Hydroponics

A Practical Guide for the Soilless Grower

Second Edition

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Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Jones, J. Benton, 1930–
Hydroponics : a practical guide for the soilless grower / J. Benton Jones, Jr. — 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-3167-6 (alk. paper)
1. Hydroponics. I. Title.

SB126 .5 .J65 2005
631.5'85--dc22 2004054203

Direct all inquiries to CRC Press, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

Visit the CRC Press Web site at www.crcpress.com

International Standard Book Number 0-8493-3167-6
Library of Congress Card Number 2004054203
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

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

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[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

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[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 [$Ca(NO_3)_2 \cdot 4H_2O$]	0.8
Monopotassium phosphate (KH_2PO_4)	0.2
Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	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

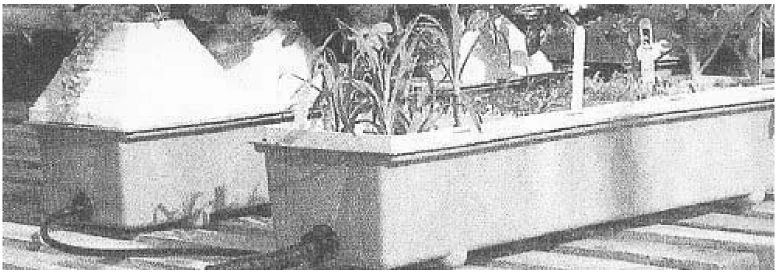

Figure 4.1 Pyramid-shaped container designed for optimum root development for hydroponic growing (a plant pot configuration designed by Dr. Robert Irvine). See Savage, A.J., 1995, *The Growing Edge* 6(3):40–47.

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.

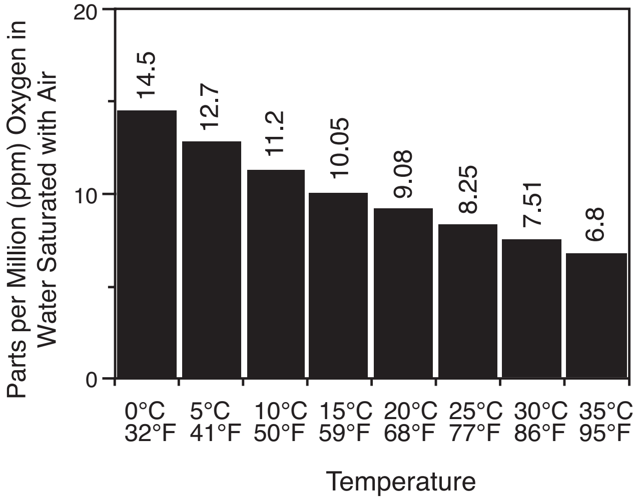

Figure 4.2 Dissolved oxygen (O_2) saturation limits for water at sea level pressure and temperature. ***Source:*** **Brooke, L.L., 1995a, *The Growing Edge* 6(4):34–39, 70–71.**

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