (Figure 13.2), and conductivity meters (Figure 13.3) (Raper, 1987). The grower needs to determine how best to monitor the nutrient solution based on cost and the requirement of the selected growing system.

Figure 13.1 Horiba specific ion electrode meter. There are three different meters, one for determining nitrate (NO_3), one for potassium (K), and another for calcium (Ca). The K- and Ca-specific ion meters require some sample manipulation to ensure that reliable analytical results are obtained.

Figure 13.2 Single body pH meter. A wide variety of pH meters can be used to determine the pH of water and nutrient solutions. The reliability and accuracy of determinations will depend on how the meter is used and stored between use. The meter requires calibration with each use.

Electrical conductivity (EC) is frequently used as a means of determining elemental replenishment needs in closed recirculating nutrient solution growing systems (see page 106). This technique is useful if previous knowledge is available as to which elements are likely to change and by how much. It is far more desirable to do an elemental analysis that quantifies each individual element and its ratio in the nutrient solution so that specific adjustments can be made to bring the nutrient solution back to its original composition.

The analysis of the nutrient solution should include pH and tests to determine the concentration of the major elements N (i.e., NO_3 and NH_4), P, K, Ca, and Mg. Although laboratory analysis is recommended, on-site analysis is possible with the use of kits and relatively simple analytical devices (Schip-

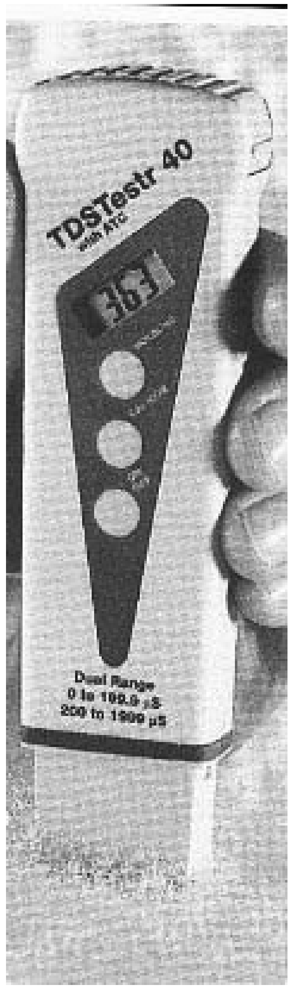

Figure 13.3 Single body conductivity meter. Other similar meters are available. Most conductivity meters can also be used to measure TDS (total dissolved solids).

pers, 1991; Hershey, 1992b). These determinations also can be made on-site by the use of a HACH Chemical Company Water Analysis Kit.[1] Although test kit procedures are available for determination of some of the micronutrients, laboratory analysis is recommended. However, concentration monitoring of the micronutrients is not as critical as monitoring of the major elements unless a micronutrient problem is suspected. For any diagnostic problem, laboratory analysis is always recommended, including all the essential elements — both the major elements and micronutrients.

[1] HACH Chemical Company, P.O. 389, Loveland, CO 80539.

Sampling Procedures

If a sample is to be collected for a laboratory analysis, it is best to contact the laboratory beforehand to obtain their recommended sampling (volume of solution required) and shipping procedures. A directory/registry of analytical laboratories that specialize in water and nutrient solution assays has been published for the United States and Canada (Anon., 1992). Keeping the water and/or nutrient solution sample from being contaminated is essential; therefore, clean sampling devices and sample bottles should be used. One of the best sampling/shipping bottles is a new baby formula bottle. Remove the rubber nipple and tightly seal the lid after the sample has been drawn. When drawing a water sample or nutrient solution, run the water or nutrient solution for a few minutes, fill the bottle, dump, and then fill the bottle again.

Elemental Analysis of the Growth Medium

Elemental analysis of plant growth medium is an important part of the total evaluation of the elemental status of the medium-crop system. When coupled with a plant analysis, it allows the grower to determine what elemental stresses exist and how best to bring them under control. This analysis may be comprehensive, to determine the concentration present in the growth medium by element, or more general, measuring the total soluble salt (EC measurement) content of effluent from the medium or by extraction of an equilibrium solution. A comprehensive test is more valuable as a means of pinpointing possible elemental problems than just a determination of the EC of the effluent or extracted solution.

A test of an inorganic growth medium, such as gravel, sand, perlite, or rockwool, measures the accumulation of salts that will significantly affect the elemental composition of the nutrient solution being circulated through it. Knowing what is accumulating in the growth medium, it then becomes possible to alter the nutrient solution composition sufficiently to utilize the accumulated elements or to begin to make adjustments in the nutrient solution formula with the idea of reducing the rate of accumulation while partially utilizing those elements already present in the medium.

For those using perlite in bags or buckets or rockwool slabs, the recommendation today is to periodically draw solution with a syringe from the bag or bucket or slab for assay. Based on either a complete analysis of this solution or only its EC, water leaching may be recommended to remove accumulated salts. In some management schemes, leaching of the growth medium is performed on a regular basis as a matter of normal routine. Systems using regularly scheduled leaching should also be subjected to periodic analysis of the growth medium effluent to confirm that the leaching schedule is in fact doing the job intended.

For an organic growth medium, such as peat mixtures or composted milled pinebark, the sampling and assay procedures are quite different. Monitoring of the medium is not necessary as a matter of routine, but an assay should be made at its initial use, whenever plant stress appears, or when a significant change in a cultural practice occurs. Cores of media taken to the rooting depth or to the bottom of the growing vessel are randomly collected and composited, and the composite sample sent to the laboratory for analysis. The various methods of extraction and analysis of soilless organic media can be found in the laboratory guide by Jones (2001). The ranges in concentration for the various elements, pH, and soluble salts have been established by researchers at Michigan State University (Warnke, 1986), as shown in Table 13.1.

Although the testing procedures are quite different for each growing medium, the objective of the analysis is the same: determine the pH and elemental status of the medium for diagnostic evaluation. The elements present in the growth medium serve as a major contributor toward meeting the crop requirement. Therefore, one objective for an analysis is to determine the level of each of the essential elements in the growing medium that will contribute toward satisfying the crop requirement.

The other purpose of medium analysis is to track preferential element accumulation by the medium. In systems where the bulk of the elemental requirement is supplied by the nutrient solution, growth medium analysis serves to determine accumulation rates so as to avoid imbalances and potential toxicities. In such cases, an EC measurement of the effluent from the medium, or an extraction of it, is not sufficient.

By tracking, the elemental composition of the growth medium can be followed and adjustments made based on changing concentrations away from or beyond the sufficiency range. Therefore, these periodic analyses become the means for regulating the input of the essential elements in order to prevent deficiencies or excesses from occurring.

Plant Analysis

The objective of a plant analysis (sometimes referred to as leaf analysis) is to monitor the elemental content of the plant in order to ensure that all of the essential elements are being supplied in sufficient quantity to satisfy the crop requirement as well as ensuring against elemental imbalances and excesses (Berry and Wallace, 1981; Faulkner, 1993; Mills and Jones, 1996; Reuter and Robinson, 1997). The grower should develop a routine of sampling and analysis during critical periods in the growth cycle (Bloom, 1987; Mills and Jones, 1996; Jones, 2003). Such a system of periodic sampling and analysis based on various stages within the growth cycle has been suggested by Tapia (1985) for tomato and pepper as shown in Table 13.2 and Table 13.3, respectively. These tables are given as only an example of what is available in the literature, which is quite extensive on the use of plant analysis as a diagnostic and monitoring tool.

Unfortunately, plant analysis has largely been thought of as a diagnostic device, while its usefulness for monitoring is of greater significance. The procedure of routine sampling and analysis is frequently referred to as "tracking." Tracking provides the information needed to establish what nutrient

Table 13.1 Interpretation Levels for Five Test Parameters for Organic Rooting Media Analyzed by the Saturated Extract Method

	Category (mg/kg, ppm)				
Test Parameter	*Low*	*Acceptable*	*Optimum*	*High*	*Very High*
Nitrate-N	0–39	40–99	100–199	200–299	300+
Phosphorus (P)	0–2	3–5	6–9	11–18	19+
Potassium (K)	0–59	60–149	150–249	250–349	350+
Magnesium (Mg)	0–29	30–69	70+		
Soluble salts (mS/cm)	<0.75	0.75–2.0	2.0–3.5	3.5–5.0	5.0+

Source: Warnke, D.D., 1988, in W.C. Wahnke (Ed.), Recommended Chemical Soil Test Procedures, North Central Regional Publication No. 221 (revised), North Dakota Agricultural Experiment Station, Fargo, ND.

Table 13.2 Stages of Tomato Plant Development When Leaf Tissue Is to Be Collected for Elemental Content Evaluation

Sampling Number	*Development Stage*
1	Four to five true leaves
2	Eight true leaves
3	First cluster in anthesis
4	Second cluster in anthesis and first cluster with set fruits
5	Third cluster in blossom, second cluster in anthesis, first cluster with developing fruits
6	Third cluster in anthesis, second and first clusters with developing fruits, fourth and fifth clusters in blossom
7	Fourth cluster in anthesis
8	Fifth cluster in anthesis
9 to 12	Full production stages

Source: Tapia, M.L., 1985, in A.J. Savage (Ed.), *Hydroponics Worldwide: State of the Art in Soilless Crop Production,* International Center for Special Studies, Honolulu, HI.

solution management procedure is required to ensure that all of the essential element levels are within the sufficiency range for the crop being grown. It is well worth the time and expense to develop a track of elemental sufficiency in order to firmly establish the proper nutrient solution management system for future use.

The diagnostic role for plant (leaf) analysis is equally important. A grower faced with a suspected essential element deficiency or imbalance should verify the suspected insufficiency by means of plant (leaf) analysis. Many symptoms of elemental stress are quite similar and can fool the best-trained grower or advisor. In addition, some stress conditions can be due to the relationship between or among the elements and therefore may require more than just a minor change in the nutrient solution formula to correct them. Without an analysis result, a change could be made which would only further aggravate the problem. An excellent review on the principles and practice of plant

Table 13.3 Stages of Sweet Pepper Plant Development When Leaf Tissue Is to Be Collected for Elemental Content Evaluation

Sampling Number	*Development Stage*
1	Four to six expanded leaves
2	Seven to nine expanded leaves
3	First flower in blossom
4	Five to thirteen flowers in blossom
5	One to thirteen flowers in anthesis
6	Full anthesis and starting set fruits
7	Full set fruits
8	Developing fruits
9 to 10	Full production stages

Source: Tapia, M.L., 1985, in A.J. Savage (Ed.), *Hydroponics Worldwide: State of the Art in Soilless Crop Production,* International Center for Special Studies, Honolulu, HI.

analysis has been given by Munson and Nelson (1990). The techniques of sampling, handling, and analyzing plant tissue have been reviewed by Jones and Case (1990). Methods of plant tissue sampling, analysis, and assay utilization are covered in the books edited by Kalra (1998) and Reuter and Robinson (1997).

Since a plant leaf analysis requires the use of a competent laboratory, contact with the laboratory should be made before samples are collected and sent. Most laboratories have specific sampling and submission procedures, which are important to follow. Sampling procedures for several commonly grown hydroponic crops are given in Table 13.4. It is important to remember that different plant parts are not to be mixed together, such as leaves and stems or petioles, or to use a whole plant as that sampled unless the plant is in its seedling stage of growth. Roots also should not be a part of a sample collected for analysis.

If no specific sampling procedures are given or known for a particular plant, including the time for sampling, the rule of thumb is to collect recently mature leaves below the growing point. Normally, the times for sampling are scheduled at major changes in the growth cycle, such as at flowering and initial fruit set. In addition, these same sampling procedures should be followed if the plant is being monitored periodically over the course of its life cycle, a procedure necessary to maintain a track of the elemental content of the plant.

For diagnostic testing, when visual symptoms of plant stress are evident, it is advisable to take similar plant tissues from both affected and normal plants. In this way, a comparison of analytical results can be made, which is far more helpful in the interpretation than just an analysis of the stressed plants alone.

Great care should be used when selecting plants for sampling as well as when selecting the plant part. In addition to what should be sampled, there are also avoidance criteria as to what not to sample or include in the sample:

Table 13.4 Recommended Leaf Sampling Procedures for Cucumber, Lettuce, Pepper, and Tomato

Crop	*Plant Part*	*Time*	*Number of Plants to Sample*
Cucumber	Fifth leaf from top	First fully developed	12
Lettuce	Wrapper leaf	Mature	12
Pepper	Recent fully developed leaf	First bloom	25
	Recent fully developed leaf	Mid-season	25
Tomato	Leaf tip opposite and below most recent fruit cluster (see Figure 13.4)	When setting fruit	12

- Diseased, insect-damaged, or mechanically damaged plants or tissues
- Dead plant tissue
- Dusty or chemical-coated tissue

Tissue that is covered with dust or chemicals can be decontaminated by careful washing using the following procedure:

- Prepare a 2% detergent solution and place in a large container.
- Place the fresh leaf tissue in the detergent solution and gently rub with the fingers for no longer than 15 sec.
- Remove the tissue from the detergent solution and quickly rinse in a stream of flowing pure water.
- Blot dry with a clean cloth or paper towel.

Great care is needed to ensure that the tissue being "washed" is not being contaminated by some other substance present in the wash water or by contact with other substances or that the elements K and B are not being lost from the tissue in the washing process, as both can be easily leached if the time washing and rinsing with water is longer than that specified in the instructions.

Once the tissues have been collected, it is best to air dry them (one day in the open air is usually sufficient) before shipping to the laboratory for analysis. This will keep them from rotting while in transit, as any loss in dry weight will affect the analysis result. Details on sampling, sample preparation, and analysis of plant tissue have been given by Jones and Case (1990) and Jones (2001).

The interpretation of an analysis result is performed by comparing the assay results obtained with established critical values or sufficiency ranges; the latter are more commonly used (Martin-Prevel et al., 1987; Jones et al., 1991; Walinga et al., 1995; Mills and Jones, 1996; Reuter and Robinson, 1997). Categories of sufficiency for bell pepper, cucumber, lettuce, and tomato from a number of

Table 13.5 Elemental Concentrations in Upper Fully Developed Leaf of Bell Pepper for Diagnostic Evaluation

Element	*Low*	*Sufficient*	*High*
Major Elements		**% Dry Weight**	
Nitrogen (N)	3.00–3.49	3.50–5.0	>5.0
Phosphorus (P)	0.18–0.21	0.22–0.7	>0.8
Potassium (K)	3.00–3.49	3.50–0.5	>4.5
Calcium (Ca)	1.00–1.29	1.30–2.8	>2.8
Magnesium (Mg)	0.26–0.29	0.30–1.0	>1.0
Micronutrients		**ppm Dry Weight**	
Boron (B)	23–24	25–75	>75
Copper (Cu)	4–5	6–25	>25
Manganese (Mn)	4–49	50–250	>250
Zinc (Zn)	18–19	20–200	>200

Source: Mills, H.A. and Jones, J.B., Jr., 1996, *Plant Nutrition Handbook II*, MicroMacro Publishing, Athens, GA.

Table 13.6 Criteria for Interpretation of a Foliar Analysis for Greenhouse Tomato

	Normal Range	
Element	*Before Fruiting*	*Fruiting*
Major Elements	**% Dry Weight**	
Nitrogen (N)	4.5–5.0	3.5–4.0
Phosphorus (P)	0.5–0.8	0.4–0.6
Potassium (K)	3.5–5.0	3.0–4.0
Calcium (Ca)	0.9–2.0	1.0–2.0
Magnesium (Mg)	0.5–1.0	0.4–1.0
Sulfur (S)	0.3–0.8	0.3–0.8
Micronutrients	**ppm Dry Weight**	
Boron (B)	33–60	35–60
Copper (Cu)	8–20	8–20
Iron (Fe)	50–200	50–200
Manganese (Mn)	50–125	50–125
Zinc (Zn)	25–100	25–100

Source: Faulkner, S.P., 1993, *The Growing Edge* 4(1):24–28, 67–68.

sources are given in Table 13.5 through Table 13.8. Note that these interpretative ranges relate to a specific plant part taken at a designated time period or stage of growth. Therefore, these interpretative ranges are not applicable to other types of plant tissues or those taken at a time other than that given in these

Figure 13.4 Proper tomato leaf sample for nutritional evaluation. The tomato leaf is a compound leaf; the proper sample is the end terminal leaf as shown in this photograph. The selected leaf for sampling should be a recently mature leaf, usually just above the fruit cluster just being set. Only the end leaf as shown is removed from the plant.

tables. This is why it is important to follow given sampling instructions, so that the analytical results obtained can be interpreted based on established sufficiency ranges. For example, the proper sample to be taken for tomato is the tip leaf from a recently fully matured leaf as shown in Figure 13.4.

Tissue Testing

Plant analysis is basically defined as a testing method for determining the total elemental content based on a laboratory analysis of collected plant tissue, whereas a tissue test is conducted on extracted plant sap or an extraction of a particular plant part; the test is done on site using specially designed kits. For more comprehensive tests, the methods given with use of the HACH kit can be used. There are other analysis kits available on the market; some are sound and some are not. Cost can be a measure of quality; low-cost kits are usually of questionable use and value. Schippers (1979) and Hershey (1992b) have described analytical procedures that can be conducted using relatively simple analytical procedures and devices.

TABLE 13.7 Elemental concentrations in first fully developed cucumber leaves used for diagnostic evaluation

Element	*Low*	*Sufficient*	*High*
		%, Dry Weight	
Major Elements			
Nitrogen (N)	3.50-4.29	4.30-6.0	>6.0
Phosphorus (P)	0.25-0.29	0.30-0.7	>0.7
Potassium (K)	2.00-3.09	3.10-5.5	>5.5
Calcium (Ca)	1.50-2.49	2.50-4.0	>4.0
Magnesium (Mg)	0.25-0.34	0.35-1.0	>1.0
Sulphur (S)	<0.40	0.40-0.7	>0.7
Micronutrients		**mg/kg, ppm, Dry Weight**	
Boron (B)	25-29	30-100	>100
Copper (Cu)	6-7	8-10	>10
Iron (Fe)	35-49	50-300	>300
Manganese (Mn)	25-49	50-300	>300
Moplybdebum (Mo)	0.40-0.7	0.8-3.5	>3.5
Zinc (Zn)	18-24	25-200	>200

Source: Mills, H. A and Jones, J.B., Jr., 1996, *Plant Analysis Handbook II*, Micro-Macro Publishing, Athens, GA, 1996.

A tissue test is usually made using conductive tissue, such a petioles, leaf mid-ribs, or plant stalks. The commonly determined elements are:

- Nitrogen as nitrate (NO_3)
- Phosphorus as phosphate (PO_4)
- Potassium (K^+)
- Iron (Fe^{3+})

These "quick tests," as they are frequently referred to, can be useful in certain circumstances (Scaife and Stevens, 1981), but they are not to be used as substitutes for a laboratory-conducted analysis. Although the test procedures themselves may be relatively easy to conduct, the difficulty comes in interpreting the results, as it takes considerable skill and practice to be able to use tissue test results effectively. In addition, the user needs to have suitable standards available to ensure that the results obtained are analytically correct.

Other Analytical Devices

With the rapid developments that are being made in all aspects of analytical and diagnostic chemistry, various types of testing kits and devices are coming into the marketplace, which can have application for the hydroponic/soilless

TABLE 13.8 Elemental concentrations defining deficient, normal and toxic levels in lettuce leaves.

Element	*Deficient (less than)*	*Normal Range*	*Toxic (more than)*
Major Elements		**%, Dry Weight**	
Nitrogen (N), total	--	2.1-5.6	--
Nitrate-N (NO3-N)	--	2.5-9.3	--
Phosphorus (P)	0.4	0.5-0.9	--
Potassium (K)	4.0	4.0-10.0	--
Calcium (Ca)	0.8	0.9-2.0	--
Magnesium (Mg)	0.3	0.4-0.8	--
Sulfur (S)	0.2	0.2-0.5	--
Micronutrients		**ppm, Dry Weight**	
Boron (B)	22	25-65	300
Iron (Fe)	*	50-500	--
Manganese (Mn)	22	25-200	250
Copper (Cu)	2.5	5-18	--
Zinc (Zn)	25	30-200	350
Molybdenum (Mo)	0.2	0.5-3.0	--

*Not diagnostic.

Source: Gerber, J.M., Plant growth and nutrient formulas, pp. 58–59 in A.J. Savage (Ed), Hydroponics Worldwide: State of the Art in Soilless Crop Production, Intenational Center for Special Studies, Honolulu, HI.1985.

culture grower. For example, single-body pH and conductivity meters are now readily available at a very reasonable cost. Hand-held specific ion meters, such as the Cardy Nitrate Meter, are very useful for accurately determining the NO_3-N content in water, nutrient solutions, or plant tissue sap or extract. Similar meters for the determination of other ions, such as K^+ and Ca^{2+}, are being developed, and some are already on the market (source of kits and measurement devices: Spectrum Technologies, Inc., 23839 West Andrew Road, Plainfield, IL 60544; tel: 800-248-8873; fax: 815-436-4460: www.specmeters.com).

However, many of these meters have significant limitations in terms of the types of solution that can be assayed. As stated earlier, reliable standards and solutions of known composition need to be on hand to verify an analysis made by these devices.

The Minolta SPAD 502 chlorophyll meter (Figure 13.5) is finding wide use for estimating the N content of leaf tissue (Wood et al., 1993), although its application for commonly grown greenhouse crops has not been explored.

Detailed descriptions of various tissue testing techniques have been provided by Jones (1993b) as well as shown in video form (Jones, l993).

Figure 13.5 Minolta SPAD 502 chlorophyll meter for determining the nitrogen (N) content of a plant leaf. The meter must be specifically calibrated for the crop in order to obtain reliable N content determinations.

The Internet

The Internet has played and will continue to play an increasing role for obtaining diagnostic information. It is possible for a grower to take a digital picture or video and send it to an expert for evaluation. Good photography skills are needed so that the photograph is a good representation of what exists. The challenge for the grower is selecting the right individual(s) to make the evaluation and/or diagnosis and then learning how to select information from the Internet that has foundation in fact and is reliable. As with a medical diagnosis, seeking a second (or even third) opinion is essential. Even the best experts can make misjudgments. A Web site (Hydroponic Resource List) that gives sources for diagnostic as well as other services is: http://www.oardc.ohio-state.edu/hydroponcs/Links/links.htm.

Being a Diagnostician

The author has toured many greenhouses, observed plant problems in both field and greenhouse settings, and designed diagnostic procedures (Jones, 2003). The old adage that "a picture is worth a thousand words" holds true. A hydroponic tomato greenhouse grower was experiencing a tomato plant seedling problem. Based on a description of the symptoms told to a seasoned greenhouse advisor by phone and from plants sent to him, the grower was told that the problem was probably due to herbicide damage or similar cause. On my visit to the greenhouse and looking at the plants, I suspected either Ca or B deficiency was affecting the plants. From some key questions asked, the grower admitted that in the making of the nutrient solution, he did not have sufficient micronutrient concentrate when making the full batch of nutrient solution, so the final nutrient solution being given the seedlings did not contain the proper micronutrient concentration. A plant analysis confirmed my suspicion that the seedlings were B deficient. Bringing the B content of the nutrient solution up to the proper level quickly corrected the deficiency.

Just as a greenhouse grower's tomato plants began to set fruit, the newly emerging leaves began to look as if they had been burned along their margins. Calling around to other growers and a greenhouse advisor, the grower received various opinions as to the cause of the problem. When the grower brought a number of leaves showing the symptoms to the author, I asked if a leaf analysis had been made recently — the answer was no, although both leaf and nutrient solution assays had been conducted some weeks earlier, and the assay results seemed to the grower "normal." An assay of the leaves found that the leaves were low (<10 ppm) in Zn and the P level was very high (>1.00%). The symptoms were corrected by leaving P out of the next batches of nutrient solution applied to the tomato crop. The monitoring of the crop from that point on provided the basis for a study on the effect of high P in plant tissue on Zn tomato plant nutrition (Jones, 1996).

Summary

It is common practice to focus on single-element deficiencies when dealing with nutritional problems in plants. Since intensive plant production is the basis of hydroponic/soilless growing systems, equal attention should be given to excesses and imbalances in the concentration of any given element (Berry and Wallace, 1981). This is particularly important with hydroponic systems, where nutrient solution management is so critical to success. Careful monitoring of the nutrient solution as well as the plants themselves should be the normal practice. It is much easier to catch a potential nutrient element problem in its initial stages than to correct it when symptoms appear. The hydroponic/soilless culture grower always needs to be prepared to meet any difficulty with the tools required to solve the problem. Laboratory mailing kits and the required containers should be always on hand. If tests are to be conducted in-house, then the kits and testing devices required should be in good working order, with fresh reagents and standards on hand.

With the increasing complexity and the many facets of today's growing systems, proper management may be beyond the ability of any one person. Therefore, the hydroponic/soilless culture grower needs to know to whom to turn when important decisions are to be made and/or when a problem arises. Assistance may be provided by a well-trained and experienced county agent, crop consultant, or hydroponic supplier, but it is important that prior contact be made with such individuals to determine their degree of expertise so that time is not lost when a timely decision needs to be made.

Best Management Practices (BMP)

Best management practices began with field crop production although the basic principles have application to the hydroponic/soilless grower. The BMP manual written by Potash & Phosphate Institute[1] (Anon., 1991) defines how the Diagnostic Approach can be applied to any crop production system. The recently introduced Good Agricultural Practices (GAP) established by the Food and Drug Administration and U.S. Department of Agriculture (FDA/USDA) are "guidelines established to ensure a clean and safe working environment for all employees while eliminating the potential for contamination of food products." The trend is toward tighter regulation of chemical use that will equally apply to the hydroponic/soilless grower. For more information, visit the following Web sites:

http://www.gaps.cornell.edu/
http://www.growingformarket.com/links.html

1. Potash Phophate Institute, Suit 110, 655 Engineering Drive, Norcross, 6 30092–2837

Chapter 14

Pest Control

There is nothing unique about hydroponic/soilless growing with respect to pest control. The same procedures used for growing in soil must be practiced to avoid disease and insect problems. In fact, control measures are more important for the hydroponic grower, as the entire system provides an ideal environment for various types of pests unless measures are taken to control them.

In most instances, good pest control is based on common sense — keeping growing and working areas clean and using good sanitation practices. Keeping pests out of a crop is easier than attempting to control them after they have made their appearance. The trend today is away from chemical control (Jensen and Malter, 1995; Cloyd, 2003b), with biological control considered preferable if at all possible (Burnham, 1990; Gunstone, 1994; Kellither, 1994; Jensen and Malter, 1995; Jackson, 1996; Yoemans, 1996; Johnson, 1998; Morgan, 1998a,b; Spillane, 2003). Bottomley (2001) suggests that light can have a significant effect on pests; light can be used to attract insects to a control device or adjustment of light wavelengths can be used to keep pests, both insects and diseases, under control.

Since pest control is highly specific, depending on the crop and method of growing, only general recommendations can be given in this text. However, general recommendations can go a long way in preventing the occurrence of a pest problem, thereby avoiding the hazard of a lost crop or the expense of continuous chemical measures in order to maintain some level of control (Cloyd, 2003b).

The kinds of pest problems a grower may confront and their control vary considerably from one geographic area to another. It is essential that the grower become familiar with the commonly occurring pests in the area and with the recommended control measures. For chemical control, the recommended pesticides and fungicides should be on hand and application equipment made ready for use at the first sign of a problem, which may have economic consequences if not quickly brought under control (Becker, 2003). Daily monitoring procedures must be developed and routinely practiced. It is important to be familiar with those levels of pest incidence considered damaging and therefore economically important to control. Every grower must be able to recognize at what level a pest can be tolerated and therefore requires no treatment (Johnson, 2002).

How to Control Pests

An effective pest control program includes several elements:

1. Use of good sanitation and cultural practices
2. Selection of resistant cultivars
3. Chemical and/or biological control

The best pest management program is based on prevention rather than control after infestation.

A pest problem must be properly identified before any corrective step is taken. In certain cases, it may be necessary to call on a trained expert to assist in the identification and to prescribe pest control measures. Sources for such assistance should be identified and located for quick reference when needed.

Insect control can be accomplished by several means. Insects are normally brought to the crop, and it is usually their progeny that do the damage. Knowing something of the life cycle of the insect pest can pinpoint the step easiest to interrupt. Therefore, as with most diseases, prevention is more effective than attempting to bring a damaging population under control. Knowing that an insect infestation might occur and the conditions suitable for it, the grower can then use the appropriate means for control even though the present population is insufficient to damage the crop. For example, whitefly is a very common pesky insect which, if given a chance to gain a foothold, will damage a crop quickly, before control measures become effective. With this pest, active (chemical and predator) and passive (yellow sticky boards) control measures must be in place at all times.

One aspect of insect control that varies to some degree compared to disease control is that some level of presence can be tolerated without the need for chemical action. This aspect does require some knowledge of insects and how to judge when control is or is not needed. In some instances, expert advice is required to make this decision. Since most growers are not experts in pest identification and control, the use of consultants to assist in developing an effective pest management program is important. It is knowing what to expect, what to do, and how to do it that can keep pests out or salvage a crop if a pest gets in.

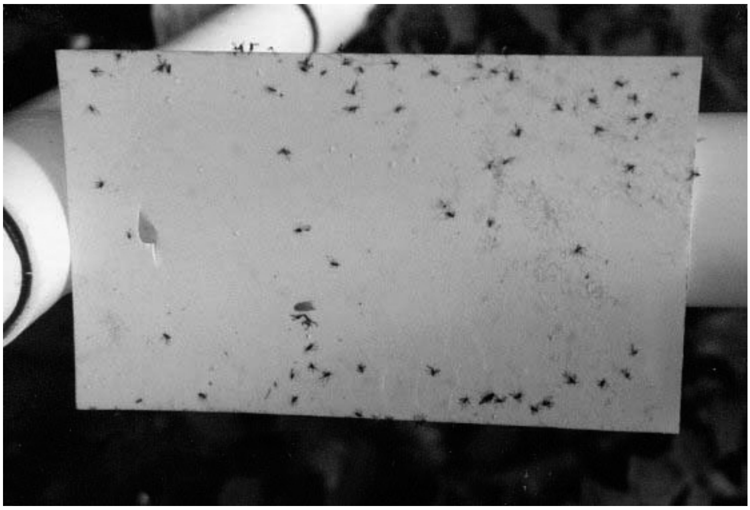

Figure 14.1 Yellow sticky board. These boards are placed about the greenhouse in order to monitor insect types and populations by daily examination. They are not to be used as a means of reducing insect populations. Frequency of replacement is determined by the number of insects making contact with the board.

Insects

The control of insects involves six steps:

Exclusion — keeping insects out of the greenhouse
Sanitation — keeping source material for insect breeding out of the greenhouse
Cultural — engaging in practices that minimize insect infestations
Biological — use of predator insects and other biological methods
Scouting — use of yellow sticky boards and daily plant observations to judge insect types and populations
Insecticides — use of recommended and approved chemicals for foliage application, chemigation, or fogging

It is possible to gain control over insect populations by the use of just plain water rinsing, use of homemade oil and soap sprays, horticultural oil or insecticidal soap products, and botanically derived products as well as the use of beneficial and predatory insects. Regulating the growing environment by keeping humidity, temperature, and air movement under precise control can do much by preventing the build-up of insect populations (Cloyd, 2003c).

Some of the more common insects found in the greenhouse that can adversely affect a growing crop are aphids, spider mites, thrips, whitefly, fungus gnats, shore flies, tomato leafminer, American serpentine leafminer, tomato pinworm, caterpillars, corn earworm, tomato fruit worm, cabbage lopper, army worms, and hornworms (Lindquist, 1985). Drawings of these insects can be found in *Knott's Handbook for Vegetable Growers* (Maynard and Hochmuth, 1997).

Integrated Pest Management (IPM)

For most pest control situations, the grower is advised to develop an integrated pest management (IPM) program, which is a system of monitoring both plant and pest populations using a variety of controls — chemical, cultural, and/or biological — in order to keep plant damage below economic levels (Kellither, 1990; McEno, 1994; Ferguson, 1995; Waterman, 1996).

Sanitation

Sanitation is by far the simplest and most important pest control procedure one can adopt. Since most pest problems are "brought to" the crop, preventing their entrance lies at the root of a good pest management program. Prevention includes using "clean" or sterilized containers, plants, water, growth media, etc. (Morgan, 2001). It means keeping the growing area free of foreign plants. Tools, equipment, materials (including clothing), hands, and footwear must be kept free of disease organisms. The vast majority of pest problems are preventable if such procedures become routine practice. Cleanup of the greenhouse between crops or cropping seasons is discussed by Richerson (2002).

Maintenance of the area around the growing area or greenhouse is equally important. There may be plants in the immediate vicinity of the greenhouse that provide a breeding ground for insects and diseases, which are then carried into the growing area or greenhouse by wind or human activity. It may be necessary to examine the surrounding area for as much as a mile or more, looking upwind first. The installation of windbreaks or wind diversions may be the simplest way to solve a downwind problem.

Prevention Procedures

Chemical-based prevention procedures are also important when dealing with pest problems known to be of common occurrence (Kellither, 1992; Kinro, 1999a,b). For example, the best practice may be to keep plants "covered" with a fungicide to prevent commonly occurring fungus diseases from gaining a foothold. Maintaining specific spray or fumigation schedules may also be good practices in order to keep insect populations under control (Cloyd, 2003b). If the grower waits until there are signs of disease or insect pressures, it may be too late to regain the upper hand. An equally common practice is to vary the type of chemicals applied to prevent the development of pest immunity.

Today, the trend is toward "natural" control of insect pests using predators (Burnham, 1990; Gunstone, 1994; Jackson, 1996; Spillane, 2003). Again, success is based on having the predator present in the greenhouse rather than waiting until an insect is seen in large numbers. Passive measures, such as "yellow sticky boards" and insect traps, can be used to provide some degree of control as well as to alert the grower to what is present and at what population level. The application of a pest chemical or other measures may not be economically sound, based on insect counts and the costs to control versus possible crop losses.

Because some diseases are carried by insects, plant infection can be prevented by controlling the insect vector. Therefore, it is important to know the disease cycle and how it is carried from one plant to another because effective control can be obtained by interrupting any one of the steps in the cycle.

Cultivar Selection

Another very important means of pest control is the selection and use of resistant cultivars (Mohyuddin, 1985; Grossman, 1999). Many of the more common plant diseases that once plagued growers have been essentially eliminated by new cultivars that have been bred specifically for disease resistance. New cultivars are introduced almost every year, and the grower must be aware of them. They offer one of the best means of disease control. Bacterial and viral diseases are best controlled by selecting resistant cultivars.

Environmental Conditions and Cultural Practices

Control of pest problems that occur as a secondary effect becomes difficult or ineffective until the primary cause is identified and corrected. Such is the case, for example, in induced pest problems that gain a foothold because the crop is under elemental or environmental stress. Elemental deficiencies and water and temperature stresses can set up a crop for invasion by some ever present, but not usually seen, pest. Older plant tissues become easy targets for some types of plant diseases and a desirable habitat for insects. A grower frequently finds a pest management program ineffective until the growing system is sufficiently well managed to control elemental and environmental stresses.

Therefore, it becomes important to determine the primary cause of a developing pest problem so that the correct action can be taken to regain control. Some environmental and plant species associations make hydroponic growing difficult (Green, 1990; Morgan, 2001). For example, in warm climates, roots of tomato in gravel or solution media are easily attacked by the fungus *Pythium aphanidermatum* as well as *Phythophthera*, *Fusarium*, and *Olpidium brassicae*. Most chemical and other techniques are normally ineffective for adequate control of this fungus disease, which forces the grower to select another crop. It is not unusual for the grower to have an excellent first crop free of disease infestation, only to find succeeding crops of the same species increasingly attacked by disease. Complete sterilization of the entire system between crops with steam or a chemical sterilant can eliminate disease, but the cost is high (Richerson, 2002).

Common disease pests are the various fungi, bacterial blight (*Alternaria*), *Botrytis*, gray mold (*B. cinerea*), leaf mold (*Fulvia fulva*; *Cladosporium fulvum*), leaf spot (caused by *Alternaria*, *Cercospora*, *Pseudornonas*, *Septoria*, and *Xanthomonas*), powdery mildew, and root rot], and viruses [tobacco mosaic (TMV), and cucumber mosaic (CMV), and fungi wilt (*Fusarium* and *Verticillium*)] that inhabit plant leaves (Mohoyuddin, 1985; Daughtrey, 2003). They vary in type and occurrence, depending on the plant species and environmental conditions. These diseases are particularly severe when environmental conditions are warm and moist. Therefore, the essential control measures are devoted to keeping plant foliage dry and avoiding extremes in temperature. In some instances, keeping plant leaf surfaces covered with a recommended fungicide is required for control in order to keep the disease from gaining a foothold (Cloyd, 2003b). As mentioned earlier, prevention is far more economical and effective than attempting to bring an infestation under control (Daughtrey, 2003).

Another aspect of growing that affects the extent of pest infestations relates to the density of the plant canopy. Dense plant canopies make an ideal habitat for many insects and diseases. The penetration of pest chemicals is commonly inhibited by the foliage, leaving areas of leaf surfaces uncovered, with temperature and humidity often ideal for the regeneration and rapid growth of pests. By keeping the plant canopy open, accomplished by proper plant spacing, staking, and pruning, providing air movement up through the plant canopy, and reducing humidity, a less-than-ideal environment for these pests is created.

The Nutrient Solution

The nutrient solution is an ideal environment for the growth of algae and other pests. Minimizing exposure of the nutrient solution to light can prevent the growth of algae, which if given a foothold in the nutrient solution will clog delivery tubes, pipes, and valves. Filters of various kinds can remove suspended substances from the nutrient solution. Millipore filtering (Millipore Corporation, Ashby Road, Bedford, MA 01730) will, to some extent, remove some disease-producing organisms from the solution. Some pest control chemicals can be added to the nutrient solution to control disease; however, great care is required to keep the concentration at levels that will provide pest control but not harm the crop.

Chemical Use Regulations

In the United States and many other countries, the sale and use of pest control chemicals are carefully regulated. Licenses are required to purchase and/or use most pest control chemicals. The label plays an essential role in providing information on crops that are cleared for use and application procedures. Those who violate these regulations and label clearances are subject to stiff penalties. The greatest health concern arises in connection with food crops, where residues left on the edible portion may be hazardous. Because the laws and label clearances are constantly changing, the grower needs to be sure that use of a particular pest chemical is legal. The best sources for current information on pest chemical use are the Agricultural Cooperative Extension Service in the United States and similar governmental agencies elsewhere. Worker protection standards are set by various government agencies, mainly the Environmental Protection Agency (EPA) and the United States Department of Agriculture (US-USDA) (Cloyd, 2003c).

Chapter 15

Educational Role for Hydroponics

In 1993, Silberstein and Brooke wrote, "Increasingly, hydroponics, long a tool of university researchers, is finding a place in elementary and secondary education. It offers students great opportunities to learn from their successes and from their failures. On the way, they learn about making observations, recording and interpreting data, and the need for control in scientific research." Peterson Middle School, located in Silicon Valley, began a hydroponic project in 1992 by designing a simulated space capsule (ASTRO 1) to house various hydroponic growing systems (Figure 15.1). "Tending the plants and monitoring their progress teaches responsibility and a respect for living organisms that no textbook biology lesson could convey," was the comment made by the two lead teachers (Silberstein and Brooke, 1993). The lettuce and tomatoes produced were served in the school's cafeteria. The ASTRO 1 project has led to teacher presentations at hydroponic camps and teacher conferences (Silberstein, 1995) as well as workshops for teachers held mainly in California with the assistance of the Hydroponic Society of America (HSA) (Silberstein and Spoelstra-Pepper, 1999).

Recognizing the need to "know where to look to find valuable information for all grade levels, the right lesson plan, that important grant, and intuitively designed equipment," Peckenpaugh (2001f) lists 15 Internet sites (Table 15.1), and sources for grants and classroom materials to assist the teacher who wishes to use hydroponics as an educational tool (Table 15.2). Hankinson (2000b) developed "A Hydroponic Lesson Plan" to guide the teacher on topics and experiments for instructing students in hydroponic studies, including the following topics: Plant Nutrition Basics, Preparing the Plants, Containers, Aeration, and Nutrient Solution. The author then describes how to conduct hydroponic experiments to produce nutrient element deficiency symptoms in

Figure 15.1 Peterson Middle School hydroponic simulated space capsule, ASTRO 1. The crops produced are served in the school's cafeteria. (*Source*: Siberstein and Brooke, 1994).

test plants. Similarly, Hershey (1994b) gives instructions for the teacher on how inexpensive equipment can be used to conduct hydroponic experiments. Those interested in a wider range of plant biology science projects will find the book by Hershey (1995) helpful. For the more advanced student, Morgan (2002d) provides sources of instructional material on all aspects of the hydroponic growing technique, nutrient solution formulations and their chemical characteristics, and systems of plant production (Table 15.3). In addition, experiments to study the following topics are described:

1. Effects of gravity
2. Light, gases, and temperature
3. Effects of different fertilizers
4. Effects of different media
5. Effects of nutrient solutions made with various water sources

Basic plant physiology, growth, and development concepts, plus procedures and objectives for conducting hydroponic experiments by students (Table 15.4), are included; these demonstrations could serve as science fair projects.

A numbers of articles have appeared in *The Growing Edge* magazine from 1993 to 2003 describing a wide range of school activities for elementary and

Table 15.1 Internet Sources for Hydroponic Teachers

Aquaponics/Hydroponics; http://www.bergen.org/BCTC/Projects/Aquaponics/2001/
Building and Using a Hydroponic/Aquaculture System in the Classroom; http://www.accessexcellence.com/AE/AEC/AEF/1995/nicol_aquaculture.html
Farming in Space Video Clips; http://www.quest.arc.nasa.gov/ltc/farming/farmingexperts.html
Feeding Hydroponics Plants; http://www.open.k12/mars/etag/mmpht152.html
The NEA Foundation for the Improvement of Education, 1201 16th Street, NW, Washington, D.C. 20036; tel: (202) 822-7840, Fax: (202) 822-7779; e-mail: info@nfie.org; http://www.nfie.org/
Preparing Tomorrow's Teachers to Use Technology, U.S. Department of Education, OPE, 1990 K Street, NW, Room 6156, Washington, DC 20006-8526; tel: (202) 502-7788; fax: (202) 502-7775; e-mail: Teacher_Technology@ed.gov; http://www.ed.gov/teachertech/
The Teacher's Network, 285 West Broadway, New York, NY 10013 tel: (212) 966-5582; fax: (212) 941-1787; http://www.teachnet.org/grantsbbs/default/htm
Foothill Hydroponics Library: Brochures; http://www.foothillshydroponics.com/brochure/brochure1.htm
Hydroponics Class; http://www.hydrogarden.com/classl/curriculum.htrm
Hydroponics Module; http://www.webflife.arc.nasa.gov/stellar/Activities/hydro/Hydroponics.html
Hydroponic University; http://www.simplyhydro.com/hydrou.htm
Plants in Space; Grades 5–8: http://www.nasaexplores.com/lessons/01-048/5-8_index.html; Grades 9–12: http://www.nasaexplores.com/lessons/01-048/9-12_index.html
Simply Hydroponics-An E-School Project; http://www.k12 hi.us/~ckuroda/hydroponics.html
Tortoise Shell Hydroponic Reference Center; http://www.luminet.net/~wenonah/hydro/index.html
A Windowsill Hydroponic Farm Projects by H. M. Hahn; http://www.bnl.gov/scied/mste/res/hydrolesson1.html

Source: Peckenpaugh, D.S., 2001f , *The Growing Edge* 13(2):48–57.

Table 15.2 Grant Sources for Supporting Educational Projects

The Danforth Foundation, 231 S. Bemiston Ave., Suite 1080, St. Louis, MO 63105-1996; tel: (314) 862-6200
The General Mills Foundation, Reatha Clark King, P.O. Box 1113, Minneapolis, MN 55440; tel: (612) 540-7891; e-mail: mills999@mail.genmills.com
National Gardening Association, 100 Dorset Street, South Burlington, VT 05403; tel: (800) 538-7476; fax: (802) 864-6889; e-mail: joanw@kidsgardening.com; http://www.kidsgardening.com/grants.asp
National Science Teacher's Association, Toyota TAPESTRY, 1804 Wilson Blvd., Arlington, VA 22201-3000; tel: (888) 400-6782 (doc. #591); http://www.nsta.org/programs/tapestry/

Source: Peckenpaugh, D.S., 2001f , *The Growing Edge* 13(2):48–57.

Table 15.3 Resources for Conducting Student Hydroponic Experiments

Aquaponics Journal (http://www.aquaponics.com)
Bradley Hydroponics, "Hydroponics Class" (http://www. hydrogarden.com/class 1/ curriculum.html)
Crowe, Paul S., 1992, Hydroponics for Schools and the Home Growers, National Resource Conservation League, Victoria, Australia.
Goins, Greg, "Nutrient Delivery System NASA Kennedy Space Center" (http:// bioscience.ksc,nasa.gov/oldal/plant/nds.htm)
Hershey, David R., 1995, Plant Biology Science Projects, John Wiley & Sons, New York
Institute for Simplified Hydroponics, The Global Classroom (http://www.carbon.org/ GlobalClassroom.htm)
NASA Quest, "Farming in Space" (http://quest.arc.nasa.gov/space/ challenlearning.farming)
National Gardening Association GrowLab, 1998, Exploring Classroom Hydroponics, National Gardening Association, South Burlington, VT
Sci+MATE= Hydroponics (http://science-math-technology.com/hydroponics.html)
University of Guelph Department of Botany, "Hydroponic in the Classroom" (http:// www.cpes.uoguelph.ca/STAO/hydrop.html)

Source: Morgan, L., 2002d, *The Growing Edge*, 13(6):56–70.

Table 15.4 Procedures and Objectives for Conducting Hydroponic Experiments by Students

1. Use the scientific method whenever cause and effect is documented.
2. Include the objective of the experiment and a hypothesis.
3. Make a comprehensive list of required materials.
4. Start experiments with plants of a similar size and stage of development and clearly label each plant.
5. Keep track of all growing variables, such as daily temperatures, changes in nutrient electrical conductivity (EC) and pH, amount of solution used, and any pest and disease problems encountered.
6. Record all observations.
7. Discuss results and ask questions — results that show nothing happened are still valid and worth reporting and discussing.
8. Outline how the experiment was undertaken in detail using photographs and diagrams.
9. List all sources consulted, including any expert advice, books, magazines articles, Web sites, and so on — such documentation shows that a well-researched experiment has been conducted.

Source: Morgan, L., 2002d, *The Growing Edge*, 13(6):56–70.

secondary schools (Karpeles, 1996; Spillane, 2000; Bartels, 2000; Peckenpaugh, 2001a,b; Montgomery, 2002) and at the college level (Alexander, 2001b; Meade, 2002b; 2003) (Table 15.5). At the State University of New York (SUNY) in Oswego, hydroponic systems are being used to teach technology as "students are challenged to design and build a hydroponic setup to serve as a model of a simple energy system" (Meade, 2003).

Table 15.5 Articles on Educational Topics Appearing in Issues of *The Growing Edge* Magazine from 1993 to 2003.

Author	*Title*	*Volume (Issue):Page (Year)*
Brooke, L.L. and O. Silberstein	Hydroponics in schools: an educational tool	5(1):20 (1993)
Silberstein, O.	Hydroponics: making waves in the classroom	6(4):16(1995)
Karpeles, K.	It's catching on … The hydroponic curriculum	8(1):28 (1996)
Silberstein, O. and C. Spoelstra-Pepper	Hydroponic workshops for teachers: a traveling roadshow	11(2):10(1999)
Hankinson, J.	A hydroponic lesson plan	11(5):28 (2000)
Spillane, M.	Getting schooled in hydro	11(6):74 (2000)
Bartels, P.L.	Washington Middle School	12(1):65 (2000)
Jensen, M.H. and O. Silberstein	Controlled academic expansion	12(2):27 (2000)
Brentinger, D.	Making science alive	12(6):15(2001)
Peckenpaugh, D.J.	Soilless growing at Arcadia school	12(1):42 (2001)
Peckenpaugh, D.J.	Frontier Middle School	13(1):49 (2001)
Peckenpaugh, D.J.	Hydroponic resources for teachers	13(2):48 (2001)
Alexander, T.	An interview with Georgia Crosby	13(2):64 (2001)
Montgomery, L.	Austin High hydroponics	13(3):77 (2002)
Alexander, T.	Science Alive 2002: the future of scholastic hydroponic	13(6):19(2002)
Morgan, L.	Hydroponic classroom experiments	13(6):56 (2002)
Alexander, T.	Science Alive 2003	14(5):12(200
Meade, A.	SUNY Oswego: teaching technology through hydroponics	15(2):68 (2003)

From the University of Arizona's Controlled Environment Agriculture (CEA) Center, an offered Plant Science course (A Hydroponic Syllabus, Table 15.6) instructs students who will be going into the greenhouse vegetable industry (Jensen and Silberstein, 2000). In addition, a national hydroponic conference called "Science Alive," geared toward students and teachers, was initiated as a yearly conference (see http.//www.arizona.edu/science.alive); the first one was held in 2001 (Brentingler, 2001; resources: Flowing Well FFA: http://www. geocities.com/Athens/Ithaca/4193/; Flowing Wells High School: http.//www.flowingwells.k12,az.us/Schools/High—school.htm). The three-day 2002 Science Alive Conference held in Tucson, Arizona, consisted of field trips, classroom instruction, and hands-on training with both teachers and students in attendance (Alexander, 2002; resources: http.//www.arizona.edu/science —alive/).

The 2003 Science Alive Conference was held in Tucson, AZ following the same format as that in previous conferences; those attending were teachers and students as well as hobbyists and commercial growers (Alexander, 2003a). Added to the subject matter was aquaponics.

Table 15.6 Plant Science 217: A Hydroponic Syllabus

1. **Overview**: Definition of hydroponics; early history, present status — state and worldwide, including economics and markets
2. **The Plant Crops**: Varieties for greenhouse/hydroponic technology, basic plant requirements
3. **Greenhouse Environments**: Fulfilling basic plant requirements, site selection (water source, light, temperature, greenhouse orientation, road access, labor, etc.), greenhouse structures (frames, glazings, flooring, etc.), environmental controls (heating, cooling, light, carbon dioxide, oxygen, etc.), sanitation
4. **Preparing the Greenhouse for Hydroponic Production**: Ground covers, layout; plant spacing, overhead support, fertilizer system (mixing tanks, injectors, delivery system, irrigation, controller, etc.), drainage systems: open versus closed
5. **Basic Principles of Hydroponic Systems**: Water culture (basic wick, air-gap, raft, Nutrient Film Technique (NFT), and aeroponics) and media culture (top feed and flood-and-drain using various media — perlite, vermiculite, peat, sand, gravel, foams, pumice, coir, etc.)
6. **Cultural Practices**: Plant pruning and training, nutritional disorders, flower pollination — manual versus bees, including bee management
7. **Transplant Production**: Varieties and sources for seeds, containers, seeding, water and nutrient management, transplanting
8. **Plant Protection**: Plant diseases, plant insect pests, biological control and integrated pest management
9. **Product Harvest**: Picking, sorting, storage, marketing

Source: Jensen, M.N. and Silberstein, O., 2000, *The Growing Edge* 12(2):27–29.

Demonstration Project

A common school science fair project demonstrates some form of hydroponic/soilless plant growing, and the information presented here can be helpful to a student contemplating such a project. The hydroponic procedures that a student can follow in order to generate nutrient element deficiency symptoms and monitor their effects on plant growth and development are described. With easily obtainable items and properly prepared nutrient solutions, the student should be able to undertake such a science project and obtain good results in about 6 to 8 weeks. The references in this section provide specific information that will be helpful to a student with this project.

Required Items

The items required for this project are as follows:

- One-liter plastic beverage bottles
- Horticultural perlite (available at most garden centers)
- 6" × 6" plastic refrigerator storage boxes with lids
- 50-mL graduated cylinder (available from most chemical apparatus supply houses)

- Green bean seeds (bush beans recommended)
- Pure water
- Nutrient solution reagents (obtainable from most chemical supply houses or hydroponic suppliers)

Reagent	*Formula*
Major Element Reagents	
Calcium nitrate	$Ca(NO_3)_2{\bullet}4H_2O$
Calcium sulfate	$CaSO_4{\bullet}2H_2O$
Monocalcium phosphate	$Ca(H_2PO_4)_2{\bullet}H_2O$
Potassium nitrate	KNO_3
Potassium sulfate	K_2SO_4
Monopotassium phosphate	KH_2PO_4
Magnesium sulfate	$MgSO_4{\bullet}7H_2O$
Magnesium nitrate	$Mg(NO_3)_2{\bullet}6H_2O$
Micronutrient Reagents	
Boric acid	H_3BO_3
Copper sulfate	$CuSO_4{\bullet}5H_2O$
Manganese chloride	$MnCl_2{\bullet}4H_2O$
Manganese sulfate	$MnSO_4{\bullet}H_2O$
Molybdic acid	$H_2MoO_4{\bullet}H_2O$
Zinc sulfate	$ZnSO_4{\bullet}H_2O$
Iron chelate	FeDTPA

Growing Requirements

Light

Plant growth is best when plants are exposed to full sunlight for at least 8 hours each day. Placing plants by a window, even one that is well lit, is not sufficient for best growth. Use of lights to extend the exposure time is not an adequate substitute for natural sunlight. Slow growth and development, usually seen as spindly-looking plants, are signs of inadequate light. If a nutrient element deficiency symptom is to be developed, plant exposure to full sunlight is required for success.

Plant Species Selection

For best results in a reasonable length of time, a plant species that is rapid growing and responsive to its environment should be selected. Experience has shown that green bean is probably the best plant species, and corn is second best. Although other plant species, such as radish and lettuce, are faster growing, the larger plant size of the green bean and corn plants makes them the best choices.

Temperature

Plants grow best when the air temperature is maintained between 75 and 85°F (24 and 30°C). Air temperatures above or below these limits are not conducive to normal plant growth and development.

Moisture

Plants that are cycled through periods of adequate and then inadequate water supply will develop abnormal growth appearances due to that stress. Therefore, plants must have access to an adequate supply of water at all times. However, overwatering is as detrimental to plant growth and development as inadequate watering. Frequent small doses of water added to the rooting medium are better than infrequent heavy doses. The growing technique described in this section will maintain an adequate water supply for the plants at all times.

Pest Control

Insects and disease problems can be avoided by keeping the growing area clean at all times and free from potential sources of infestation. Although neighboring plants may be free from visible pests, it is wise to conduct the experiments given in this section free from the presence of other plants that are not part of the study.

Procedure

1. Remove the top of a one-liter plastic soft drink bottle by cutting around the bottle at the upper label level (Figure 15.2). The number of bottles needed will depend on which experiments will be conducted. Only one bottle per treatment is needed, although duplicates will ensure that

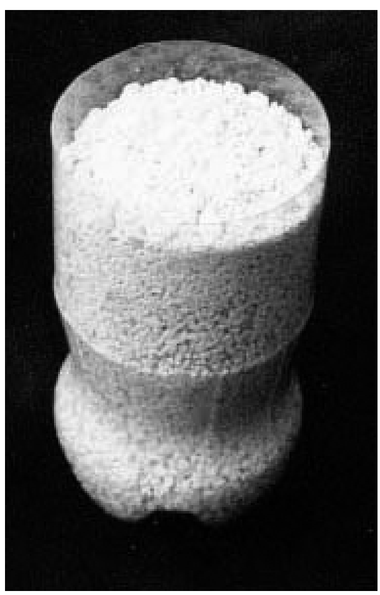

Figure 15.2 One-liter soft drink bottle with its top removed, filled with perlite.

there will be a backup treatment bottle(s) if one bottle is lost. Also, one bottle plus its backup will be needed as the check (that without a treatment change).

2. Drill a 1/2-in.-diameter hole in the center of the bottom of the bottle (see Figure 15.2)
3. On the inside of the bottle, cover the hole in the bottom of the bottle with plastic mesh. The plastic mesh will prevent the loss of perlite from the opening in the bottle.
4. Fill the bottle with horticultural-grade perlite all the way to the top.
5. Using the prepared nutrient solution, leach the perlite until the nutrient solution freely flows from the hole in the bottom of the bottle. The plastic mesh, if properly in place, will keep the perlite from being lost from the bottom of the bottle.
6. Place two green bean seeds about an inch deep into the moist perlite. It may be necessary to add a small amount of water (half a cup) daily to the top of the bottle to keep the perlite moist until the seeds germinate and the cotyledons appear.
7. Place the bottle into the small plastic refrigerator box and fill the box to the depth of about 2 in. with nutrient solution. With a black marker pen, put a scribe mark at the nutrient solution level on the side of the refrigerator box. When adding nutrient solution, always fill to that mark. Cut an opening in the box lid large sufficient to just accommodate the bottle. Place the refrigerator lid on the box and snap down tight (Figure 15.3). Keeping the lid in place will prevent evaporation of the nutrient solution. The nutrient solution in the box will also fill the bottle with nutrient solution at that same level.

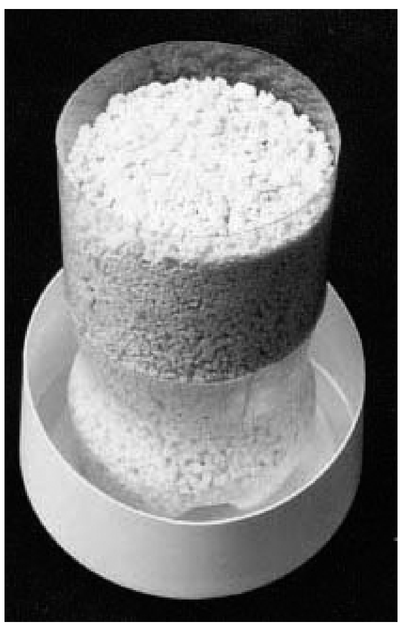

Figure 15.3 One-liter soft drink bottle set in the refrigerator box.

8. Place the bottle in its box in full sunlight. Add nutrient solution when needed (usually every day) to maintain the level in the box at the scribe mark using a 50-mL graduated cylinder so that water use can be monitored.
9. When the seeds germinate, remove one of the seedlings to leave just one plant per bottle.
10. When the plants reach the two-leaf stage, begin the treatments.

Nutrient Element Deficiency Experiments

Introduction

Visual nutrient deficiency symptoms for the major elements (Ca, Mg, N, P, and K) are fairly easy to develop using the technique that is to be described. Deficiencies of the micronutrients (B, Cl, Cu, Fe, Mn, Mo, and Zn) are more challenging and difficult to achieve. The reason is that the major elements are required in substantial quantities by plants, whereas the micronutrients are not. It is quite difficult to deplete the growing medium and the nutrient solution of trace quantities of the micronutrient elements in order to create a deficient condition. In addition, there may be a sufficient quantity of a micronutrient in the plant itself (acquired from the seed) to satisfy the requirement until the plant reaches full maturity. However, it may be worth a try if you like a challenge.

Upon reaching Step 10 in the procedure list, the composition of the nutrient solution is altered to free it of one of the essential elements, as shown in Table 15.7.

For B-, Cu-, Mn-, Mo-, and Zn-deficient solutions, substitute micronutrient stock solutions for one of the five salts in the regular micronutrient stock solution. For chlorine-deficient micronutrient solution, substitute 1.55 g $MnSO_4 \cdot H_2O$ for 1.18 g $MnCl_2 \cdot 2H_2O$.

Procedure

1. Remove the bottle from the plastic box and leach the perlite in the bottle with pure water until there is a free flow of water from the hole in the bottom of the bottle. This leaching procedure will free the perlite from any accumulated nutrient solution in the bottle.
2. When the flow of water from the bottom of the bottle ceases, place the bottle into the refrigerator box containing one of the treatment nutrient solutions derived from Table 15.7 (a nutrient solution free from one of the major elements). Be sure to keep at least one bottle on the "full" treatment so that a visual comparison can be made between a plant receiving all of the essential elements versus those missing one of the essential elements.
3. Place the bottle back into its refrigerator box and then back into full sunlight.

Table 15.7 Preparation of Hoagland Nutrient Solutions for Nutrient Deficiency Symptom Development (mL Stock Solution per L Nutrient Solution)

Stock Solution (g/L)	*Complete*	*–N*	*–P*	*–K*	*–Ca*	*–Mg*	*–S*	*–Fe*
Major Element								
1*M* $Ca(NO_3)_2 \cdot 4H_2O$ (236)	5	—	4	5	—	4	4	5
1*M* KNO_3 (101)	5	—	6	—	5	6	6	5
1*M* KH_2PO_4 (136)	1	—	—	—	1	1	1	1
1*M* $MgSO_4 \cdot 7H_2O$ (246)	2	2	2	2	2	—	—	2
Micronutrients[b]	1	1	1	1	1	1	1	1
50 m*M* FeDPTA (18.4)[a]	1	1	1	1	1	1	1	—
0.05*M* K_2SO_4 (8.7)	—	5	—	—	—	—	—	—
0.01*M* $CaSO_4 \cdot 2H_2O$ (1.72)	—	200	—	—	—	—	—	—
0.05*M* $Ca(H_2PO_4)_2 \cdot H_2O$ (12.6)	10	—	10	—	—	—	—	—
1*M* $Mg(NO_3)_2 \cdot 6H_2O$ (256)	—	—	—	—	—	—	2	—

[a] Ferric–sodium salt of diethylenediaminetetraacetic acid (DTPA). Differs from Hoagland recipe, which uses iron tartrate.

[b] Contains the following: 2.86 mL/L H_3BO_3; 1.18 mL/L $MnCl_2 \cdot 4H_2O$; 0.22 mL/L $ZnSO_4 \cdot 7H_2O$; 0.08 mL/L $CuSO_4 \cdot 5H_2O$; 0.02 mL/L $H_2MoO_4 \cdot H_2O$ (85% molybdic acid).

Source: Hoagland, D.R. and Arnon, D.I., 1950, The Water Culture Method for Growing Plants without Soil, Circular 347, California Agricultural Experiment Station, University of California, Berkeley, CA.

4. Maintain the nutrient solution level in the box by adding nutrient solution periodically (usually daily) as required, and record the milliliters of solution required to bring back the nutrient solution level to the scribe mark on the side of the box.
5. Depending on the light conditions and rate of growth, significant changes in plant appearance should become evident in about 10 days to 2 weeks.
6. The first evidence of deficiency will be slowed growth.

Photographic Record

It would be useful to have a photographic record of the plants at critical stages of development. A daily record can be expensive if a film camera is used; therefore a digital camera would be the best choice. In order to obtain a meaningful visual record, plant and camera placement is critical. A simple backdrop, called a studio box, can be constructed from a large cardboard box and a piece of blue burlap cloth.

Cut the cardboard box on the diagonal, and line the inside of the box with blue burlap cloth on the bottom and up the inside of the box, cutting to just fit the inside box opening. Take one of the box–bottle containers and place it in the center of the bottom of the cardboard box. Draw a square around the box–bottle container, which will designate where the box–bottle should be placed each time a photograph is to be taken. Be sure to also place a mark on the side of the box–bottle container so that it is always oriented in the same way when the photograph is taken.

On the back side of the box, cut small holes just on the inside edge of the back side of the box at 2-in. intervals. Using thick white string, pull a length of string through the holes, creating a series of white lines of string at 2-in. intervals up the inside back of the studio box; this will provide a 2-in. measuring backdrop. A picture of such a constructed box and a box–bottle container in place is shown in Figure 15.4.

For those who have access to a video camcorder, a similar photographic record can be made using daily short exposures of the plants placed in the studio box; be certain that each day's exposure is exactly positioned (video camera and plant). The short daily exposures can then be edited to give a time-lapse record of the plant as the deficiency symptoms develop.

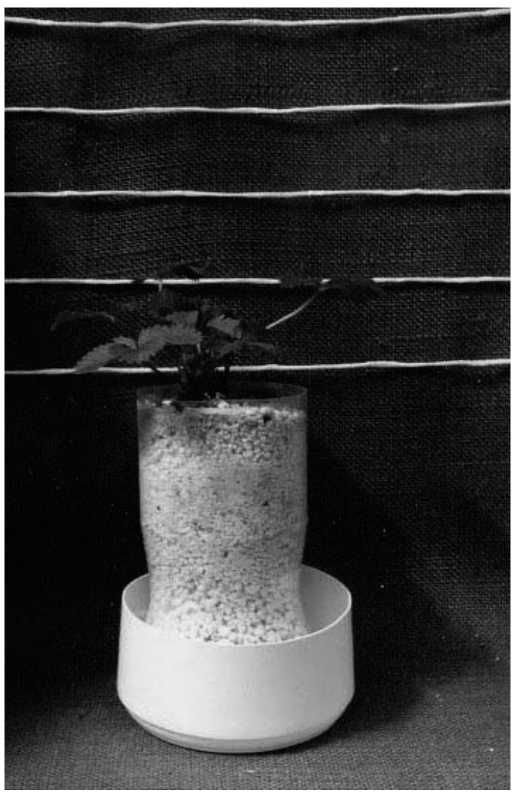

Figure 15.4 Box–bottle set in the studio box background for photographing.

Plant Growth Record

A daily record should be kept, observing water use and plant growth. Height measurements may be of little value, since, for example, the development of lateral branches is the primary indicator of plant growth for green bean, whereas plant height would be the proper measurement for corn. As the deficiency develops, changes in plant growth will also be influenced by environmental conditions, such as light and temperature. The interaction between these environmental factors and the developing deficiency symptoms can make for an interesting study.

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Appendix A: Definitions

The definitions given here are oriented primarily to the jargon of soilless media culture and hydroponic growing, although some apply broadly to all forms of plant production and the botanical and horticultural sciences.

Acid injection The addition of a strong mineral acid to an irrigation water to lower the concentration of alkalinity.

Absorptive capacity A measure of the capacity of a substance used as a growing medium in soilless culture to take (absorb) into pores and cavities nutrient solution. The trapped solution is a potential future source of water and essential elements. The composition of the nutrient solution is unaffected by this absorption. (See **Adsorptive capacity**.)

Acidity Refers to the pH of the nutrient solution or growth medium when the pH measures less than 7.0. An increasing hydrogen (H^+) ion concentration leads to increasing acidity as the pH decreases from 7.0. (See **Alkalinity**.)

Active absorption Refers to the process of ion uptake by plant roots requiring the expenditure of energy. This process is controlled and specific as to the number and types of ion species absorbed. (See **Passive absorption**.)

Adsorptive capacity A measure of the capacity of a substance used as a growing medium in soilless culture to selectively remove from the nutrient solution essential elements by precipitation, complexing, or ion exchange. Adsorbed elements may be released and therefore available to plants at a later time. The adsorptive capacity of a substance will significantly affect the composition of the nutrient solution through time, depending on the degree of adsorption or release. (See **Absorptive capacity**.)

Aerated standing nutrient solution culture A method of growing plants hydroponically where the plant roots are suspended in a container of continuously aerated nutrient solution. The usual procedure is to maintain the volume of the solution by daily addition of water and to replace the nutrient solution periodically with fresh.

Aerobic A condition in which ample O_2 is present. In a rooting environment and/or rooting medium, O_2 is not lacking. (See **Anaerobic**.)

Aeroponics A technique for growing plants hydroponically where the plant roots are suspended in a container and the roots are either continuously or periodically bathed in a fine mist of nutrient solution.

Alkalinity Refers to the pH of the nutrient solution or growth medium when the pH measures greater than 7.0. A decreasing hydrogen (H^+) ion concentration leads to increasing alkalinity as the pH increases from 7.0. (See **Acidity**.)

Anaerobic A condition in which O_2 is not present or exists at a very low concentration. In a rooting environment and/or rooting medium, O_2 is lacking. (See **Aerobic**.)

Anion An ion in solution that has a negative charge. When applied to the composition of the nutrient solution, it designates ions, such as BO_3^{3-}, Cl^-, $H_2PO_4^-$, HPO_4^{2-}, MoO_4^{2-}, NO_3^-, and SO_4^{2-}, which are common forms for these essential elements in solution. In chemical notation, the minus sign indicates the number of electrons the compound will give up. (See **Cation**.)

Aquaculture A system of hydroponics and production of fish in which the fish are cultured in the nutrient solution.

Atmospheric demand The capacity of air surrounding the plant to absorb moisture. This capacity will influence the amount of water transpired by the plant through its exposed surfaces. Atmospheric demand varies with changing atmospheric conditions. It is greatest when air temperature and movement are high and relative humidity is low. Atmospheric demand is lowest under the opposite conditions.

Availability A term used to indicate that an element is in a form and position suitable for plant root absorption.

Bag culture A technique for growing plants in a bag of soilless medium (such as mixtures of sphagnum peat moss, composted milled pinebark, vermiculite, and/or perlite) into which a nutrient solution is applied periodically.

BATO bucket A bucket that is especially designed with a small reservoir in its base and a drainage nipple in its base so that the bucket can be set on a nutrient solution drainage line.

Beneficial elements Elements not essential for plants but which, when present in the nutrient solution at specific concentrations or in rooting media, enhance plant growth (see Chapter 6).

Biological pest control The use of predator insects or disease organisms to control plant pests or the use of natural organic substances for control.

Boron (B) An essential element classed as a micronutrient. Boron exists in the nutrient solution as either the borate (BO_3^{3-}) anion or molecular boric acid (H_3BO_3). The common reagents for making a nutrient solution are boric acid, H_3BO_3; solubor, $Na_2B_4O_7{\bullet}4H_2O + Na_2B_{10}O_{16}{\bullet}10H_2O$; and borax, $Na_2B_4O_7{\bullet}10H_2O$.

Buffer capacity The ability of the nutrient solution or growth medium to resist a change in pH during the period of its use.

C3 Plants Plant species whose photosynthetic pathway results in the formation of a three-carbon carbohydrate; such plants reach maximum efficiency at lower temperatures and light intensities than C4 plants do. The optimum temperature range for photosynthesis of C3 plants is between 60 and 77°F (15 and 25°C). Tomato, cucumber, and lettuce are C3 plants.

C4 Plants Plant species whose photosynthetic pathway results in the formation of a four-carbon carbohydrate; such plants reach maximum efficiency with increasing temperature and light intensities. The optimum temperature range for photosynthesis of C4 plants is between 85 and l05°C (30 and 40°F). Many grain crops, such as corn, sorghum, rice, and sugar cane, are C4 plants.

Calcium (Ca) An essential element classed as a major element. Calcium exists in the nutrient solution as the divalent cation Ca^{2+}. The common reagents for making a nutrient solution are calcium nitrate, $Ca(NO_3)_2 \cdot 4H_2O$; calcium chloride, $CaCl_2$; and calcium sulfate, $CaSO_4 \cdot 2H_2O$.

Carbon (C) An essential element classed as a major element. Carbon is obtained from carbon dioxide (CO_2) in the air fixed during photosynthesis.

Cation An ion in solution that has a positive charge. When applied to the composition of a nutrient solution, it designates ions such as Ca^{2+}, Cu^{2+}, Fe^{3+}, H^+, K^+, Mg^{2+}, Mn^{2+}, NH_4^+, and Zn^{2+}, which are common forms for these essential elements in solution. In chemical notation, the plus sign indicates the number of electrons the element will accept. (See **Anion**.)

Chelates A type of chemical compound in which a metallic atom (such as Fe) is firmly combined with a molecule by means of multiple chemical bonds. The term refers to the claw of a crab, illustrative of the way in which the atom is held. The most commonly used chelates are: EDTA (ethylenediaminetetraacetic acid) and DTPA (diethylenetriaminepentaacetic acid).

Chlorine (Cl) An essential element classed as a micronutrient. Chlorine exists in the nutrient solution as the monovalent anion Cl^-. Since the chloride anion is ever-present in the environment and in chemicals commonly used to prepare nutrient solutions, it is not specifically added to the nutrient solution.

Chlorosis A light-green to yellow coloration of leaves or whole plants that usually indicates an essential element insufficiency or toxicity. Chlorosis is most frequently associated with Fe deficiency.

Closed hydroponic system Designates a growing system in which the nutrient solution is circulated and reused. (See **Open hydroponic system**.)

Cocopeat (coir) Organic growing medium made from the grinding of coconut hulls.

Compost A mixture of organic (sometimes includes inorganic) materials that is used as a rooting medium.

Continuous flow nutrient solution culture A method of soilless culture in which the plant roots are continuously bathed in a flowing stream of nutrient solution.

Controlled Environment Agriculture (CEA) Science that describes systems of protected agriculture for the ultimate in environmental control at both the aerial and root levels.

Copper (Cu) An essential element classed as a micronutrient. Copper exists in the nutrient solution as the cupric cation (Cu^{2+}). The common reagent for making a nutrient solution is copper sulfate, $CuSO_4 \cdot 5H_2O$.

Cuticle A very thin waxy film covering the surface of a plant leaf, derived from the outer surfaces of the epidermal cells.

Deepflow technique A method of NFT growing in which the depth of the trough is considerable.

Deficiency Describes the condition when an essential element is not in sufficient supply or proper form to adequately supply the plant or is not in sufficient concentration in the plant to meet the plant's physiological requirement. Plants therefore usually grow poorly and show visual signs of abnormality in color and plant architecture.

Diffuse radiation Light radiation that is scattered after passing through a transparent material.

Diffusion The movement of an ion in solution from a high concentration to an area of lower concentration due to the existence of a concentration gradient. Movement continues as long as the concentration gradient exists.

Drip nutrient solution culture A method of soilless culture in which the nutrient solution and/or water is slowly applied as drops onto the rooting medium.

Ebb-and-flow A system of hydroponic growing, sometimes also referred to as flood-and-drain, in which plants are rooted in a watertight vessel containing a coarse inorganic substance, and the nutrient solution, housed in a sump, periodically floods the growing vessel.

Electrical conductivity (EC) A measure of the electrical resistance of a nutrient solution, or effluent from a growing bed or pot, used to determine the level of ions in solution. Conductivity may be expressed as specific conductance in mhos (micro- or milli-) or decisiemens (dS) or as resistance in ohms. 1 dS/m = 1 mS/cm = 1000 μS/cm = 1 mmho/cm; EC (in dS/m × 640 = TDS [in mg/L (ppm)]. (See **Specific conductance**.)

Essential elements Those elements that are necessary for higher plants to complete their life cycles; also refers to the requirements established for essentiality by Arnon and Stout (see Chapter 5).

Feeding cycle The time period when the nutrient solution is circulated through the root growing medium in those systems where plant roots are only periodically exposed to the nutrient solution.

Flood-and-drain (See **Ebb-and-flow**.)

Foliar feeding The application of a fertilizer solution to the foliage of a plant as a means of correcting a nutrient element deficiency or supplying a nutrient element needed by the plant to sustain growth.

Footcandle (fc) A unit of illuminance when the foot was taken as the unit of length. It is the illumination on a surface, one square foot in area, on which there is uniformity distributed energy level of one lumen.

Fruit truss A plant structure on which fruit is set.

Fungicide A chemical compound that is applied to a plant to kill disease organisms.

Glazing Light-transmitting materials, such as glass, polyethylene film, fiberglass, or polycarbonates, which are used to cover a greenhouse.

Gravel culture A soilless culture technique where plants are grown in beds containing gravel, which are periodically bathed in nutrient solution. The gravel serves as a root support for the plants.

Hoagland/Arnon nutrient solution A formulation of reagents mixed in water to form a solution for supplying a plant with its essential elements hydroponically, frequently only referred to a Hoagland nutrient solution. Designates a nutrient solution that has been widely used and modified. (See Table 7.10.)

Humate An organic substance that has unique physical and chemical properties and is obtained by alkaline extraction from soil or an organic material, such as peat moss.

Hydrogen (H) An essential element classed as a major element. Hydrogen is obtained from water (H_2O) and after splitting is combined with carbon dioxide (CO_2) to form a carbohydrate in the process called photosynthesis. (See **Photosynthesis**.)

Hydroponics A word coined in the early 1930s by Dr. W.F. Gericke (a University of California researcher) to describe a soilless technique for growing plants. The word was derived from two Greek words: *hydro* meaning water, and *ponos* meaning labor — literally, working water. Hydroponics has been defined as the science of growing plants without the use of soil or in an inert medium to which a nutrient solution containing all the essential elements needed by the plant for normal growth and successful completion of its life cycle is periodically added. In this text, hydroponics refers only to those systems of soilless growing that do not use a rooting medium.

Insect predators Insects that are cultured and brought into the greenhouse to combat insect infestations that are adversely affecting a plant.

Integrated pest management (IPM) A precise system designed to combat the infestation of plants by disease organisms and insects.

Intermittent flow nutrient solution culture A method of soilless culture in which the nutrient solution is only periodically brought into contact with plant roots.

Ion An atom or group of atoms having either a positive or negative charge from having lost or gained one or more electrons. (See **Anion** and **Cation.**)

Ion exchange A method of water purification in which water is passed through a resin bed to remove both cations and anions from the water. Ion exchange also refers to the phenomenon of physical–chemical attraction between charged colloidal substances with cations and anions. Ions of the essential elements can be removed from or released into the nutrient solution by ion exchange characteristics of sphagnum peat moss, pinebark, vermiculite, and clay colloids adhering to sand and gravel particles. Plant roots also have ion exchange properties.

Iron (Fe) An essential element classed as a micronutrient. Iron exists in the nutrient solution as either the ferrous (Fe^{2+}) or ferric (Fe^{3+}) cation. The common reagents for making a nutrient solution are iron tartrate, iron citrate, and the chelate forms, FeEDTA and FeDTPA. There are also inorganic compounds that can be used as a Fe source, such as ferrous and ferric sulfates, iron ammonium sulfate, and iron citrate and tartrate.

Langley A unit of incident solar radiation equal to one calorie per square centimeter.

Leaf analysis A method of determining the total elemental content of a leaf and relating this concentration to the well-being of the plant in terms of its elemental composition. (See **Plant analysis**.)

Macronutrient Refers to those nine essential elements (Ca, C, H, Mg, N, O, P, K, and S) that are found in the plant at relatively high concentration. (See **Major essential elements** and **Micronutrients**.)

Magnesium (Mg) An essential element classed as a major element. Magnesium exists in the nutrient solution as the divalent cation (Mg^{2+}). The common reagent for making a nutrient solution is magnesium sulfate ($MgSO_4{\bullet}7H_2O$).

Major essential elements The nine essential elements found in relatively large concentrations in plant tissues. These elements are Ca, C, H, Mg, N, O, P, K, and S.

Manganese (Mn) An essential element classed as a micronutrient. Manganese exists in the nutrient solution as the manganous cation (Mn^{2+}). The common reagent for making a nutrient solution is manganese sulfate ($MnSO_4 \cdot 4H_2O$).

Mass flow The movement of ions as a result of the flow of water; the ions are carried in the moving water.

Medicinal plants Those plants that have medicinal properties that are used for human health maintenance.

Micronutrients The seven essential elements required by and found in relatively small concentrations in plant tissue. These elements are B, Cl, Cu, Fe, Mn, Mo, and Zn.

Mil A unit of thickness equal to 0.0001 of an inch (0.0254 mm); it is used to define the thickness of glazing material. (See **Glazing material**.)

Mineral nutrition The study of the essential elements as they relate to the growth and well-being of plants.

Mist nutrient solution culture See **Aeroponics**.

Molybdenum (Mo) An essential element classed as a micronutrient. Molybdenum exists in the nutrient solution as the molybdate anion, MoO_4^{2-}. The common reagent for making a nutrient solution is ammonium molybdate, $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$.

Mycorrhizae A symbiotic association of the mycellium of a fungus that infests plant roots and provides unique characteristics that benefit the absorption of nutrient elements and protects roots against adverse chemical conditions.

Necrosis The dead tissue on plant leaves and stems that results from poor nutrition, disease damage, overheating, etc.

Neem An oil extracted from neem (*Azadirachta indica*) tree seeds that has both fungicidal and insecticidal properties. Azadirachtin is the active ingredient in neem oil.

NFT See Nutrient film technique.

Nitrogen (N) An essential element classed as a major element. Nitrogen is found in the nutrient solution as either the nitrate (NO_3^-) anion or the ammonium (NH_4^+) cation. The common reagents for making a nutrient solution are ammonium nitrate, NH_4NO_3; potassium or calcium nitrate, KNO_3 and $Ca(NO_3)_2 \cdot 4H_2O$, respectively; ammonium sulfate, $(NH_4)_2SO_4$; and ammonium mono- or di-hydrogen phosphate, $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$, respectively. Urea, $CO(NH_2)_2$, is also a commonly used N source, but it has only very special uses for the hydroponic and soilless grower.

Noncirculation hydroponic system A hydroponic growing system in which the nutrient solution is not reused.

Nutrient film technique (NFT) A technique for growing plants hydroponically in which the plant roots are suspended in a slow-moving stream of nutrient solution. The technique was developed by Dr. Allen Cooper.

Nutrient solution A water solution that contains one or more of the essential elements in suitable form and concentration for absorption by plant roots.

Open hydroponic system A growing system with one-way passage of the nutrient solution through the rooting medium or trough. After this single passage, the solution is discarded. (See **Closed hydroponic system**.)

Osmotic pressure Force exerted by substances dissolved in water that affects water movement into and out of plant cells. The salts dissolved in nutrient solutions exert some degree of force, which can restrict water movement into plant root cells or extract water from them.

Oxygen (O_2) An essential element classed as a major element. Oxygen is obtained from carbon dioxide (CO_2) in the air; it is fixed during photosynthesis. (See **Photosynthesis**.)

PAR See **Photosynthetic active radiation**.

Passive absorption The movement of ions into plant roots carried along with water being absorbed by roots. (See **Active absorption**.)

Perlite An aluminosilicate of volcanic origin. When this natural substance is crushed and heated rapidly to 1000°C, it forms a white, lightweight aggregate with a closed cellular structure. Perlite has an average density of 8 pounds per cubic foot (128 kg/m^3), has virtually no cation exchange capacity, is devoid of plant nutrients, contains some fluoride (17 mg/kg, ppm), and is graded into various particle sizes for use as a rooting medium or added to soilless mixes.

Pesticide A chemical applied on or around plants to kill pests.

pH The negative logarithm of the hydrogen ion concentration to the base 10:

$$pH = \log_{10} \times 1/[H^+]$$

As pH is logarithmic, the H^+ concentration in solution increases ten times when the pH is lowered one unit. The pH of the nutrient solution and rooting medium will significantly affect the availability and utilization of the essential elements.

Phosphorus (P) An essential element classed as a major element. Phosphorus exists in the nutrient solution as an anion, either as $H_2PO_4^-$ or HPO_4^{2-}, depending on the pH. The common reagents for making a nutrient solution are ammonium or potassium mono- or di-hydrogen phosphate, $(NH_4)_2HPO_4$, K_2HPO_4, $NH_4H_2PO_4$, and KH_2PO_4, respectively, and phosphoric acid, H_3PO_4.

Photosynthesis The process that occurs in green plant leaves by which chloroplasts in the presence of light split water (H_2O) and combine with carbon dioxide (CO_2) to form simple carbohydrates and release oxygen (O_2): $6CO_2 + 6H_2O$ —> chloroplasts in light —> $C_6H_{12}O_6 + 6O_2$.

Photosynthetic active radiation (PAR) That portion of the spectrum (450 to 700 nm) of solar radiation that participates in photosynthesis.

Pinebark A byproduct of the processing of pine, usually southern yellow pine, for lumber. Bark stripped from the tree is allowed to age (compost) in the natural environment for 6 months to 1 year and is then passed through a 1-inch screened hammer mill. The resulting material is screened into fractions of various sizes for addition to organic growing mixes. Pinebark has substantial cation exchange and water-holding capacities. Pinebark contains substantial quantities of Mn.

Plant analysis A method of determining the total elemental content of the whole plant or one of its parts and then relating the concentration found to the well-being of the plant in terms of its elemental requirements. (See **Leaf analysis**.)

Plant nutrient elements Those elements that are essential to plants. (See **Major essential elements**; **Macronutrients**; **Micronutrients**.)

Plant nutrition The study of the effects of the essential as well as other elements on the growth and well-being of plants.

Plant r equir ement That quantity of an essential element needed for the normal growth and development of the plant without inducing stress from a deficiency or an excess.

Potassium (K) An essential element classed as a major element. It exists in the nutrient solution as a monovalent (K^+) cation. The common reagents for making a nutrient solution are potassium chloride (KCl) and potassium sulfate (K_2SO_4).

Radiation The process in which energy is emitted as particles or waves. In relation to plants, it can refer to amount of solar energy impacting the plant. For greenhouse topics, it is the amount of energy that is either received into the greenhouse or that which may be lost from it.

Raft system A method of hydroponic growing in which a plant is set into an opening in a sheet of material floating on a depth of nutrient solution with the plant roots extending into the nutrient solution. This method of growing is confined to growing lettuce and herbs.

Relative humidity The percent of water vapor in air. The amount of water vapor that can be suspended in air will depend on the temperature of the air.

Reverse osmosis A method of water purification in which ions are removed from water by an electrical potential placed on either side of a membrane that acts to extract ions from a passing stream of water.

Rockwool An inert fibrous material produced from a mixture of volcanic rock, limestone, and coke, melted at 1500 to 2000°C, extruded as fine fibers, and then pressed into loosely woven sheets. rockwool has excellent water-holding capacity. For growing uses, the rockwool sheets are formed into slabs or cubes.

Salt index A relative measure of the osmotic pressure of a solution of a fertilizer material in relation to an equivalent concentration of sodium nitrate ($NaNO_3$) whose salt index is set at 100. (See Table 7.28.)

Sand cultur e A soilless culture technique where plants are grown in a bed containing sand, which is periodically bathed in nutrient solution.

Scor ch Burned leaf margins. This visual symptom is typical of potassium deficiency or chloride excess.

Secondary elements Obsolete term once used as a classification term for three of the major essential elements, Ca, Mg, and S.

Sider ophor es A substance released by plant roots to assist in the absorption of Fe. So-called "iron-sufficient" plants are those that release such substances.

Slow-r elease nutrients A form of fertilizer that has been treated or coated so that its solubility can be controlled.

Sodium Absorption Ratio (SAR) A ratio used to express the relative activity of sodium (Na^+) ions in relation to calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, expressed in milliequivalents per liter: $SAR = Na^+/\sqrt{\dfrac{Ca^{2+} + Mg^{2+}}{2}}$.

Soilless gar dening A term used to describe plant growing in other than soil.

Soilless r ooting medium A plant rooting medium that does not contain soil, but consists of inorganic (gravel, sand, vermiculite, perlite, rockwool , pumice) and/or organic (sphagnum peat moss, pinebark, coir, sawdust, rice hulls) substances.

Soluble salts A measure of the concentration of ions in water (or nutrient solution) used to determine the quality of the water or solution, measured in terms of its electrical conductivity. [See **Specifi c conductance** ; **Electrical conductivity (EC)** .]

Specifi c conductance The reciprocal of the electrical resistance of a solution, measured using a standard cell and expressed as mhos per centimeter (mho/cm) or decisiemens per meter (dS/m) at 25°C:

Specifi c Conductance This value is equal to θ /R where θ is the cell constant and R is the resistance in ohms. [See **Electrical conductivity (EC)** .]

Steiner nutrient solution A specifically formulated nutrient solution that contains the ions in solution in their ratio for ease of absorption by plant roots, a formulation developed by Dr. Steiner.

Stomata Minute openings in plant leaves where the exchange of gases (CO_2 and O_2) occurs and water vapor escapes. It is believed that the pr ocess of photosynthesis occurs in cells surrounding these openings. Stomata are surrounded by guard cells that can open and close the stomata depending on plant and atmospheric conditions.

Subirrigation A method of supplying water to plant roots by its introduction under plant roots.

Suf fi ciency Designation that an adequate supply of an essential element exists in the plant; also, an adequate concentration of an essential element in the plant to satisfy the plant's physiological requirement. The plant in such a condition will look normal in appearance, be healthy, and be capable of high production.

Sulfur (S) An essential element classed as a major element. Sulfur exists in the nutrient solution as the sulfate (SO_4^{2-}) anion. The common reagents for making a nutrient solution are potassium, magnesium, or ammonium sulfates, K_2SO_4, $MgSO_4{\bullet}7H_2O$, and $(NH_4)_2SO_4$, respectively.

Sump The reservoir for storage of the nutrient solution in closed, recirculating soilless culture systems.

Tissue testing A method for determining the concentration of the soluble form of an element in the plant by analyzing sap that has been physically extracted from a particular plant part, usually from stems or petioles. Tests are usually limited to the determination of nitrate, phosphate, K, and Fe. Tissue tests are normally performed using analytical kits, and the elemental concentration found is related to the well-being of the sampled plant. (See **Plant analysis** .)

Total dissolved solids (TDS) The concentrations of ions in solution measured in mg/L (ppm). TDS is related to the EC: EC (in dS/m) × 640 = TDS (mg/L, ppm). (See **Electrical conductivity** .)

Toxicity The condition in which an element is sufficiently in excess in the rooting medium, nutrient solution, or plant to be detrimental to the plant's normal growth and development.

Trace element Once commonly used to designate those essential elements that are currently referred to as micronutrients; designates those elements found in plants at low concentration levels, usually at a few or less than 1 mg/kg (ppm) of the dry weight.

Tracking A technique of following through time the essential element content of the rooting medium or plant by frequent time-spaced analyses.

Valence The combining capacity of atoms or groups of atoms. For example, potassium (K^+) and ammonium (NH_4^+) are monovalent, whereas calcium (Ca^{2+}) and magnesium (Mg^{2+}) are divalent. Some elements may have more than one valance state, such as Fe, which can be either divalent (Fe^{2+}) or trivalent (Fe^{3+}). This change from one valance state to another involves the transfer of an electron.

Ver miculite An aluminum–iron–magnesium silicate. When heated for about one minute to 1,000°C, this platelike, naturally occurring substance expands to 15 to 20 times its original volume, forming a lightweight, high-porosity material that has a density of about 5 pounds per cubic foot (80 kg/m^3). Vermiculite has a fairly high cation-exchange capacity (100 to 150 meq/100 g) and contains plant-available K and Mg. Normally, vermiculite is added to an organic mix to increase the water-holding capacity of the mix, particularly for germinating mixes.

Zinc (Zn) An essential element classed as a micronutrient. Zinc exists in the nutrient solution as the divalent cation (Zn^{2+}). The common reagent for making a nutrient solution is zinc sulfate, $ZnSO_4 \cdot 7H_2O$.

Appendix B: Characteristics of the Essential Elements

In this appendix, the characteristics of the essential elements are presented in outline form for easy reference. The objective is to provide the most useful information about each essential element in one easy-to-follow format. The information and data given are primarily in reference to the hydroponic/soilless growing methods for those crops thus commonly grown; therefore, the information given may not be useful for application with other growing methods or crops. The critical and excessive levels and the sufficiency ranges for the essential elements have been selected as probable levels and should not be considered specific. These levels are what would be found in recently mature leaves, unless otherwise specified.

Nitrogen (N)

Atomic Number: 7 **Atomic Weight:** 14.00
Discoverer of Essentiality and Year: DeSaussure, 1804
Designated Element: Major element
Function: Used by plants to synthesize amino acids and form proteins, nucleic acids, alkaloids, chlorophyll, purine bases, and enzymes
Mobility: Mobile
Forms Utilized by Plants: Nitrate (NO_3^-) anion and ammonium (NH_4^+) cation

Common Reagent Sources for Making Nutrient Solutions

Reagent	*Formula*	*%N*
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	11 (21% P)
Ammonium hydroxide	NH_4OH	20–25
Ammonium nitrate	NH_4NO_3	32 (16% NH_4 and 16% NO_3)
Ammonium sulfate	$NH_4(SO_4)_2$	21 (24% S)
Diammonium hydrogen phosphate	$(NH_4)_2HPO_4$	18 (21% P)
Calcium nitrate	$Ca(NO_3)_2 \cdot 4H_2O$	15 (19% Ca)
Potassium nitrate	KNO_3	13 (36% K)

Concentration in Nutrient Solutions: 100 to 200 mg/L (ppm); in a NO_3^--based nutrient solution; having 5 to 10% of the N as NH_4 will increase the uptake of N
Typical Deficiency Symptoms: Very slow-growing, weak, and stunted plants; leaves light green to yellow in color, beginning with the older leaves; plants mature early, and dry weight and fruit yield reduced
Plant Symptoms of Excess: Plants dark green in color with succulent foliage; easily susceptible to environmental stress and disease and insect invasion; poor fruit yield of low quality
Critical Plant Levels: 3.00% total N (will vary with plant type and stage of growth); 1000 mg/kg (ppm) NO_3-N in leaf petiole

Sufficiency Ranges in Plant Tissues:

Plant	*Plant Part*	*% N, Dry Weight*
Head lettuce	Whole head	2.1–5.6
Lettuce	Wrapper leaf	4.0–5.0
Bell pepper	Fully developed leaf	3.0–5.0
Tomato	Leaf opposite below flower cluster	
	First cluster	3.5–5.0
	Second cluster	3.2–4.5
	Third cluster	3.0–4.0
	Fourth cluster	2.3–3.5
	Fifth cluster	2.0–3.0
	Sixth cluster	2.0–3.0
Cucumber	Fully developed leaf	4.3–6.0

Excessive Plant Level: >5.00% total N (will vary with plant type and stage of growth); > 2000 mg/kg (ppm) NO_3-N in leaf petiole

Ammonium Toxicity: When NH_4 is the major source of N, toxicity can occur, seen as cupping of plant leaves, breakdown of vascular tissue at the base of the plant, lesions on stems and leaves, and increased occurrence of blossom-end rot (BER) on fruit

Phosphorus (P)

Atomic Number: 15 **Atomic Weight:** 30.973
Discoverer of Essentiality and Year: Ville, 1860
Designated Element: Major element
Function: Component of certain enzymes and proteins involved in energy transfer reactions and component of RNA and DNA
Mobility: Mobile
Forms Utilized by Plants: Mono- and di-hydrogen phosphates ($H_2PO_4^-$ and HPO_4^{2-}, respectively) anions, depending on pH

Common Reagents for Making Nutrient Solutions:

Reagent	*Formula*	*%P*
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	21 (11% N)
Diammonium hydrogen phosphate	$(NH_4)_2HPO_4$	21 (81% N)
Dipotassium hydrogen phosphate	K_2HPO_4	18 (22% N)
Phosphoric acid	H_3PO_4	34
Potassium dihydrogen phosphate	KH_2PO_4	32 (30% K)

Concentration in Nutrient Solutions: 30 to 50 mg/L (ppm) (The author recommends that the P content in a nutrient solution be between 10 and 20 mg/L or ppm.)
Typical Deficiency Symptoms: Slow and reduced growth, with developing purple pigmentation of older leaves; foliage very dark green in color
Symptoms of Excess: Plant growth will be slow, with some visual symptoms possibly related to a micronutrient deficiency, such as Zn

Critical Plant Level : 0.25% total; 500 mg/kg (ppm) extractable P in leaf petiole

Sufficiency Ranges in Plant Tissues :

Plant	*Plant Part*	*%P, Dry Weight*
Head lettuce	Whole head	0.4–0.9
Lettuce	Wrapper leaf	0.4–0.9
Bell pepper	Fully developed leaf	0.2–0.7
Tomato	Leaf opposite below flower cluster	
	First cluster	0.7–0.8
	Second cluster	0.5–0.8
	Third cluster	0.5–0.8
	Fourth cluster	0.5–0.8
	Fifth cluster	0.5–0.8
	Sixth cluster	0.5–0.8
Cucumber	Fully developed leaf	0.3–0.7

Excessive Plant Level : >1.00% total; >3000 mg/kg (ppm) extractable P in leaf petiole

Potassium (K)

Atomic Number: 19 **Atomic Weight:** 39.098
Discoverer of Essentiality and Year **:** von Sachs, Knop, 1860
Designated Element **:** Major element
Function: Maintains the ionic balance and water status in plants; involved in the opening and closing of stomata, and associated with carbohydrate chemistry
Mobility: Mobile
Form Utilized by Plants: Potassium (K^+) cation

Common Reagents for Making Nutrient Solutions :

Reagent	*Formula*	*% K*
Dipotassium hydrogen phosphate	K_2HPO_4	22 (18% P)
Potassium chloride	KCl	50 (47% Cl)
Potassium dihydrogen phosphate	KH_2PO_4	30 (32% P)
Potassium nitrate	KNO_3	36 (13% N)
Potassium sulfate	K_2SO_4	42 (17% S)

Concentration in Nutrient Solutions : 100 to 200 mg/L (ppm)

Typical Deficiency Symptoms: Initially slowed growth with marginal death of older leaves giving a "burned" or scorched appearance; fruit yield and quality reduced; fruit postharvest quality reduced
Symptoms of Excess: Plants will develop either Mg or Ca deficiency symptoms; plants can take up K easily and the amount found in the plant may exceed the biological need, called "luxury consumption"
Critical Plant Level: 2.00%

Sufficiency Ranges in Plant Tissues:

Plant	*Plant Part*	*%K, Dry Weight*
Head lettuce	Whole head	3.9–9.8
Lettuce	Wrapper leaf	6.0–7.0
Bell pepper	Fully developed leaf	3.5–4.5
Tomato	Leaf opposite below flower cluster	
	First cluster	3.0–6.0
	Second cluster	3.0–6.0
	Third cluster	5.0–7.0
	Fourth cluster	5.0–7.0
	Fifth cluster	5.0–7.0
	Sixth cluster	4.0–6.0
Cucumber	Fully developed leaf	2.5–4.0

Excessive Plant Level: >6.00%, which will be less depending on plant type and stage of growth; however, there are plants that have high K requirements greater than 6.00%

Calcium (Ca)

Atomic Number: 20 **Atomic Weight:** 40.07
Discoverer of Essentiality and Year: von Sachs, Knop, 1860
Designated Element: Major element
Functions: Major constituent of cell walls, for maintaining cell wall integrity and membrane permeability; enhances pollen germination and growth; activates a number of enzymes for cell mitosis, division, and elongation; may detoxify the presence of heavy metals in tissue
Mobility: Immobile
Form Utilized by Plants: Calcium (Ca^{2+}) cation

Common Reagents for Making Nutrient Solutions:

Reagent	*Formula*	*% Ca, Dry Weight*
Calcium chloride	$CaCl_2$	36 (64% Cl)
Calcium nitrate	$Ca(NO_3)_2 \cdot 4H_2O$	19 (15% N)
Calcium sulfate	$CaSO_4 \cdot 2H_2O$	23 (19% S)

Concentration in Nutrient Solutions: 200 to 300 mg/L (ppm)
Typical Deficiency Symptoms: Leaf shape and appearance will change, with the leaf margins and tips turning brown or black; edges of leaves may look torn; vascular breakdown at the base of the plant; for fruit crops, occurrence of blossom-end rot (BER)
Symptoms of Excess: May induce possible Mg or K deficiency
Critical Plant Level: 1.00% (will vary with plant type and stage of growth)

Sufficiency Ranges in Plant Tissues:

Plant	*Plant Part*	*% Ca, Dry Weight*
Head lettuce	Whole head	0.9–2.0
Lettuce	Wrapper leaf	2.3–3.5
Bell pepper	Fully developed leaf	1.3–2.8
Tomato	Leaf opposite below flower cluster	
	First cluster	1.4–3.0
	Second cluster	2.2–4.0
	Third cluster	2.2–4.0
	Fourth cluster	2.2–4.0
	Fifth cluster	2.2–4.0
	Sixth cluster	2.2–4.0
Cucumber	Fully developed leaf	2.5–4.0

Excessive Plant Level: >5.00% (will vary with level of K and/or Mg)

Magnesium (Mg)

Atomic Number: 12 **Atomic Weight:** 24.30
Discoverer of Essentiality and Year: von Sachs, Knop, 1860
Designated Element: Major element
Functions: Major constituent of the chlorophyll molecule; enzyme activator for a number of energy transfer reactions
Mobility: Moderately mobile
Form Utilized by Plants: Magnesium (Mg^{2+}) cation

Common Reagent for Making Nutrient Solutions :

Reagent	*Formula*	*% Mg*
Magnesium sulfate	$MgSO_4 \cdot 7H_2O$	10 (23% S)

Concentration in Nutrient Solutions : 30 to 50 mg/L (ppm)
Typical Deficiency Symptoms : Interveinal chlorosis on older leaves; possible development of blossom-end rot (BER) in fruit
Symptoms of Excess : Results in cation imbalance among Ca and K; slowed growth with the possible development of either Ca or K deficiency symptoms
Critical Plant Level : 0.25%

Sufficiency Ranges in Plant Tissues :

Plant	*Plant Part*	*% Mg, Dry Weight*
Head lettuce	Whole head	0.4–0.9
Lettuce	Wrapper leaf	0.5–0.8
Bell pepper	Fully developed leaf	0.3–1.0
Tomato	Leaf opposite below flower cluster	
	First cluster	0.3–0.7
	Second cluster	0.3–0.8
	Third cluster	0.3–0.8
	Fourth cluster	0.3–0.8
	Fifth cluster	0.3–0.8
	Sixth cluster	0.3–0.8
Cucumber	Fully developed leaf	0.5–1.0

Excessive Plant Level : > 1.50% (will vary with level of K and/or Ca)

Sulfur (S)

Atomic Number: 16 **Atomic Weight:** 32.06
Discoverer of Essentiality and Year: von Sachs, Knop, 1865
Designated Element: Major element
Functions: Constituent of two amino acids, cystine and thiamine; component of compounds that give unique odor and taste to some types of plants
Mobility: Moderately mobile
Form Utilized by Plants: Sulfate (SO_4^{2-}) anion

Common Reagents for Making Nutrient Solutions:

Reagent	*Formula*	*%S*
Ammonium sulfate	$(NH_4)_2SO_4$	24 (21% N)
Calcium sulfate	$CaSO_4{\cdot}2H_2O$	23 (26% Ca)
Magnesium sulfate	$MgSO_4{\cdot}7H_2O$	23 (10% Mg)
Potassium sulfate	K_2SO_4	17 (42% K)

Concentration in Nutrient Solutions: 70 to 150 mg/L (ppm)
Typical Deficiency Symptoms: General loss of green color of the entire plant; slowed growth
Symptoms of Excess: Not well defined
Critical Plant Level: 0.30%
Sufficiency Ranges: 0.4 to 1.0%; cucumber, fully developed leaf: 0.4 to 0.7%

Boron (B)

Atomic Number: 5 **Atomic Weight:** 10.81
Discoverer of Essentiality and Year: Sommer and Lipman, 1926
Designated Element: Micronutrient
Functions: Associated with carbohydrate chemistry, pollen germination, and cellular activities (division, differentiation, maturation, respiration, and growth); important in the synthesis of one of the bases for RNA formation
Mobility: Immobile
Forms Utilized by Plants: Borate (BO_3^{3-}) anion as well as the molecule H_3BO_3

Common Reagents for Making Nutrient Solutions :

Reagent	*Formula*	*% B*
Boric acid	H_3BO_3	**16**
Solubor	$Na_2B_4O_7 \cdot 4H_2O$ + $Na_2B_{10}O_{16} \cdot 10H_2O$	**20**
Borax	$Na_2B_4O_7 \cdot 10H_2O$	**11**

Concentration in Nutrient Solutions : 0.3 mg/L (ppm)
Typical Deficiency Symptoms : Slowed and stunted new growth, with possible death of the growing point and root tips; lack of fruit set and development; plants are brittle and petioles will easily break off the stem
Symptoms of Excess : Accumulates in the leaf margins, resulting in death of the margins
Critical Plant Level : 25 mg/kg (ppm)

Sufficiency Ranges in Plant Tissues :

Plant	*Plant Part*	*mg/kg (ppm) B (Dry Weight)*
Head lettuce	Whole head	22–65
Lettuce	Wrapper leaf	25–60
Bell pepper	Fully developed leaf	25–75
Tomato	Leaf opposite below flower cluster	
	First cluster	25–75
	Second cluster	25–75
	Third cluster	25–75
	Fourth cluster	25–75
	Fifth cluster	25–75
	Sixth cluster	25–75
Cucumber	Fully developed leaf	30–100

Toxic Plant Level : >100 mg/kg (ppm)

Chlorine (Cl)

Atomic Number: 17 **Atomic Weight:** 35.45
Discoverer of Essentiality and Year: Stout, 1954
Designated Element: Micronutrient

Functions: Involved in the evolution of oxygen (O_2) in photosystem II; raises cell osmotic pressure and affects stomatal regulation; increases hydration of plant tissue
Mobility: Mobile
Form Utilized by Plants: Chloride (Cl^-) anion

Common Reagent for Making Nutrient Solutions:

Reagent	*Formula*	*% Cl*
Potassium chloride	KCl	47 (50% K)

Concentration in Nutrient Solutions : 50 to 1000 mg/L (ppm) (depends on reagents used)
Typical Deficiency Symptoms : Chlorosis of the younger leaves; wilting
Symptoms of Excess : Premature yellowing of leaves; burning of leaf tips and margins; bronzing and abscission of leaves
Critical Plant Level : 20 mg/kg (ppm)
Sufficiency Range in Plant Tissue : 20 to 1500 mg/kg (ppm)
Excess Level : >0.50%

Copper (Cu)

Atomic Number: 29 **Atomic Weight:** 64.54
Discoverer of Essentiality and Year: Sommer, 1931
Designated Element: Micronutrient
Functions : Constituent of the chloroplast protein plastocyanin; participates in electron transport system linking photosystem I and II; participates in carbohydrate metabolism and nitrogen (N_2) fixation
Mobility: Immobile
Form Utilized by Plants: Cupric (Cu^{2+}) cation

Common Reagent for Making Nutrient Solutions :

Reagent	*Formula*	*% Cu*
Copper sulfate	$CuSO_4{\bullet}5H_2O$	25 (13% S)

Concentration in Nutrient Solutions : **0.01 to 0.1 mg/L (ppm); highly toxic to roots when in excess of 1.0 mg/L (ppm) in solution**
Typical Deficiency Symptoms : **Reduced or stunted growth, with a distortion of the young leaves; necrosis of the apical meristem**
Symptoms of Excess : **Induced iron deficiency and chlorosis; root growth will cease and root tips will die and turn black**
Critical Plant Level : **5 mg/kg (ppm)**

Sufficiency Ranges in Plant Tissues :

Plant	*Plant Part*	*mg/kg (ppm) Cu (Dry Weight)*
Head lettuce	Whole head	5–17
Lettuce	Wrapper leaf	8–25
Bell pepper	Fully developed leaf	6–25
Tomato	Leaf opposite below flower cluster	
	First cluster	5–20
	Second cluster	5–20
	Third cluster	5–20
	Fourth cluster	5–20
	Fifth cluster	5–20
	Sixth cluster	5–20
Cucumber	Fully developed leaf	8–10

Toxic Plant Level : >30 mg/kg (ppm)

Iron (Fe)

Atomic Number: 26 **Atomic Weight:** 55.85
Discoverer of Essentiality and Year: von Sachs, Knop, l860
Designated Element: Micronutrient
Functions: Component of many enzyme and electron transport systems; component of protein ferredoxin; required for NO_3 and SO_4 reduction, N_2 assimilation, and energy (NADP) production; associated with chlorophyll formation
Mobility: Immobile
Forms Utilized by Plants: Ferrous (Fe^{2+}) and ferric (Fe^{3+}) cations

Common Reagents for Making Nutrient Solutions :

Reagent	*Formula*	*% Fe*
Iron chelate	FeDTPA	6–12
Iron citrate		
Iron tartrate		
Iron lignin sulfonate		6
Ferrous sulfate	$FeSO_4{\bullet}7H_2O$	20 (11% S)
Ferrous ammonium sulfate	$(NH_4)_2SO_4{\bullet}FeSO_4{\cdot}6H_2O$	14

Concentration in Nutrient Solutions : 2 to 12 mg/L (ppm)
Typical Deficiency Symptoms : Interveinal chlorosis of younger leaves; as deficiency intensifies, older leaves are affected and younger leaves turn yellow, deficiency can be genetically induced
Symptoms of Excess : Not known for crops commonly grown hydroponically

Critical Plant Level : **50 mg/kg (ppm)**

Sufficiency Ranges in Plant Tissues :[a]

Plant	*Plant Part*	*mg/kg (ppm) Fe (Dry Weight)*
Head lettuce	Whole head	56–560
Lettuce	Wrapper leaf	50–100
Bell pepper	Fully developed leaf	60–300
Tomato	Leaf opposite below flower cluster	
	First cluster	60–300
	Second cluster	60–300
	Third cluster	60–300
	Fourth cluster	60–300
	Fifth cluster	60–300
	Sixth cluster	60–300
Cucumber	Fully developed leaf	50–300

[a]Extractable Fe may be a better indicator of sufficiency than total.

Excess Plant Level : Not known

Manganese (Mn)

Atomic Number: 25 **Atomic Weight:** 54.94
Discoverer of Essentiality and Year **:** McHargue, 1922
Designated Element: Micronutrient
Functions: Involved in oxidation–reduction processes in the photosynthetic electron transport system; photosystem II for photolysis; activates IAA oxidases
Mobility: Immobile
Form Utilized by Plants: Manganous (Mn^{2+}) cation

Common Reagents for Making Nutrient Solutions :

Reagent	*Formula*	*% Mn*
Manganese sulfate	$MnSO_4 \cdot 4H_2O$	24 (14% S)
Manganese chloride	$MnCl_2 \cdot 4H_2O$	28

Concentration in Nutrient Solutions : 0.5 to 2.0 mg/L (ppm); high P in the nutrient solution can increase the uptake of Mn
Typical Deficiency Symptoms : Reduced and stunted growth, with interveinal chlorosis on younger leaves

Symptoms of Excess : Older leaves show brown spots surrounded by chlorotic zone or circle; black spots (called "Measles") will appear on stems and petioles
Critical Plant Level : 25 mg/kg (ppm)

Sufficiency Ranges in Plant Tissues :

Plant	*Plant Part*	*mg/kg (ppm) Mn (Dry Weight)*
Head lettuce	Whole head	30–200
Lettuce	Wrapper leaf	15–250
Bell pepper	Fully developed leaf	50–250
Tomato	Leaf opposite below flower cluster	
	First cluster	50–250
	Second cluster	50–250
	Third cluster	50–250
	Fourth cluster	50–250
	Fifth cluster	50–250
	Sixth cluster	50–250
Cucumber	Fully developed leaf	30–300

Toxic Plant Level : >400 mg/kg (ppm)

Molybdenum (Mo)

Atomic Number: 42 **Atomic Weight:** 95.94
Discoverer of Essentiality and Year: Sommer and Lipman, 1926
Designated Element: Micronutrient
Functions: Component of two enzyme systems, nitrogenase and nitrate reductase, for the conversion of NO_3 to NH_4
Mobility in Plant: Immobile
Form Utilized by Plants: Molybdate (MoO_4^-) anion

Common Reagent for Making Nutrient Solutions :

Reagent	*Formula*	*% Mo*
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\bullet}4H_2O$	8 (1% N)

Concentration in Nutrient Solutions : 0.05 mg/L (ppm)
Typical Deficiency Symptoms : Resemble N deficiency symptoms, with older and middle leaves becoming chlorotic; leaf margins will roll; growth and flower formation restricted

Symptoms of Excess : Not known
Critical Plant Level : Not exactly known, probably 0.10 mg/kg (ppm)
Sufficiency Range : 0.2 to 1.0 mg/kg (ppm)
Excess Plant Level : Not known

Zinc (Zn)

Atomic Number: 30 **Atomic Weight:** 65.39
Discoverer of Essentiality and Year : Lipman and MacKinnon, 1931
Designated Element: Micronutrient
Functions: Involved in same enzymatic functions as Mn and Mg; specific to the enzyme carbonic anhydrase
Mobility: Immobile
Form Utilized by Plants: Zinc (Zn^{2+}) cation

Common Reagent for Making Nutrient Solutions :

Reagent	*Formula*	*% Zn*
Zinc sulfate	$ZnSO_4 \cdot 7H_2O$	22 (11% S)

Concentration in Nutrient Solutions : 0.05 mg/L (ppm), may need to be 0.10 mg/L if a chelated form of Fe is in the formulation; can be highly toxic to roots when in excess of 0.5 mg/L (ppm)
Typical Deficiency Symptoms : Upper new leaves will curl with rosette appearance; chlorosis in the interveinal areas of new leaves produces a banding effect; leaves will die and fall off; flowers will abscise
Symptoms of Excess : Plants may develop typical Fe deficiency symptoms; chlorosis of young leaves

Critical Plant Level : 15 mg/kg (ppm)

Sufficiency Ranges in Plant Tissues :

Plant	*Plant Part*	*mg/kg (ppm) Zn (Dry Weight)*
Head lettuce	Whole head	33–96
Lettuce	Wrapper leaf	25–250
Bell pepper	Fully developed leaf	20–80
Tomato	Leaf opposite below flower cluster	
	First cluster	20–80
	Second cluster	20–80
	Third cluster	20–80
	Fourth cluster	20–80
	Fifth cluster	20–80
	Sixth cluster	20–80
Cucumber	Fully developed leaf	25–80

Excess Plant Level : >100 mg/kg (ppm), high Zn can interfere with Fe nutrition

Appendix C: Reference Books

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Appendix D: Conversion Factors

Common Prefixes

Factor	*Prefix*	*Symbol*
1,000,000	Mega	M
1000	Kilo	k
1/100	Centi	c
1/1000	Milli	m
1/1,000,000	Micro	μ

Metric Conversion Factors (Approximate)

When You Know		Multiply By	To Find	Symbol
Length	Inches	2.54	Centimeters	cm
	Feet	30	Centimeters	cm
	yards	0.9	Meters	m
	miles	1.6	Kilometers	km
Area	Square inches	6.5	Square centimeters	cm^2
	Square feet	0.09	Square meters	m^2
	Square yards	0.8	Square meters	m^2
	Square miles	2.6	Square kilometers	km^2
	Acres	0.4	Hectares	ha
Weight	Ounces	28	Grams	g
	Pounds	0.45	Kilograms	kg
	Short tons (2000 pounds)	0.9	Metric tons	t
Volume	Teaspoons	5	Milliliters	mL
	Tablespoons	15	Milliliters	mL
	Cubic inches	16	Milliliters	mL
	Fluid ounces	30	Milliliters	mL
	Cups	0.24	Liters	L
	Pints	0.47	Liters	L
	Quarts	0.95	Liters	L
	Gallons	3.8	Liters	L
	Cubic feet	0.03	Cubic meters	m^3
	Cubic yards	0.76	Cubic meters	m^3
Pressure	Inches of mercury	3.4	Kilopascals	kPa
	Pounds/square inch	6.9	Kilopascals	kPa
Temperature (exact)	Degrees Fahrenheit	5/9 (after subtracting 32)	Degrees Celsius	˚C

Useful Information and Conversion Factors

Name	*Symbol*	*Approximate Size or Equivalent*
Length		
Meter	m	39.5 inches
Kilometer	km	0.6 mile
Centimeter	cm	Width of a paper clip
Millimeter	mm	Thickness of a paper clip
Area		
Hectare	ha	2.5 acres
Weight		
Gram	g	Weight of a paper clip
Kilogram	kg	2.2 pounds
Metric ton	t	Long ton (2240 pounds)
Volume		
Liter	L	1 quart and 2 ounces
Milliliter	mL	1/5 teaspoon
Pressure		
Kilopascal	kPa	Atmospheric pressure is about 100 kPa
Temperature		
Celsius	˚C	5/9 after subtracting 32 from ˚F
Freezing	0˚C	32˚F
Boiling	100˚C	212˚F
Body temp.	37˚C	98.6˚F
Room temp.	20 to 25˚C	68 to 77˚F
Electricity		
Kilowatt	kW	
Kilowatt-hour	kWh	
Megawatt	MW	
Miscellaneous		
Hertz	Hz	One cycle per second

Yield or Rate

Ounces per acre (oz/acre) × 0.07	= Kilograms per hectare (kg/ha)
Tons per acre (ton/acre) × 2240	= Kilograms per hectare (kg/ha)
Tons per acre (ton/acre) × 2.24	= Metric tons per hectare (kg/ha)
Pounds per acre (lb/acre) × 1.12	= Kilograms per hectare (kg/ha)
Pounds per cubic foot (lb/ft^3) × 16.23	= Kilograms per cubic meter (kg/m^3)
Pounds per gallon (lb/gal) × 0.12	= Kilograms per liter (kg/L)
Pounds per ton (lb/ton) × 0.50	= Kilograms per metric ton (kg/MT)
Gallons per acre (gal/acre) × 9.42	= Liters per hectare (L/ha)
Gallons per ton (gal/ton) × 4.16	= Liters per metric ton (L/MT)
Pounds per 100 square foot (lb/100 ft^2) × 2	= Pounds/100 gallons water (assumes that 100 gallons will saturate 200 square feet of soil)
Pounds per acre (lb/acre)/43.56	= pounds per 1000 square feet (lb/1000 ft^2)

Volumes and Liquids

Teaspoon = 1/2 tablespoon = 1/16 ounce
Tablespoon = 3 teaspoons = 1/2 ounce
Fluid ounces (fl oz) = 2 tablespoons = 6 teaspoons
Pint/100 gallons = 1 teaspoon per gallon
Quart per 100 gallons = 2 tablespoons per gallon
3 teaspoons = 1 tablespoon (tsp) = 14.8 milliliters (mL)
2 tablespoons (tsp) = 1 fluid ounces = 29.6 milliliters (mL)
8 fluid ounces (fl oz) = 16 tablespoons (tsp) = 1 cup = 236.6 milliliters (mL)
2 cups = 32 tablespoons (tsp) = 1 pint = 473.1 milliliters (mL)
2 pints = 64 tablespoons (tsp) = 1 quart (qt) = 946.2 milliliters (mL)
1 liter (L) = 1000 milliliters (mL) = 1000 cubic centimeters (cc) = 0.264 gallons (gal)= 33.81 ounces (oz)
4 quarts (qt) = 256 tablespoons (tsp) = 1 gallon (gal) = 3785 milliliters (mL)
1 gallon (gal) = 128 ounces (oz) = 3.785 liters (L)

Elemental Conversions

P_2O_5 × 0.437 = Elemental P	Elemental P × 2.29 = P_2O_5
K_2O × 0.826 = Elemental K	Elemental K × 1.21 = K_2O
CaO × 1.71 = Elemental Ca	Elemental Ca × 1.40 = CaO
MgO × 0.60 = Elemental Mg	Elemental Mg × 1.67 = MgO
$CaCO_3$ × 0.40 = Elemental Ca	

Weight/Mass

Ounce (oz) = 28.35 grams (g)
16 ounces (oz) = 1 pound (lb) = 453.6 grams (g)
Kilogram (kg) = 1000 grams (g) = 2.205 pounds (lb)
Gallon water = 8.34 pounds (lb) = 3.8 kilograms (kg)
1cubic foot of water (ft^3) = 62.4 pounds (lb) = 28.3 kilograms (kg)
1 kilogram of water (kg) = 33.81 ounces (oz)
Ton (t) = 2000 pounds (lb) = 907 kilograms (kg)
1 metric ton (MT) = 1000 kilograms (kg) = 2205 pounds (lb)

Volume Equivalents

Gallon in 100 gallons = 1 1/4 ounces (oz) in 1 gallon (gal)
Quart in 100 gallons = 5/16 ounce (oz) in 1 gallon (gal)
1 pint in 100 gallons = 1/16 ounce (oz) in 1 gallon (gal)
8 ounces (oz) in 100 gallons = 1/2 teaspoon in 1 gallon (gal)
4 ounces (oz) in 100 gallons = 1/4 teaspoon in 1 gallon (gal)

Temperature

˚C	˚F	˚C	˚F
S	40	120	248
10	50	125	257
19.4	67	180	356
20	68	200	392
21	70	330	626
23	73	350	662
25	77	370	698
27	80	400	752
32	90	450	842
38	100	500	932
40	105	550	1022
50	122	600	1122
80	176	900	1652
100	212	1350	2462
110	230		

°F= (°C + 17.78) × 1.8
°C = (°F – 32) × 0.556

Comparison of Commonly Used Concentration Units for the Major Elements and Micronutrients in the Dry Matter of Plant Tissue

	Concentration Units[a]			
Elements	**%**	**g/kg**	**cmol(p+)/kg**	**cmol/kg**
Major Elements				
Phosphorus (P)	0.32	5.2	—	10
Potassium (K)	1.95	19.5	50	50
Calcium (Ca)	2.00	20.0	25	50
Magnesium (Mg)	0.48	4.8	10	20
Sulfur (S)	0.32	3.2	—	10
Micronutrients	**ppm**	**mg/kg**	**mmol/kg**	
Boron (B)	20	20	1.85	
Chlorine (Cl)	110	100	2.82	
Iron (Fe)	111	111	1.98	
Manganese (Mn)	55	55	1.00	
Molybdenum (Mo)	1	1	0.01	
Zinc (Zn)	33	33	0.50	

[a] Concentration levels were selected for illustrative purposes only.

To Convert Molar Units to Parts per Million

Multiply the millimols per liter (mmol/L) or micremols per liter (μmol/L) by the atomic weight of the element = parts per million (ppm)

Macroelement (millimols/liter)	*Symbol*	*Atomic Weight*	*mmol/L**	*ppm*
Nitrogen	N	14	17.25	242
Potassium	K	39	11.00	429
Phosphorus	P	31	2.25	70
Calcium	Ca	40	5.5	220
Magnesium	Mg	24	1.50	36
Sulfur	S	32	2.27	88
Macroelement (micromoles/liter)	*Symbol*	*Atomic Weight*	*µmol/L**	*ppm*
Boron	B	11	31.25	0.34
Copper	Cu	64	0.625	0.04
Iron	Fe	56	1.25	7.00
Manganese	Mn	55	43.75	2.40
Molybdenum	Mo	96	0.625	0.06
Zinc	Zn	65	1.875	0.12

* chosen for illustrative purposes

To Convert lb/acre to Milliequivalents/100 g

Element	*Multiply by*
Calcium (Ca)	400
Magnesium (Mg)	780
Potassium (K)	240
Sodium (Na)	460

Conversion Values Useful for Completing Nutrient Solution Calculations

1.0 pound (lb) = 454 grams (g)
2.2 pounds (lb) = 1 kilogram (kg)
1.0 gram (g) = 1000 milligrams (mg)
1.0 gallon (gal) = 3.78 liters (L)
1.0 liter (L) = 1000 milliliters (mL)
1.0 milligram/liter (mg/L) = 1 part per million (ppm)
1.0 pound = 16 ounces (oz)
1.0 gallon (gal) water = 8.3 pounds (lb)
1.0 quart (qt) = 0.95 liters (L)
1.0 gallon (gal) = 128 ounces (oz)
1.0 gallon (gal) = 3780 milliliters (mL)

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