International
Fertilizer Industry
Association

Fertigation

A Tool for Efficient Fertilizer and Water Management

U. Kafkafi and J. Tarchitzky

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About the book

This book on fertigation is a joint project of the International Potash Institute (IPI) and the International Fertilizer Industry Association (IFA) intended for the fertilizer industry, scientists, extension workers and policy makers as a source of information on soil-water-fertilizer interactions during fertigation. The authors attempted to bring together various knowledge and information on plant physiology, plant nutrition and irrigation, which they synthesized into practical information in relation to fertigation of field and greenhouse operations. Through fertigation, the principles of the 4Rs (right source, at the right rate, right time and right place) are reaffirmed as the reader is given advice on the selection of appropriate fertilizer products for fertigation in growing various field and horticultural crops. The suitability of some fertilizers for fertigation is explained from the point of the plant's physiological demand at various growth stages, the soil or growing media type, climatic conditions and irrigation water quality.

About the authors

Uzi Kafkafi

Born 1934 in Tel Aviv, Israel, Uzi Kafkafi received his PhD in Soil Science in 1963 from The Hebrew University of Jerusalem on the topic of "Phosphorus Placement." His early research works include the evaluation of nutrient availability in soils and identifying the form of phosphate sorption to clay particles.

In 1977, he was appointed to head the first "Research and Development Center" in Israel that brought together research institutes scientists and practicing growers in developing crops for protected agriculture on sand dunes. The fertigation of tomatoes in sand dunes was his first work on fertigation in 1968. Since 1966, his main interest has been the effect of nitrogen forms in soils and in nutrient solutions and the competition between nitrate and chloride in plant uptake. In 1986, he joined The Hebrew University of Jerusalem, Faculty of Agriculture in Rehovot as a professor of plant nutrition and arid land agriculture.

Uzi Kafkafi served in the scientific board of the International Potash Institute (IPI), and as a consultant to the Israeli fertilizer industries. In 1996 he was awarded the "IFA International Crop Nutrition Award" for his research and contribution to the development of fertigation.

Throughout his entire academic career, Uzi Kafkafi has taken a particular interest in various aspects of root activities in field and in solution culture. In this work, he developed the study of root activity of field crops using an innovative radioactive placement method in the field to map root zone activity and introduced the course on root activities to the curriculum of The Hebrew University. He also joined his colleagues as an editor of the book "Plant Roots- the Hidden Half" to which world experts on root studies contributed their works. This highly successful collaboration has resulted in three successive editions of an internationally recognized text. Although he officially retired from active teaching in 1999, Uzi Kafkafi is still involved in teaching PhD students, consulting in Israel and in China and in writing scientific papers.

Jorge Tarchitzky

Born 1951 in Bahía Blanca, Argentina, Jorge Tarchitzky graduated as an Agricultural Engineer in Argentina in 1974. He completed his MSc studies in Soil and Water Sciences, in the Faculty of Agriculture, Rehovot in 1980. His PhD thesis, the "Interactions between humic substances, polysaccharides and clay minerals and their effect on soil structure" was awarded in 1994 by The Hebrew University of Jerusalem. In 1980, he was appointed as a Regional Advisor in the Field Service for Soil and Water in the Extension Service of the Ministry of Agriculture, Israel, advising farmers in irrigation and fertilization management of crops and fertigation systems. In 1992, he was appointed as National Advisor for Salinity and Effluent Water Irrigation where he was in charge of training regional extension agents and consultants on water quality, soil and water salinity, wastewater use for crop irrigation, agricultural and municipal solid wastes usage for crop nutrition and soil amendments. From 1998, he served as the Advisor on Environmental Quality in Agriculture to the management board of the Ministry of Agriculture and Rural Development. In 2006, he was appointed as Head of the Soil and Water Field Service Department, in the Extension Service, of the Ministry of Agriculture and Rural Development.

In 2008, Jorge Tarchitzky joined the Department of Soil and Water Sciences in the Robert H. Smith Faculty of Agricultural, Food and Environmental Sciences of the Hebrew University of Jerusalem and currently is a Senior Associate Researcher. He is responsible for teaching a graduate course on "Treated wastewater re-use for crop irrigation and its environmental impact." As well as teaching MSc and PhD students, he also serves as a consultant for governmental institutions and private companies in the field of water quality and environmental issues in agriculture.

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We are grateful for their support during our tedious work of screening the world literature on trickle irrigation and weaving this information together with our own experience, to provide the grower a practical tool to handle and safely operate fertigation of various field, plantations and garden crops.

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Uzi Kafkafi and Jorge Tarchitzky, April 2011

List of abbreviations, acronyms, and symbols

Abbreviations

ADP	adenosine di-phosphate
APP	ammonium polyphosphate
ATP	adenosine tri-phosphate
BOD	biochemical oxygen demand
CEC	cation exchange capacity
cm	centimeter
cm^3	cubic centimeter
cmol$_c$	centimole charge
C/N	carbon/nitrogen ratio
DAS	days after sowing/seeding
DM	dry matter
dS m^{-1}	deci-Siemens per meter
DTPA	diethylene-triamine-pentaacetic acid
EC	electrical conductivity
EDDHA	ethylene-diamine di ortho-hydroxyphenylacetic acid
EDTA	ethylene-diamine-tetraacetic acid
g	gram
ha	hectare
HAP	hydroxyapatite
HDP	hydroxydicalcium phosphate
kg	kilogram
kg ha^{-1}	kilogram per hectare
kPa	kilo Pascal
L	liter
lb	pound
lb a^{-1}	pound per acre
m^3	cubic meter
meq	milliequivalent
meq g^{-1}	millequivalent per gram
	(note: cmol per 100g is now used to replace meq in CEC)
mm	millimeter
mg	milligram
mg L^{-1}	milligram per liter

MKP	mono potassium phosphate
mL	milliliter
mmol	millimole
mM	millimolar
mol	mole
MOP	muriate of potash (also known as potassium chloride)
pH	H ion concentration (measure of acidity or alkalinity)
ppm	part per million
SAR	sodium adsorption ratio
SAT	soil aquifer treatment
SDI	sub-surface drip irrigation
SOP	sulfate of potash or potassium sulfate
TSS	total suspended solids
TWW	treated waste water
t ha^{-1}	tonne per hectare

Acronyms

EPA	Environmental Protection Agency
USA	United States of America
EU	European Union

Symbols

Al	aluminum
B	boron
$B(OH)_3$	boric acid
$B(OH)_4^-$	borate
Ca	calcium
CaCl	calcium chloride
$CaCO_3$	calcium carbonate
$Ca(NO_3)_2$	calcium nitrate
$5\ Ca(NO_3)_2 \cdot NH_4NH_3 \cdot 10H_2O$	calcium ammonium nitrate
Cd	cadmium
Cl	chloride
$CO(NH_2)_2$	urea
Cu	copper
Fe	iron
Fe^{2+}	ferrous ion
Fe^{3+}	ferric ion
H^+	hydrogen ion
HCO_3	bicarbonate

HPO_4^{2-}	hydrogen phosphate
$H_2PO_4^-$	dihydrogen phosphate
H_3PO_4	phosphoric acid
K	potassium
KCl	potassium chloride
K_2O	potash
KH_2PO_4	monopotassium phosphate (MKP)
KNO_3	potassium nitrate
K_2SO_4	potassium sulfate
Mg	magnesium
$Mg(NO_3)_2$	magnesium nitrate
Mn^{2+}	manganese ion
N	nitrogen
Na	sodium
NaCl	sodium chloride
NH_3	ammonia
NH_4^+	ammonium ion
NH_4CO_3	ammonium carbonate
$NH_4H_2PO_4$	monoammonium phosphate (MAP)
NH_4NO_3	ammonium nitrate
NH_4OH	ammonium hydroxide
$(NH_4)_2SO_4$	ammonium sulfate
Ni	nickel
NO	nitric oxide
NO_3^-	nitrate ion
N_2O	nitrous oxide
P	phosphorus
Se	selenium
Si	silicon
SO_4^{2-}	sulfate
Zn	zinc

Summary

The aim of this book is to provide the advanced grower and extension personnel with a broad spectrum of expertise and knowledge on fertigation. In the 16 chapters presented here, the reader is given advice on appropriate selection of fertilizer compounds used in fertigation for growing various field and horticultural crops in particular locations based on soil type and climatic conditions, which synchronize the crop's nutrient demand with fertilizer supply throughout its growth in effect applying the 4R principles. The book is mainly focused on the interactions of fertilizers in the soil and their ability to supply nutrients to plants. Fertigation is a tool to supply the plant with its daily demand of water and nutrients as required by its specific growth stage throughout its development to achieve maximum efficiency of the fertilizer applied. Using this "spoon feeding" approach to fertilization, the units of fertilizer application in fertigation are calculated on the basis of individual plant demand expressed in units of milligram of nutrient (N, P or K) per day over the entire growing period. By adopting this approach, readily soluble nutrients can be supplied directly to the root volume thereby maximizing nutrient efficiency and minimizing over fertilization and leakage to underground water with possible damage to the environment. The authors have attempted to bring together knowledge of plant nutrition and physiology from many research centers and laboratories throughout the world and to integrate this information with actual fertilizer application in field and greenhouse commercial operations. A detailed discussion of soil water and its distribution has purposely been avoided partly because of shortage of space but also because there are many excellent earlier reviews on this topic, which the authors have cited in describing fertilizer transport in the soil. The authors' extensive experience of fertilizer usage in the field and in greenhouse cropping systems is reflected in their treatment of specific case studies and from their wide knowledge of the many referenced citations covering more than half a century of publications from all over the world. The fertilizers suitable for fertigation are explained from the viewpoint of the plant's physiological demand at various growth stages, the soil and the growing media type, climatic conditions and irrigation water quality. Fertigation has enabled growers to use sand dunes for crop production which, in the past, were classified as "non agricultural lands." The introduction of well tested and efficient fertigation techniques into the world will help turn vast areas of desert soils into productive agricultural areas as well as saving precious water from being wasted in conventional agricultural systems.

1. Introduction

The chemical compositions of soluble single-nutrient and compound fertilizers produced by the fertilizer industry are usually almost the same worldwide. On the other hand, the application of these fertilizers is highly site-specific, depending on soil type, climatic conditions and water quality. Fertilizer demand in intensive plant production systems is particularly variable, changing rapidly during the season and the year and even within day and night. The nutrient requirements of annual crops is very much dependent on the biological stage of growth, varying from seeding to harvest, and likewise in orchard crops from vegetative to fruiting periods.

Traditional flood and overhead sprinkle irrigation systems result in a wet soil profile. Plant nutrients are distributed in this wet soil volume depending on their mobility, their sorption and precipitation reactions with soil particles.

The movement of water in the soil from a dripper point source progresses in both a horizontal circular direction on the soil surface, as well as in a vertical direction down the soil profile. This creates a wet soil volume with soil varying in moisture content over soil depth (Bressler, 1977). The interaction of soil particles with the water is mainly physical in nature and involves sorption and capillary forces that control the distribution of a unit volume of water in a unit volume of soil. Soil volume is subjected to mechanical compaction by field implements that affect pore size distribution and volumetric soil moisture content.

The need to supply enough food for a growing world population stimulated interest to increase irrigation efficiency. Sprinkler irrigation was developed before 1920 and, in the 1930s, sprinklers and lightweight steel pipes were developed (Keller and Bliesner, 1990).

The first experiments leading to the development of trickle irrigation date from the end of the 19th century, but real progress was not achieved until the late 1950s and early 1960s (Keller and Bliesner, 1990). The rapid implementation of trickle irrigation started in the 70s as a result of the invention of cheap plastic pipes. The trickle or micro irrigation systems include drip, micro-jet and sprayers, and micro sprinkler emitters. The worldwide area irrigated by these systems in 1974, was about 66,000 hectares, rising to 2.98 million hectares in 1996 (Magen and Imas, 2003) and 6 million hectares in 2006 (Sne, 2006).

The adoption of trickle irrigation methods with only partial soil wetting brought about the concomitant transition in restricting crop root system distribution mainly to the wetted zone. These limited root systems considerably modify classical fertilization management. The shift from a broadcast fertilizer application to banded fertilization or to fertilizer added to the irrigation water was developed in order to meet the nutrient needs of the trickle irrigated crop. Chronologically, fertigation was an outcome of the localized irrigation.

The reactions of soil particles with the various chemical compounds delivered in the trickle irrigation solutions, however, are very complex. They involve chemical interactions between the constituents of soil particles which carry permanent electrical charges on their surfaces, precipitation reactions with calcium carbonate (lime) in basic reactive soils and with aluminum and iron in acid soils.

Nitrogen (N) in fertilizer solutions is available mainly in three forms:

- **Ammonium–N**: that has a positive electric charge (cation).
- **Nitrate–N**: that has a negative electric charge (anion).
- **Urea–N**: that is a non-charged molecule.

These N compounds encounter a highly complex environment when they come in contact with the soil. The ammonium cation is adsorbed to the negatively charged clay particles and is slowly oxidized by soil bacteria to nitrate-N. The nitrate-N enters the soil under the dripper into a water saturated zone, devoid of oxygen, which contains soil bacteria that actively seek an oxygen source to meet their respiratory demands. As a result, before it can be taken up by the plant, part of the oxidized nitrate present in the soil may be reduced to nitrous oxide (N_2O) or dinitrogen (N_2) to return in gaseous form to the atmosphere. Another part of the nitrate moves with the water and accumulates to a very high concentration at the boundary between the wet and dry soil zones. Most important is the fraction of nitrate-N taken up by plants from the fertilizer N supplied, which is a key factor in successful economic fertigation. Urea, the non-charged molecule, is able to travel considerable distances in the soil with the moving water. Once in contact with the ubiquitous soil enzyme urease, however, this molecule is rapidly converted to carbon dioxide (CO_2) and ammonia, which upon dissolving in water, results temporarily – for a few days – in a local rise in soil pH.

Phosphate soluble fertilizers are prone to precipitation reactions with calcium (Ca) and magnesium (Mg) already in the irrigation line when the solution has a pH above 7 or when soluble iron (Fe) is present at low pH. Thus, even before the phosphorus (P) emerges from the trickle, it has to be protected from precipitation both inside the trickle lines and in the fertilization tanks. Once in the soil, the distance travelled by P is the smallest of all nutrients supplied by fertigation. Phosphorus fertigation has to take into account water quality, soil chemical composition and plant age.

Potassium (K) is the most stable form of all the major nutrients supplied by fertigation always remaining in the same chemical form as a monovalent cation (K^+).

Sand dunes, highly calcareous, saline and alkali soils occupy vast areas in arid zones of the world (Richards, 1954). These soils are characterized by low available nutrient content and low to medium water-holding capacity of the upper soil surface. These features result in low vegetation density under arid climatic conditions. Desert sand dunes were hardly used for farming under regular sprinkler irrigation, or by flood irrigation as they are usually located far away from water sources and have very low water holding capacity. The introduction of fertigation had a major impact in turning these desert sand dunes and highly calcareous desert soils into productive agricultural soils for high cash crops (Kafkafi and Bar-Yosef, 1980). In desert areas, fertigation allows the cultivation of date tree plantations where irrigation water is delivered to each individual tree, thus preventing losses of large amounts of water due to direct evaporation from open soil spaces. Similarly, the trickle irrigation technique allows the cultivation of crops in marginal soils never before done under productive agriculture.

Several reviews deal with the technical aspects of fertilizer incorporation into irrigation water and the essential properties of fertilizers used in fertigation.

The main purpose of this manuscript is to explain the basic behavior of soluble fertilizers supplied by trickle irrigation in growing different crops on various soil types under varied climatic conditions. Fertigation enables the grower to select and use high quality fertilizer most suitable for his soil, irrigation water source, crop and climatic conditions to produce high quality crops and, at the same time, prevent environmental pollution.

2. Fertigation

2.1. Definition

The practice of supplying crops in the field with fertilizers via the irrigation water is called fertigation (Bar-Yosef, 1991). Fertigation - a modern agro-technique, provides an excellent opportunity to maximize yield and minimize environmental pollution (Hagin *et al.*, 2002) by increasing fertilizer use efficiency, minimizing fertilizer application and increasing return on the fertilizer invested. In fertigation, timing, amounts and concentration of fertilizers applied are easily controlled. The incorporation of fertilizers into the irrigation system demands the following basic requirements:

- Equipment
  - In pressurized irrigation systems, the injected fertilizer solution has to be greater than that of the internal pressure.
  - A filter to prevent dripper clogging by any solid particles from reaching the dripper (Elfuving, 1982).
  - A back-flow preventing valve.
- Fertilizers
  - Solubility of the fertilizers in the indigenous water source: irrigation water contains various chemical constituents some of which may interact with dissolved fertilizers with undesired effects.
  - The degree of acidity of the fertilizer solution has to be considered in relation to its corrosiveness to the irrigation system components.

2.2. Fertigation equipment

The choice of fertigation equipment has to take into account both crop requirement and irrigation system capacity.

2.2.1. Gravity irrigation systems

This very simple method is only applicable to irrigation systems working at atmospheric pressure in which water flows in open channels. The fertilizer solution drips into the irrigation channel because the fertilizer tank is above the level of the channel. In order to obtain good mixing, the velocity of the irrigation stream must be high enough.

2.2.2. Pressurized irrigation systems

Injection of the fertilizer consumes energy in order to overcome the internal pressure of the irrigation network. Fertilizer injection equipment is classified into three principal groups, according to the means employed to obtain the higher pressure for the fertilizer solution:

- Injection by a **Venturi device**: This is a unit that makes use of the Venturi suction principle by using the pressure induced by the flowing water to suck the fertilizer solution from the fertilizer tank into the irrigation line. A conical constriction in the pipe induces an increase in the water flow velocity and a pressure decrease to an extremely low value which causes fertilizer suction (through the filter screens) from the supply tank through a tube into the irrigation system. A valve can be adjusted to control the difference between the water velocities across the valves.
- Injection by **differential pressure**: This system utilizes an air tight pressure metal tank with anti-acid internal wall protection in which a pressure differential is created by a throttle valve that diverts part of the irrigation water into the tank. This is the only fertigation system that enables the use of both solid and liquid fertilizers. The entire fertilizer amount in the tank is delivered to the irrigation area. The concentration at the water emitter end is kept constant as long as a solid fertilizer is present in the tank and solubility of the fertilizer is quickly achieved. Once the solid fraction is completely dissolved the fertilizer concentration is reduced at an exponential rate. In practice, when four tank volumes have passed through it, only a negligible amount of fertilizer is left in the tank. This equipment was used in the early stages of fertigation development. A limited area can be irrigated at a time according to the tank volume. The use of solid fertilizers must be handled with care. Fertilizers that have endothermic reaction when dissolved, like KNO_3, $Ca(NO_3)_2$, Urea, NH_4NO_3, KCl and $5Ca(NO_3)_2{\cdot}NH_4NH_3{\cdot}10H_2O$ decrease the temperature in the tank and when added during cold hours in the early morning before irrigation, part of the solution can freeze, leading to unexpected changes in the nutrient concentrations.
- Injection by **positive pressure**: Injection pumps are able to raise the pressure of the liquid fertilizer from a stock solution tank at a predetermined ratio between fertilizer solution volumes to irrigation water volume, hence achieving a proportional distribution of nutrient in the irrigation water. The advantages of using injection pumps are the lack of pressure loss of the irrigation water, its accuracy and the ability to provide a determined concentration through the irrigation cycle. Two types of injectors are commonly used in fertigation: piston pumps and diaphragm pumps. The most common power sources for fertigation pumps are:
    - **Hydraulic energy:** The device uses the hydraulic pressure of the irrigation water to inject nutrient solution while the water used to propel it (approximately three times the volume of solution injected) is discharged. These pumps are suitable for fertigation in areas devoid of sources of electricity.
    - **Electric dosing pumps:** The device activates the fertilizer pump. These are common in glasshouses and in areas where electricity is available and reliable.

2.3. Fertilizer dosing in fertigation

According to Sne (2006), to apply the same doses of fertilizers during the specific phenological stage of a plant, two different patterns of application can be made depending on the crop, soil type and farm management system:

- **Quantitative dosing:** A measured amount of fertilizer is injected into the irrigation system during each water application. Injection may be initiated and controlled automatically or manually.
- **Proportional dosing:** In this process, a constant predetermined ratio between the volume of the irrigation water and the volume of the fertilizer solution is maintained, resulting in a constant nutrient concentration in the irrigation water.

2.4. Suitability of fertilizers for fertigation

A large range of fertilizers, both solid and liquid, are suitable for fertigation depending on the physicochemical properties of the fertilizer solution. For large scale field operations, solid fertilizer sources are typically a less expensive alternative to the commonly used liquid formulations. The solubility of these fertilizers does vary greatly. When switching to a solid fertilizer source, problems can be avoided in the nurse tanks by ensuring that ample water is added to the stock solution.

Four main factors in selecting fertilizers for fertigation should be considered (Kafkafi, 2005):

- Plant type and stage of growth
- Soil conditions
- Water quality
- Fertilizer availability and price

The type of fertilizer for fertigation should be of high quality, with high solubility and purity, containing low salt levels and with an acceptable pH, and it must fit in the farm management program. The fertilizer characteristics as well as their effects on soils and crops are presented later.

Hagin and Lowengart-Aycicegi (1996) enumerated the main properties relating to the suitability of the fertilizer to the injection method as follows:

- **Form**: Soluble solid and liquid fertilizers are both suitable for fertigation depending on availability, profitability and convenience.
- **Solubility**: High and complete solubility is a prerequisite for fertilizers used in fertigation. Fertilizer solubility generally increases with temperature, depending on the fertilizer.
- **Interaction between fertilizers in solution**: When one type of fertilizer or more are prepared and mixed by the grower, or in the irrigation line (but to a lesser extent), the compatibility between them must be checked (see Table 1.1). There are usually some basic precautions that must be taken:
    - Make sure that the fertilizers used are compatible to prevent precipitation. Especially, avoid mixing fertilizer solutions that contain calcium with solutions

Table 1.1. Fertilizer compatibility chart (Roddy, 2008).

	Urea	Ammonium nitrate	Ammonium sulfate	Calcium nitrate	Potassium nitrate	Potassium chloride	Potassium sulfate	Ammonium phosphate	Fe, Zn, Cu, Mn sulfate	Fe, Zn, Cu, Mn chelate	Magnesium sulfate	Phosphoric acid	Sulfuric acid	Nitric acid
Urea	√													
Ammonium nitrate	√	√												
Ammonium sulfate	√	√	√											
Calcium nitrate	√	√	x	√										
Potassium nitrate	√	√	√	√	√									
Potassium chloride	√	√	√	√	√	√								
Potassium sulfate	√	√	R	x	√	R	√							
Ammonium phosphate	√	√	√	x	√	√	√	√						
Fe, Zn, Cu, Mn sulfate	√	√	√	x	√	√	R	X	√					
Fe, Zn, Cu, Mn chelate	√	√	√	R	√	√	√	R	√	√				
Magnesium sulfate	√	√	√	x	√	√	R	x	√	√	√			
Phosphoric acid	√	√	√	x	√	√	√	√	√	R	√	√		
Sulfuric acid	√	√	√	x	√	√	R	√	√	√	√	√	√	
Nitric acid	√	√	√	√	√	√	√	√	√	x	√	√	√	√

√ = compatible x = incompatible R = reduced compatibility

  containing phosphates or sulfates when the pH in the solution is not sufficiently acidic.
  - Check the solubility and potential precipitation with the local water chemical composition. Before using a new fertilizer, mix 50 ml of the fertilizer solution with 1 liter of the irrigation water and observe for precipitation within 1-2 hours. If precipitates are formed or the sample becomes cloudy, refrain from using this fertilizer in the irrigation system (Roddy, 2008).
  - Check the temperature resulting from mixing various types of fertilizers under field conditions. Some fertilizers alone or in combination may lower the solution temperature to freezing levels (e.g. KNO_3, $Ca(NO_3)_2$, urea, NH_4NO_3, KCl and $5Ca(NO_3)_2 \cdot NH_4NH_3 \cdot 10H_2O$. However, when purchasing ready-to-use liquid fertilizers, the endothermic reaction does not occur in the field, hence, slightly higher concentrations of nutrients in the solution can be achieved.
- **Corrosivity**. Chemical reactions may occur between fertilizers and metal parts in the irrigation and fertigation systems. Corrosion can harm metallic components of the system like uncoated steel pipes, valves, filters and injection units.

Some characteristics of the fertilizers previously described are presented in Tables 1.1 to 1.3. Table 1.1 describes three grades of compatibility between various fertilizers used

Table 1.2. Solubility, pH and other characteristics of some fertilizers (adapted from Primary Industries: Agriculture, 2000).

	Maximum amount (kg) dissolved in 100 L at 20°C	Time to dissolve (min)	pH of the solution	Insolubles (%)	Comments
Urea	105	20[1]	9.5	negligible	Solution cools as urea dissolves.
Ammonium nitrate NH_4NO_3	195	20[1]	5.62	–	Corrosive to galvanised iron and brass. Solution cools as product dissolves.
Ammonium sulfate $(NH_4)_2SO_4$	43	15	4.5	0.5	Corrosive to mild steel.
Mono-ammonium phosphate MAP	40	20	4.5	11	Corrosive to carbon steel.
Di-ammonium phosphate DAP	60	20	7.6	15	Corrosive to carbon steel.
Potassium chloride KCl	34	5	7.0–9.0[2]	0.5	Corrosive to brass and mild steel.
Potassium sulfate K_2SO_4	11	5	8.5–9.5[2]	0.4–4[2]	Corrosive to mild steel concrete.
Mono-potassium phosphate MKP	213	–	5.5+/-0.5	<0.1	Non corrosive
Potassium nitrate KNO_3	31	3	10.8	0.1	Solution cools as product dissolves. Corrosive to metals.

[1] Solution temperature drops to 0°C, hence it takes longer for all material to dissolve.

[2] These figures are the ranges found in shipping analyses and refer to different sources of supply.

in fertigation. Table 1.2 describes characteristics of fertigation solutions made at field conditions. Table 1.3 describes the change in solubility of few fertilizers with change of temperature.

Table 1.3. Approximate solubility (grams product per 100 g water) at different temperatures (adapted from Primary Industries: Agriculture, 2000).

Temperature	KNO_3	KCl	K_2SO_4	NH_4NO_3	Urea
10°C	21	31	9	158	84
20°C	31	34	11	195	105
40°C	46	37	13	242	133

3. Soil properties and plant growth conditions

3.1. Water regime and distribution in soil

In traditional irrigation like flood, furrow or sprinkler systems, water is usually applied in large quantities with intervals of days or even weeks between irrigations. In contrast, trickle irrigation (drip, surface or sub-surface, spray, micro-jet and micro-sprinkler) is characterized by shorter intervals, lasting hours to a few days, delivering relatively small amounts of water per unit time from each emitter. In flood and sprinkler irrigation, water movement within the soil follows a one-dimensional vertical, percolation pattern. Trickle irrigation systems, however, normally wet only a portion of the horizontal, cross-sectional area of the soil.

Water movement within the soil follows a three-dimensional flow pattern in which two driving forces simultaneously affect the flow of water in the soil, namely gravity and capillarity. Gravity drives the water downwards. Capillary forces propel the water in all directions. In subsurface drip irrigation, the wetting pattern is quite different in that water may also move to some extent upwards (Sne, 2006). The percentage wetted area compared with the entire cropped area depends on the volume and rate of discharge at each emission point, the spacing of emission points, and type of soil being irrigated (Keller and Bliesner, 1990). Drip irrigation is characterized by delivering relatively small amounts of water per unit time from each dripper. In dry summer seasons, part of the soil remains dry during the whole irrigation period (eg. cotton irrigation when lines are laid every second row, as in Figure 3.1).

Figure 3.1. Cotton irrigation (© Haifa Chemicals).

One of the early reviews on water distribution in a homogeneous soil, compacted to a constant bulk density, from a point source in soil was conducted by Bresler (1977). In this work, Bresler was able to show that, for a specific soil type, the vertical and horizontal distance of water traveling in the soil with time from a point source is a function of the discharge rate. At a low discharge rate (2 L h^{-1}), water penetrates deeper into the soil than the same amount of water discharged at a rate of 20 L h^{-1}.

While theoretical principles of water transport are used in planning dripper line installations (Dasberg and Or, 1999), the actual water distribution from a point source in the field is very much affected by a number of soil related factors. These include the type and clay content of the soil, mechanical soil surface preparations, the soil's chemical composition, as well as lime content and salinity or sodicity development due to irrigation. Recent research on water distribution pattern using treated wastewater in drip irrigation (Tarchitzky *et al.*, 2007), showed that dissolved organic compounds present in treated wastewater induce significant changes in water movement as compared with fresh water irrigation. These workers measured an increase in hydrophobic characteristics of the soil due to the adsorption of organic films on the soil particles after soil drying between irrigation cycles. This cycle of drying and wetting of the soil, changed its wetting characteristics. Such an alteration in the wetting properties of the soil during wetting and drying cycles in field irrigated soils could also be expected in the presence of intense organic excretions from roots (Imas *et al.*, 1997a and 1997b), and from high activity of microorganisms in the soil, or as a result of heavy applications of organic manures.

3.2. Oxygen regime

Following sprinkler or flood irrigation, the whole soil profile is wetted and then, dried due to the effects of plant transpiration and direct evaporation from the soil surface. Crop irrigation operation especially on heavy clay soils during hot summer conditions is subject to long irrigation periods to replace the depleted water from the root zone. Such heavy irrigation periods that may last for several hours during the irrigation cycle, in the presence of an actively growing plant, may cause spatial over-saturation in the soil profile leading to zones of oxygen deficiency and to large losses of soil nitrate by denitrification (Bar-Yosef and Kafkafi, 1972).

In heavy soils, the discharge rate of the emitter often exceeds that of infiltration in the soil and water ponding below the dripper is observed (BarYosef and Sheikolslami, l976). The pond area under the dripper is larger in clay soils than in sandy soils (Ben-Gal and Dudley, 2003). Ponding induces a shortage of oxygen below the dripper. The rate of water penetration into a soil from a point source was studied by Silberbush *et al.* (1979) who measured the distribution of moisture, oxygen content, and plant roots at various distances from the point of water entry. Huck and Hillel (1983) found that the moisture content just below the point of entry almost saturated the soil and resulted in minimum oxygen content.

3.3. Root distribution

Water and nutrient distribution in soils under trickle irrigation is vital in determining the plant root distribution pattern. This varies depending on numerous factors including time, plant type, soil moisture, soil temperature, N-fertilizer type and concentration. In the saturated zone below the dripper discharge, roots die very quickly due to lack of oxygen in the soil (Huck and Hillel, 1983) and, therefore, living roots are only found in the soil space that provides both moisture and oxygen (further discussion on high losses of NO_3-N see Chapter 4).

Trickle irrigation allows the delivery of water from a water source directly to a point of demand near a growing plant with minimum water losses by evaporation from non-planted soil areas. The plant roots proliferate where water and nutrients are available. This root adaptation to wet soil conditions enables the use of only one line between 2 rows of plants (Figure 3.1) or using one irrigation line for 3 rows of pepper (Figure 3.2) or partial wetting of the soil surface with fertigation of orchards (Figure 3.3) and plantations (Figure 3.4).

Figure 3.2. One drip irrigation line for three rows of pepper in Southern Israel (© Hillel Magen).

Frequent and small water applications with drip irrigation lead to shallow and compact root systems (Sne, 2006) in comparison with a deeper and extended root systems in sprinkler or flood irrigated crops. In contrast, because of improved aeration and nutrition in the transition zone of the drip irrigated soil volume, the density of the fine roots is significantly higher than the density of root systems growing under sprinkler irrigation (Figure 3.5; Sne, 2006). Hence growers' activities during soil preparation need to avoid the creation of compacted soil in the planting zones (Huck, 1970).

Figure 3.3. Partial wetting of the soil surface with fertigation of a citrus plantation (© Yara International ASA).

Figure 3.4. Partial wetting of the soil surface with fertigation of a banana plantation in South China (© Hillel Magen).

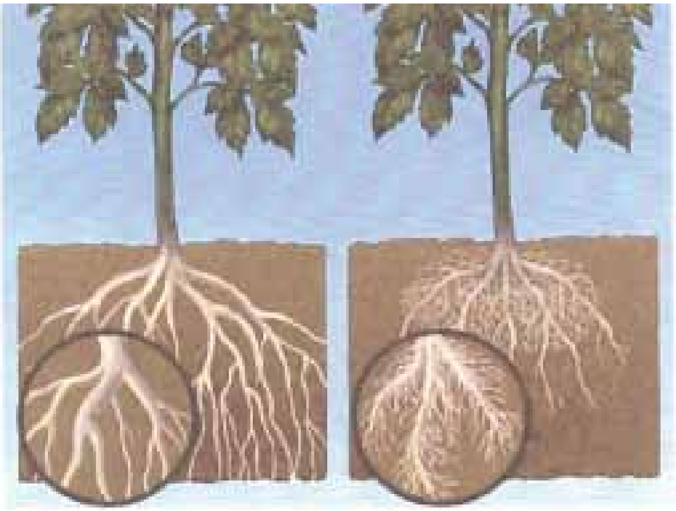

Figure 3.5. Illustration of a root system in drip irrigation (right) vs. root system in sprinkler irrigation (left) (© Netafim).

3.4. Salt and nutrient distribution

The pattern of water penetration has further influence on nutrient and salt distribution in the wetted soil volume. With furrow irrigation, salts tend to accumulate in the seed beds because leaching occurs primarily below the furrows. Flooding and sprinkler irrigation systems that wet the entire soil surface create a profile that steadily increases in salinity with soil depth to the bottom of the root zone (Hoffman *et al.*, 1990).

In drip irrigation systems, shallow soil wetting implies that larger wet surface areas are exposed to direct water evaporation and to a gradual built up of salt accumulation at the soil surface. Repeated frequent irrigation and evaporation cycles, creates a washed area just below the dripper and salt accumulates at the fringes of the wetted volume on the soil surface (Kafkafi and Bar-Yosef, 1980). The salt distribution in the wetted volume is presented in Figure 3.6 (Kremmer and Kenig, 1996).

When a non-adsorbing solute (e.g. nitrate or chloride) is added to the soil via the irrigation water the resulting concentration gradient in the soil is expected to be similar to the salt distribution previously described. In contrast, adsorbing nutrients (e.g., phosphorus, potassium and ammonium) are lower in their mobility in soil. In clay and sandy soils, the nitrate distribution is similar to the water distribution. In contrast, phosphorus movement is restricted- distances of 11 cm and about 6 cm from the emitter in sand and clay soils, respectively have been reported by Bar-Yosef and Sheikholslami (1976). Potassium is strongly retained in clay soils, especially in the presence of illite. Fertigation with phosphorus in sprinkler irrigation should be avoided, because the movement of this nutrient is limited more than in drip irrigation. Almost all the applied

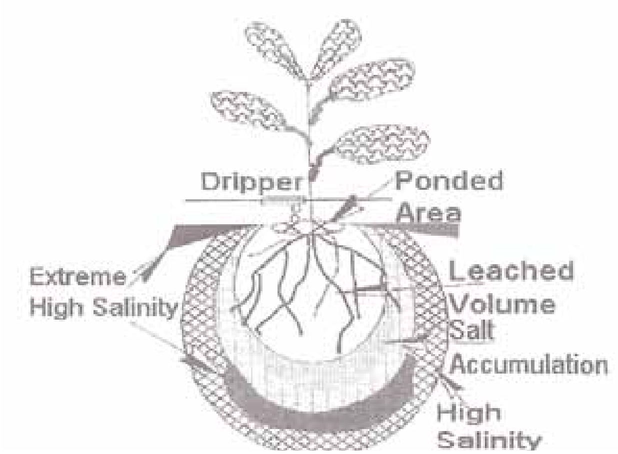

Figure 3.6. Salt distribution in the wetted soil volume below the emitter (Adapted from Kremmer and Kenig, 1996).

P in sprinkler irrigation is accumulated in the upper few centimeters of the soil profile, which quickly dry-off between irrigation cycles.

3.5. Nutrients supply from a point source

The root volume under trickle irrigation is relatively small, compared to a whole soil volume under sprinkler or surface irrigated crops (Sagiv *et al.*, 1974). This requires that crops growing on poor sandy soils receive a continuous supply of water and mineral nutrients during the entire plant growth cycle, from seeding to harvest. The basic knowledge of nutrient supply to crops under fertigation stems from early physiological studies on plant nutrition using hydroponic media (Benton-Jones, 1983). In hydroponics and soilless cultures, the technique is to replace the whole nutrient solution with a fresh one at short periodic intervals. This procedure ensures that no deficiency of any nutrient element will develop during the growing cycle. A close approach to this method was adopted by Assouline *et al.* (2006). They employed multiple daily irrigations for bell pepper grown on a sandy loam soil. Using such a growing protocol of continuous nutrient supply on a sandy soil under field conditions, however, could lead to an over supply of nutrients that might leach below the root zone and result in nitrate contamination of underground water sources.

In comparing daily multiple irrigations under field condition, with once a day or once a week irrigation in a citrus orchard, Bartal *et al.* (2006, unpublished report) reported that an increase in salinity of the upper soil layer was formed in the treatments with multiple daily irrigations. This problem developed because of insufficient irrigation water to leach the chlorides. In frequent irrigation cycles, the proportion of evaporation loss of water from the upper wet soil layer is higher, leaving the salt to accumulate on the soil surface.

Another strategy of fertigation for field grown crops has been described by Scaife and Bar-Yosef (1995), in which the actual daily amounts of nutrients and water supply follow the transpiration demand as it develops with time during plant growth. In fertigation, the daily water and nutrients requirements by the crops have to be supplied by the grower. This growing procedure is more environmentally friendly but needs daily care from the farmer to follow plant demand for water and nutrients. Using a “daily feeding” technique in growing maize under micro gravity trickle system allowed nutrients to be supplied to the plant, as was evident by the ability of the plants to take up all nutrients, leaving no excess to the neighboring plants (Abura, 2001). In well-equipped farms, where a computer is programmed to control water and nutrient sources, it is possible to follow the daily nutrient demand and, thus, save a significant amount of water and nutrients.

3.6. Fertigation in alkaline vs. acid soils

3.6.1. Alkaline soils

The characteristics of basic or alkaline soils are: the presence of active Ca-carbonate, excess of soluble Ca ions, a rapid nitrification rate, and mild fixation of additional P from fertilizers. All types of N fertilizers are suitable to be added with the irrigation water. Even urea, which is completely soluble and causes an initial increase in pH due to the activity of urease in the soil, is safe to use in trickle irrigation as no local increase in urea concentration is expected in the soil. In alkaline soils, the clays are mainly of the 2:1 type and ammonium is adsorbed to the clay, and does not cause ammonium toxicity to roots since it is diluted by the irrigation water. The same reasoning applies to all ammonium-based fertilizers. The soil pH has no influence on any priority selection for K, secondary nutrients and all the micronutrients that are supplied in chelated forms, except for Fe^{2+}. Since Fe-EDTA is not stable above pH 6.5 in basic soil, Fe-DTPA is recommended for soils with a pH up to 7.5, while Fe-EDDHA is recommended in extremely high pH soils since it is stable up to pH 9.

3.6.2. Acid soils

Acid soils are characterized by active aluminium (Al) ions, shortage of Ca, slow nitrification rate, and strong fixation of additional P from fertilizers. The use of nitrate fertilizers as N source as suggested in Table 3.1, increases the pH in the rhizosphere due to nitrate nutrition (See chapter 4 for full description). The increase of the pH in the rhizosphere alleviates Al ions toxicity and allows root elongation.

Table 3.1. Recommended fertilizers for fertigation in neutral - alkaline (6.5-8.5) and acid (4.5-6.5) soils.

<table>
<tr><th></th><th colspan="2">Soil pH</th></tr>
<tr><th>Nutrient</th><th>Neutral – basic soils
pH 6.5 - 8.5</th><th>Acidic – neutral soils
pH 4.5 - 6.5</th></tr>
<tr><td>Nitrogen</td><td colspan="2">ammonium nitrate (NH_4NO_3)</td></tr>
<tr><td></td><td colspan="2">potassium nitrate (KNO_3)</td></tr>
<tr><td></td><td colspan="2">calcium nitrate ($Ca(NO_3)_2$)</td></tr>
<tr><td></td><td colspan="2">Urea</td></tr>
<tr><td></td><td>ammonium sulfate ($(NH_4)_2SO_4$)</td><td></td></tr>
<tr><td></td><td>ammonium phosphate ($NH_4H_2PO_4$)</td><td></td></tr>
<tr><td>Phosphorus</td><td colspan="2">Mono potassium phosphate (KH_2PO_4)</td></tr>
<tr><td></td><td colspan="2">ammonium polyphosphate</td></tr>
<tr><td></td><td>phosphoric acid (H_3PO_4)</td><td></td></tr>
<tr><td>Potassium</td><td colspan="2">muriate of potash (KCl)</td></tr>
<tr><td></td><td colspan="2">potassium sulfate (K_2SO_4)</td></tr>
<tr><td></td><td colspan="2">potassium nitrate (KNO_3)</td></tr>
<tr><td>Secondary nutrients</td><td colspan="2">calcium nitrate ($Ca(NO_3)_2$)</td></tr>
<tr><td></td><td colspan="2">magnesium nitrate ($Mg(NO_3)_2$)</td></tr>
<tr><td></td><td colspan="2">potassium sulfate (K_2SO_4)</td></tr>
<tr><td>Micronutrients</td><td colspan="2">B as boric acid</td></tr>
<tr><td></td><td colspan="2">Mo as sodium molybdate</td></tr>
<tr><td></td><td colspan="2">EDTA complex with Cu, Zn, Mo, Mn</td></tr>
<tr><td></td><td>Fe-EDDHA</td><td>Fe-EDTA</td></tr>
<tr><td></td><td>Fe-DTPA</td><td></td></tr>
</table>

4. Nitrogen (N) in fertigation

4.1. Nitrogen forms in fertilizers

There are three basic forms of nitrogen fertilizers

- **Urea–N**: an electrically neutral molecule – $CO(NH_2)_2$.
- **Ammonium–N**: which carries a positive electric charge – NH_4^+ cation.
- **Nitrate–N**: which carries a negative electric charge – NO_3^- anion.

4.2. Reactions in the soil

4.2.1. Urea

Urea [$CO(NH_2)_2$] does not carry an electric charge when dissolved in pure water. Once urea comes in contact with the soil, it is transformed very quickly (within 24-48 h after application) into ammonia (NH_3) and carbon dioxide (CO_2). This rapid transformation is brought about by the enzyme urease, which is present in most soils. The ammonia produced interacts immediately with water to give ammonium hydroxide ($NH_3 + H_2O = NH_4OH$), which results in a localized increase in soil pH. The immediate field observation (within a day) after urea application is an increase in soil pH near the site of urea incorporation into the soil (Court *et al.*, 1962).

When spread as urea prills on the soil surface, losses of NH_3-N directly to the atmosphere is well documented (Black, 1968; Hoffman and Van Cleemput, 2004). The main soil factors influencing ammonia volatilization after urea application are:

- Cation exchange capacity (CEC)
- Soil pH
- $CaCO_3$ content
- Moisture content

The CEC is a direct function of the clay content of the soil. Ammonia losses from the soil decrease with an increase in CEC. Ammonia losses are significant in soils where the CEC is below 10 $cmol_c\ kg^{-1}$ (Volk, 1959), but becomes negligible in clay soils (in excess of 100 $cmol_c\ kg^{-1}$). The reason for lower loss from clay soils is that the ammonia produced during urea hydrolysis is strongly adsorbed to clay particles and is not released into the atmosphere provided the urea is incorporated into the soil.

Soil pH is the second major factor regulating ammonia loss during urea hydrolysis (Hoffman and Van Cleemput, 1995 and 2004), the extent depending on urea incorporation into the soil (Terman and Hunt, 1964). Spreading urea on the surface of a soil with a pH of 5.2 resulted in N losses of up to 70% of the applied urea. This figure was increased to 82% when urea was applied to the same soil after it had been limed to pH 7.5. However, when the urea was mixed together with the original soil at pH 5.2, only 25% of the urea applied was lost (Terman and Hunt, 1964).

In fertigation, applied urea travels with the water in the soil. Its distribution in the soil wet zone depends on the timing of its incorporation with the irrigation water. When added during the third quarter of the irrigation cycle, followed by the flushing of the remaining irrigation cycle, the fertigated urea on reaching the boundaries of the wet zone becomes susceptible to volatilization. Evaporation from the soil surface results in increased urea concentration near the soil surface. This residual urea at the soil surface is also certain to be lost to the atmosphere as ammonia. Such losses are difficult to monitor under field conditions, but many works that have measured N recovery by plants suggest this as an avenue for direct N loss (Haynes, 1985). When either ammonium or urea is used as nitrogen source in fertigation, significant gaseous losses as N_2O and nitric oxide (NO) have also been recorded (Hoffman and Van Cleemput, 2004). Another concern about urea is the potential problem related to harmful effects of biuret, an impurity normally found at low concentrations. During germination and early growth of seedlings, biuret levels of up to 2% can be tolerated in most fertilizer programs recorded (Tisdale *et al.*, 1985).

4.2.2. Ammonium

Ammonium (NH_4^+) carries a positive electric charge (cation) and is adsorbed to the negatively charged sites on clay and can also replace other adsorbed cations on the clay surfaces. These are mainly Ca and Mg that constitute the major sorbed cations in the soil. As a result of these interactions, ammonium is concentrated near the trickle and the displaced Ca and to a lesser extent Mg, travels with the advancing water. Within a few days, the soil ammonium is usually oxidized by soil bacteria to the nitrate form that is dispersed in the soil with further irrigation cycles.

4.2.3. Nitrate

Nitrate (NO_3^-) carries a negative electric charge (anion). It cannot, therefore, bind to the clay particles of basic and neutral soils which carry negative charges. However, nitrate binds to positively charged iron and aluminum oxides present in acid soils. As in the case of urea, nitrate travels with the water and its distribution in the soil depends on the timing of its injection to the irrigation line. Nitrate is a strong oxidizing agent. Under the trickle, there is usually a certain soil volume that is saturated with water and, therefore, lacks oxygen (anaerobic conditions) (Silberbush *et al.*, 1979; Bar-Yosef and Sheikolslami, 1976; Martinez *et al.*, 1991). Under such conditions, many soil microorganisms use the oxygen from the nitrate ion instead of molecular oxygen for their respiratory needs, resulting in the loss of nitrous oxide and dinitrogen gases to the atmosphere. This mechanism, the biological reduction of nitrate to nitrous oxide or dinitrogen (usually termed as "denitrification") is responsible for some losses of N applied. In an irrigated maize field on clay soil, a continuous irrigation of 70 mm resulted in a loss of 250 kg N ha^{-1} as gaseous dinitrogen. The combined effect of excess water with factors that cause shortage of oxygen is responsible for large N_2 gaseous losses usually unnoticed by the grower (Bar-Yosef and Kafkafi, 1972). These factors include high soil clay content and high soil temperature in the presence of active roots, which provide the condition for the microorganisms in the rhizosphere to use nitrate in respiration.

4.3. Basic considerations in N fertilizer application in fertigation

The amount of N taken up by a crop depends on the growing conditions of the particular field and varies according to the growing conditions of the year. Mineralization of N from soil organic matter also varies annually. The 'correct' application rate of N fertilizer for the same crop in the same field is, therefore, different from year to year, and may need adjustment during the growing season.

In relation to N fertilization and irrigation, the grower should consider the points made in the two sub-sections below.

4.3.1. Potential losses of N fertilizer from the actual viable root volume.

There are three main potential avenues of N losses:

- Leaching of N (nitrate and urea) outside the root zone;
- Accumulation of N salts on the dry soil surface due to soil solution evaporation; and
- Losses of nitrate by denitrification.

4.3.2. Irrigation schedule or rate of discharge, to prevent water ponding under the trickle

An on/off automatic irrigation command to allow the presence of air in the root zone below the trickle may be necessary, a procedure that might save large quantities of N from being lost to the atmosphere.

The water front movement in sand and loam soil was described by Zhang *et al.* (2004) who presented a general analysis on the effects of water application rate on the water distribution pattern. For a given volume applied, increasing the water application rate augments water distribution in the horizontal direction, whereas, decreasing the rate allows more water to be distributed in the vertical direction. A similar conclusion was reached earlier from calculations made by Bresler (1977).

4.4. Suitability of N fertilizer forms to soil and growing conditions

At high soil temperature in heavy clay soil, urea fertilizer might be a better source of N since it is not lost by denitrification. However, as clay soils in general are alkaline, more volatilization would be expected, because the equilibrium between NH_3: $NH_4OH \rightarrow NH_3$ ((gas) + H_2O) moves towards ammonia gas under these conditions. In sandy soil, nitrate would be a better N source as compared with urea because the high pH generated during urease activity might produce toxic concentrations of ammonia. Sandy soil has a low water holding capacity and low CEC. Soils with high CEC hold the ammonia produced during urea hydrolysis as adsorbed ammonium, thereby preventing ammonia from damaging the root.

Consideration of the N forms and their reaction products and their behavior in various soil types is basic to the understanding of the potential benefits or otherwise toxic effects on the growing plant as discussed later. In a field experiment, the movement and transformations of N from ammonium, urea and nitrate in the wetted soil volume below the trickle emitter was studied by Haynes (1990) who compared ammonium sulfate, urea and calcium nitrate. During a fertigation cycle (emitter discharge of 2 L h^{-1}), the applied ammonium was concentrated in the upper 10 cm of the soil immediately below the emitter, and little lateral movement occurred. In contrast, because of their greater mobility in the soil, urea and nitrate were more evenly distributed down the soil profile below the emitter and had moved laterally in the profile to a 15 cm radius from the emitter. The urea-N applied, converted to nitrate-N more rapidly than the ammonium-N applied as ammonium sulfate. Haynes (1990) suggests that the accumulation of large amounts of ammonium below the emitter probably retarded nitrification. This observation means that, under these circumstances, plant roots must take up ammonium and not nitrate under field conditions with its consequences on plant physiology and root growth. Following conversion to nitrate-N, fertigation with both ammonium sulfate and urea caused acidification in the wetted soil volume. Acidification was confined to the upper 20 cm of soil in the ammonium sulfate treatment. However, because of its greater mobility, fertigation with urea (2 L h^{-1}) resulted in acidification occurring down to a depth of 40 cm. Such subsoil acidity is likely to be very difficult to ameliorate, and in non-calcareous soils, might induce aluminum toxicity. By increasing the trickle discharge rate from 2 L h^{-1} to 4 L h^{-1}, lateral spread of urea in the surface soil layer was encouraged. As a consequence, acidification was confined only to the surface (0–20 cm) soil.

Choosing the most suitable N fertilizer to suit local soil, plant type and climate conditions are key decisions a grower and the fertilizer adviser must make. For example, when the same fertilization treatments as used above by Haynes (1990) in calcareous soil with irrigation water that contains bicarbonate ions (HCO_3^-), the same reactions of the N fertilizer are expected, but the high basic soil condition will prevent a significant change in soil pH.

In orchards, the trickle lines remain at the same place for many years. The soil and plants are exposed to the same type of fertigation for several years, and the accumulated N effects on soil and roots can be detrimental. Zhang *et al.* (1996) studied the effects of N fertilization methods on root distribution and mineral element concentrations of White Marsh grapefruit (*Citrus paradise* MacFadyen) trees on sour orange (*C. aurantium* Lush) rootstock on a poorly drained soil. At the 0-15 cm soil depth, root density was significantly greater for trees receiving 112 kg N ha^{-1} yr^{-1} as dry granular fertilizer broadcast than those receiving the same amount of N supplied through fertigation. With fertigation, of the total roots in the top 60 cm soil, >75% were found at 0-15 cm and <10% at 30-60 cm. Root density was greatest near the emitter. N concentration of roots was greater for the trees which received fertigation as compared to the trees which received dry fertilizer broadcast or no N. Such a study stresses the point that plant root morphology results from the response of roots to local concentrations of specific nutrients supplied by fertigation. The accurate study on the exact location of each N form in the soil volume is of no practical value, as the roots respond and develop in the suitable soil volume and extract the available N compounds present.

4.5. Movement of N forms in fertigation and application strategies

The main considerations and attentions of the growers using fertigation should be focused on the N source (urea, ammonium or nitrate salts) best suited to the farmer's plant, soil and climate conditions. This is especially important in nursery and crops under glass or plastic cover.

4.5.1. Ammonium-nitrate

The distribution of ammonium and nitrate concentrations in the soil was measured under different fertigation strategies that varied in the order in which water and nutrient were applied. In the solution emitted from the dripper, the concentration of ammonium was equal to that of nitrate. Just below the trickle, an extremely high soil ammonium concentration exists because of adsorption to the clay particles in soil. At the same time, nitrate ions moves to the boundaries of the wetted zone. This observation suggests that in field practice, flushing of the remaining fertilizer solution in the drip pipeline system should be as short as possible after nitrate dose injection has ended, to avoid the potential loss of nitrate from the root zone. Zhang *et al.* (2004) recommended the following fertigation procedure for nitrate fertilizer:

- Apply only water for one-fourth of the total irrigation time.
- Apply nitrate fertilizer solution for one-half of the total irrigation time.
- Apply water for the remaining one-fourth of the total irrigation time.

This procedure maintained most of the nitrate close to the trickle emitter.

4.5.2. Urea

Soluble urea moves with the water in the soil. The timing of fertilizer injection to the irrigation line has a vital influence on N distribution in the wet soil. For the same irrigation amount, if urea is applied in the first quarter of the irrigation cycle, the urea will continue to travel with the later supplied water, pushing the urea to the far end of the wet zone. If urea is injected to the irrigation line in the last quarter of the irrigation period, however, the urea will be found closer to the trickle. As mentioned above, the secondary reactions in soil for nitrate and urea should not be neglected.

4.6. Plant physiological considerations

Because of the important role of N and the reaction of the different N sources in the soil, the main consideration and attention of the growers in fertigation should be focused on N nutrition. The main available N sources should be selected according to crop, soil and local climate conditions. The key points to consider in selecting the specific N fertilizer relative to the plant's physiological conditions are:

- Sensitivity of the plant to ammonium nutrition (Moritsugu *et al.*, 1983; see 4.6.1)
- The temperature range at the root zone (Ganmore-Newman and Kafkafi, 1985; see 4.6.2)
- The physiological stage of the plant

In non-fertigated field crops, where all the N fertilizer is applied during soil preparation before planting or even when top dressing of N fertilizer is given, the type of N fertilizer chosen is usually made on economic grounds and on rainfall distribution expectations, to prevent nitrate leaching below the root zone. In the field, plant roots usually take up nitrate-N, even if applied as ammonium or urea fertilizers. Under water saturated soil conditions, as in paddy rice cultivation, the regular choice would be urea or ammonium fertilizers for the plant to take up the N usually in ammonium form. When the N fertilizer is given to plants grown in small containers, as in intensive greenhouse plant production, or fertigated on a daily basis in a sand dune soil, the daily supply of nitrogen fertilizer dictates the N form that will be taken up by the plant roots since the rate of uptake by the plant will be faster than the nitrogen transformation by bacterial activity.

4.6.1. Plants sensitivity to ammonium

According to Moritsugu *et al.* (1983), different plant species respond differently to a constant source of N supply. The accurate works of Moritsugu and Kawasaki (1983), (Figure 4.1) have demonstrated that, when N was maintained at 5mM in the solution (70 mg N L^{-1}), plants like rice, barley, maize, sorghum and bean, were insensitive to the form of N supplied. However, tomato, radish, Chinese cabbage and spinach, suffered from the presence of the ammonium in the solution. Chinese cabbage and spinach plants actually died in 5 mM NH_4^+ concentration. Moritsugu *et al.* (1983) showed further that ammonium sensitive plants that died at 5 mM NH_4^+, grew very well when grown on very low ammonium concentration (lower than 0.05 mM NH_4^+) that was continuously supplied via a titration equipment to maintain a constant N concentration in the solution following plant uptake (Figure 4.2).

4.6.2. Temperature of the root zone

Ganmore-Newman and Kafkafi (1983) grew strawberry plants in nutrient solutions at different ratios of ammonium to nitrate but at the same total N concentration (Figure 4.3). The plants grew very well on the ammonium source when the roots were kept below 17°C but died after four weeks when root temperature was raised to 32°C. As the root temperature increased, the root sugar content decreased in both N treatments.

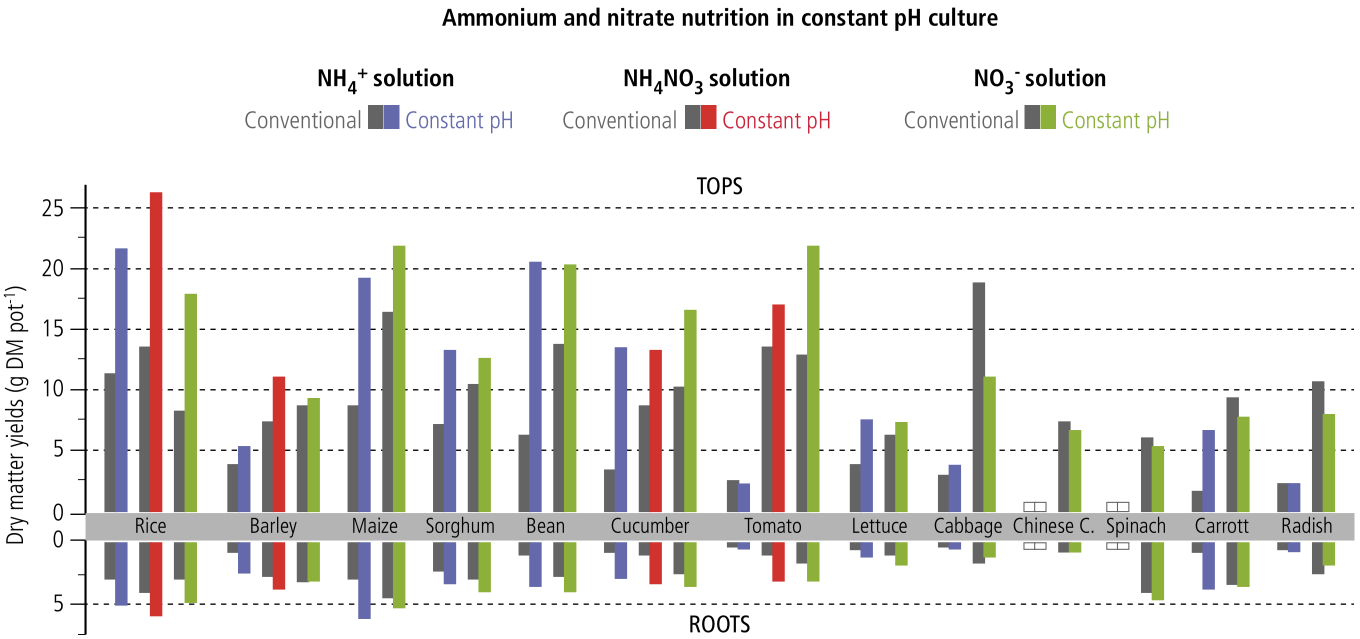

Figure 4.1. Effect of nitrogen source on plant growth (Adapted from Moritsugu and Kawasaki, 1983).

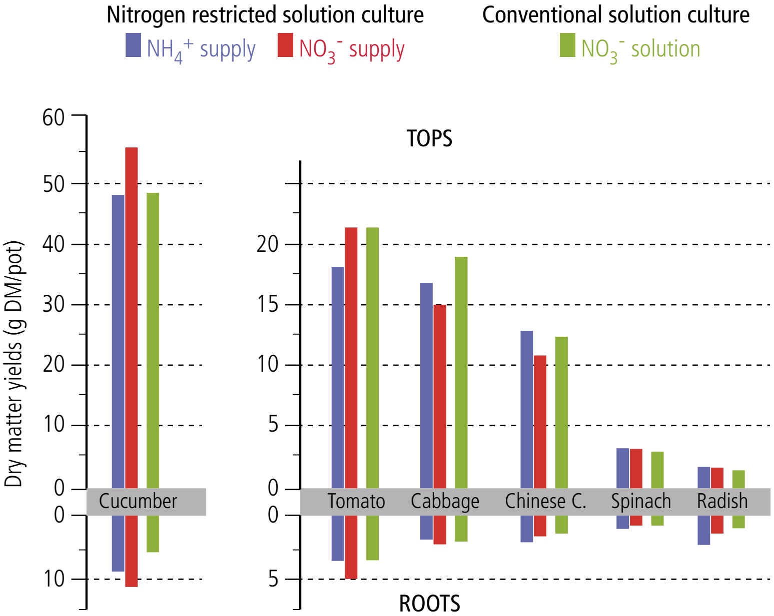

Figure 4.2. Effect of nitrogen source on plant growth by the nitrogen-restricted culture method (Adapted from Moritsugu *et al.*, 1983)

With ammonium nutrition, the sugar content was lower at each root temperature in comparison with nitrate fed roots. In practice, the sensitivity to the N form by different plants in different root temperatures explains many cases and problems especially in plastic potted plants growing during warm periods in the field and mainly in nurseries. The reason for the differences found between plants in their sensitivity to ammonium in the root zone results from variation in distribution of sugar between shoots and roots. The monocotyledonous plants are less sensitive to ammonium N concentration than the leafy dicotyledonous plants which are highly sensitive to ammonium concentration (Moritsugu *et al.*, 1983).

Nitrogen assimilation in plants (Marschner, 1995) occurs both in the roots and in the leaves. When nitrate-N is taken up, between 70 to 90% is transported as nitrate to the leaves (van Beusichem *et al.*, 1988). In the leaf, nitrate is reduced to ammonia. Ammonia toxicity in the leaf is prevented as ammonia combines immediately with sugar to produce an amino acid, usually glutamine (Marschner, 1995). The sugar produced in the leaf cells is in close proximity to the site of its consumption and is used in the detoxification of ammonia in the leaf cell. However, when ammonium enters the root, all the ammonium-N is completely metabolized in the root, consuming the sugar that is transported to the root by the phloem flow (Marschner, 1995). In the root, there are two main consumption sinks for sugar: (i) cell respiration and (ii) ammonium metabolism. When the root temperature increases, its sugar concentration is reduced due to increase

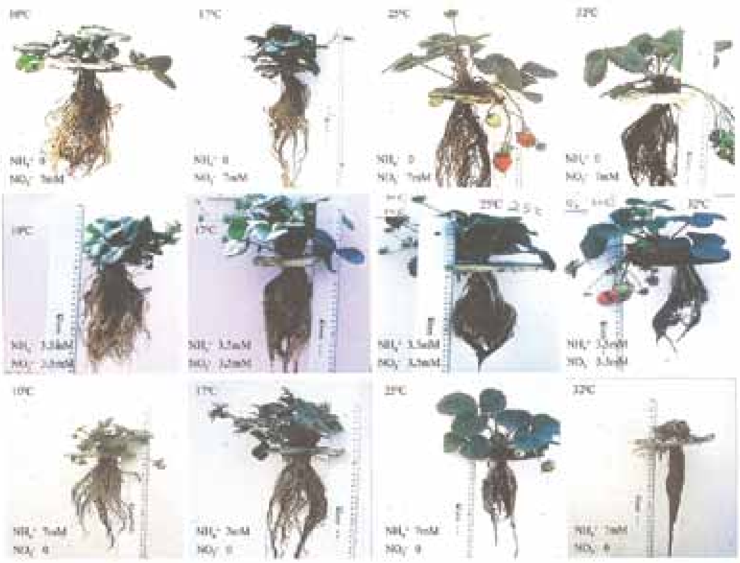

Figure 4.3. Strawberry plants grown in nutrient solutions at different NH_4^+ to NO_3^- ratios but at the same total N concentration and different temperatures (Ganmore-Newman and Kafkafi, 1983).

in its consumption by root cell respiration. It was shown (Ganmore-Newman and Kafkafi, 1985) that when sugar level falls to a low point where it is not available for ammonium metabolism, free ammonia accumulates in the cell, which is toxic to cell respiration, and the plant roots die. These findings explain many greenhouse failures during hot summer growing periods. Hence, in hot soil temperatures, nitrate would be a better choice for fertigation, especially in restricted root growth volume in greenhouse containers. On the other hand, in field grown plants, not all the root volume is exposed to the same temperature, ammonium concentration or oxygen shortage. Consequently, fertigation of field grown plants is less sensitive to the N source. However, other soil conditions as detailed below must be taken into consideration.

4.6.3. The physiological stage of the plant

When ammonium is the N source, the concentrations of Mg and Ca in the plant are lower as compared to nitrate (Van Tuil, 1965). During the vegetative growth, a slight reduction in Ca and Mg concentration in the xylem transport within the plant is hardly seen in sensitive plants like tomato (Chio and Bould, 1976). However, during fruit development, ammonium induced Ca deficiency causes severe blossom end rot in tomato fruits. In pepper, Xu *et al.* (2001) reported that supplying up to 30% of the total N as ammonium until flowering did not cause any reduction in plant development. However, after fruit setting only nitrate treatment was free of blossom end rot. To explain these observations, it is suggested that ammonium reduces the internal root pressure that is responsible for the turgor pressure and fruit expansion during the night. As Ca is delivered to the expanding fruits by the root pressure during the night, in the presence of ammonium, less Ca reaches the developing fruit.

4.7. Quantitative schemes for N fertigation according to plant growth

4.7.1. Plant demand schedule

Nitrogen partitioning in rose plants over a flowering cycle was studied by Cabrera *et al.* (1995). Lowest N uptake by greenhouse roses were found when shoots were elongating rapidly and highest when flower shoots had ceased elongation. In order to study the partitioning of recently absorbed N and the dynamics of total N within the plant, fertilizer labeled with ^{15}N was supplied at different stages of one flowering cycle to hydroponically grown 'Royalty' rose plants. It was observed that during the period of rapid shoot elongation, N uptake from the nutrient solution supplied only 16-36% of flower shoot N. The remainder, representing most of the N in the growing shoots, came from N stored in other plant organs, particularly old stems and leaves. The increased N uptake that occurred later in the flowering cycle was sufficient to meet flower shoot N demand and to replenish the N supply in the old foliage and woody tissues. These organs continued to accumulate N until the subsequent bud break, when it became available for the next cycle of flower shoot development.

In apples, Millard and Neilsen (1989) demonstrated that increasing the N supply increased leaf growth but had no effect upon root mass which altered the root/leaf dry matter ratio. Plants receiving no fertilizer N had to rely entirely on stored reserves of N for their seasonal growth. Initially, this N was used for leaf growth, which stopped after a few weeks. Thereafter, in the N-deficient plants, some of the N from the leaves was re-translocated to support root growth. Increasing N supply had little effect on the amount of N remobilized for growth, although well-fertilized plants accumulated N in their leaves, which was not re-translocated to support root growth. This work showed that the major forms of N remobilized during growth were protein rich in asparagine and arginine. These results demonstrate the importance of internal N cycling for the growth of young apple trees and of N cycling in all deciduous trees (Millard and Neilsen, 1989). Mattos, Jr *et al.* (2003) studied biomass distribution of 6-year-old 'Hamlin' orange trees [*Citrus sinensis* (L.) Osbeck] on 'Swingle citrumelo' [*Poncirus trifoliata* (L.) Raf. x *C. x paradisi* Macfad.] rootstock, grown in a sandy soil under low volume irrigation in Florida. About 70% of dry matter biomass of trees was aboveground. Most of the feeder roots were concentrated at a depth of 0-15 cm below the soil surface, and their density varied from 1.87 to 0.88 cm cm^{-3} at 0.5 and 1.5 m distance from the trunk, respectively. Total recoveries of ^{15}N by the trees were 25.5% for urea and 39.5% for ammonium nitrate at fruit harvest, 280 days after fertilization. Mean accumulation of applied ^{15}N in recent leaf flush was 4.2% and that of older leaves was 2.5%. However, accumulation of ^{15}N was low in woody tissue. The fruit represented the largest sink for N (10.2 and

18.4% recovery of ^{15}N applied as urea and ammonium nitrate, respectively). Their work confirmed the importance of N fertilization in citrus before fruit development.

In apples (Frith and Nichols, 1975), various proportions of the roots were subjected to nutrient stress by placing some of the roots in zero N solution. Under optimum lighting it was found that, if part of the root system was deprived of N, then the remaining root system that received N partially compensated for this deficiency by increasing its uptake. This adaptation is, however, substantially reduced under low levels of lighting. From a fertigation viewpoint the results of these experiments demonstrate that it is not necessary to evenly distribute the fertilizer in the soil since the roots compensate for low presence of nutrient in one part of the soil by excessive uptake from locations in the soil with high fertilizer concentration.

4.7.2. Oscillation in N uptake with plant development

When nitrate is the sole N source in flowing solution culture, the net rate of N uptake by un-nodulated soybean (*Glycine max* L. Merr. cv Ransom) plants, cycles between maxima and minima with a periodicity of oscillation that corresponds with the interval of leaf emergence (Henry and Raper, Jr., 1989). During a 21-day period of vegetative development, net uptake of ammonium was also measured daily. The net rate of ammonium uptake oscillated with a periodicity that was similar to the interval of leaf emergence. Instances of negative net rates of uptake indicate that the transition between maxima and minima involved changes in influx and efflux components of net ammonium uptake. Therefore, it can be concluded that the actual uptake of N by plants is controlled internally by mechanisms within the plant, whereas the grower's role is to maintain sufficient available N near the root through proper fertigation supply.

4.8. N uptake

The uptake of all mineral nutrients throughout plant development must be adequate for particular nutrients at specific growth stages to meet plant demand. For example, K is stored in juicy fruits like grapes (Conradie, 1981), sugar beet, cassava, potatoes, citrus and most juicy fruits. Potassium, therefore, is removed from soils by the harvested part of the crops. Grain seeds mainly remove the N and P when harvested but are not considered as exporters of K from the field unless the harvest is taken at peak green dry matter production at heading, or when the straw is also removed from the field.

Changes in function as an individual root ages has important implications for understanding resource acquisition, competitive ability and optimal lifespan. Both nitrate uptake and root respiration decline rapidly with increasing root age as reported on fine roots of grapes (Volder *et al.,* 2005). The decline in both N uptake and root respiration corresponded with a strong decline in root N concentration, suggesting translocation of N from the roots. The main decline in root uptake occurs within five days of the fine roots activity. These findings emphasize the importance of maintaining fertile soil conditions to allow uninterrupted root growth and adequate nutrient acquisition to stimulate plant growth. Measured N demands in field grown crops are given in Table 4.1.

Table 4.1. Nitrogen uptake by various field and vegetable crops with respect to relative time of growth (Kafkafi and Kant, 2004).

Crop	Relative time of growth (%)					Total uptake (g plant^{-1})	Plants (no. ha^{-1})	Expected yield (t ha^{-1})
	0-20	20-40	40-60	60-80	80-100			
	Uptake* (g plant^{-1})							
Cotton	0.20 (6)	1.80 (58)	3.80 (123)	2.20 (71)	1.60 (52)	9.60 (62)	25,000	1.3**
Maize	0.25 (11)	1.58 (70)	1.00 (44)	0.83 (37)	0.50 (22)	4.17 (37)	60,000	8
Tomato	0.50 (19)	0.75 (28)	2.50 (91)	4.25 (156)	3.25 (119)	11.25 (83)	20,000	100
Sweet pepper	0.40 (20)	1.80 (90)	1.10 (55)	0.70 (35)	0.60 (30)	4.60 (46)	50,000	55
Potato	0.08 (4)	1.00 (50)	1.08 (54)	0.50 (25)	0.17 (9)	2.83 (28)	60,000	50
Muskmelon	0.20 (10)	0.60 (30)	1.60 (80)	2.80 (140)	0.80 (40)	6.00 (60)	25,000	50
Watermelon	0.83 (41)	1.67 (84)	3.33 (166)	6.67 (333)	2.50 (125)	15.00 (150)	12,000	75
Cabbage	0.10 (8)	0.20 (16)	0.80 (63)	1.90 (150)	0.60 (47)	3.60 (56)	50,000	29
Cauliflower	0.10 (8)	0.20 (16)	0.50 (40)	2.00 (157)	1.40 (110)	4.20 (66)	50,000	9
Eggplant	0.50 (14)	3.25 (89)	2.00 (55)	2.50 (69)	1.50 (41)	9.75 (54)	20,000	40

*The numbers in parentheses are the daily amounts of N (mg N plant^{-1} day^{-1}) to be added with drip fertigation during the respective relative time of growth. This amount includes 10% additional N for root consumption.

**Seed cotton (lint) yield

5. Phosphorus (P) in fertigation

5.1. Phosphate interactions with soil particles: sorption, desorption, precipitation and recovery

Phosphorus (P) in solution is subject to interactions with inorganic and organic constituents in the soil. The $H_2PO_4^-$ ion remains stable in the solution inside the irrigation line as long as the pH is kept low. Once it is released to the soil it reacts very quickly with clay minerals like, montmorillonite and illite in basic soils, and with kaolinite clay, iron and aluminum compounds in acid soils. P reacts mainly with lime ($CaCO_3$) in basic soil conditions. The range of relatively insoluble chemical products of P with soil constituents is so large that it is generally called “fixed P.” From the grower`s point of view it is fruitless to identify each soil P compound. In practice, the main important question the farmer would ask is whether there is enough “available P” in the soil to ensure adequate P supply to the plant. To answer this question many soil extracting methods have been developed during the last century, which provide a correlation between a soil test for P and actual plant response to P addition (Kafkafi, 1979).

5.1.1. Phosphate ions and soil solution pH

Phosphoric acid – H_3PO_4 also written as $PO(OH)_3$ – has three hydroxyl groups that actively interact in the soil with the Ca (usually present as carbonate) in basic soils and with Al and Fe hydroxides in acid soils to form many potential combinations which are pH dependent. The main phosphate ions soluble in water in the pH range of 5 to 9 are: $H_2PO_4^-$ and HPO_4^{2-}. While the total P in solution remains constant, the relative distribution between mono and divalent P ions is pH dependent as shown in Figure 5.1. At pH=7.2, 50% of the P is present as $H_2PO_4^-$. As the pH increases above 7.2, the proportion of the divalent P increases very quickly, while below pH 7.2, the monovalent P anion is the major constituent.

Plants take up only the monovalent P as $H_2PO_4^-$ (Marschner, 1995). It is clear from Figure 5.1 that the availability of P in the solution decreases as solution pH increases. For example, if a container holds 1 g of P in the solution at pH 5, all the P is fully available (100%) to the plant. However, if the pH in the container is increased to about 8, only 0.1 g P (10%) is then available despite the fact that the total amount of P in the container has not changed. When plants take up ammonium, the surrounding roots become acidic, whereas when nitrate is taken up, the root excretion is basic (Marschner, 1995). The N form taken up by the plant, thus, controls the pH near the roots. As a result, the soil that is in direct contact with the root is the main source of P. Diffusion of P in the soil is rather slow as compared to the rate of root elongation, unless a huge local concentration of P is introduced (Lewis and Quirk, 1965).

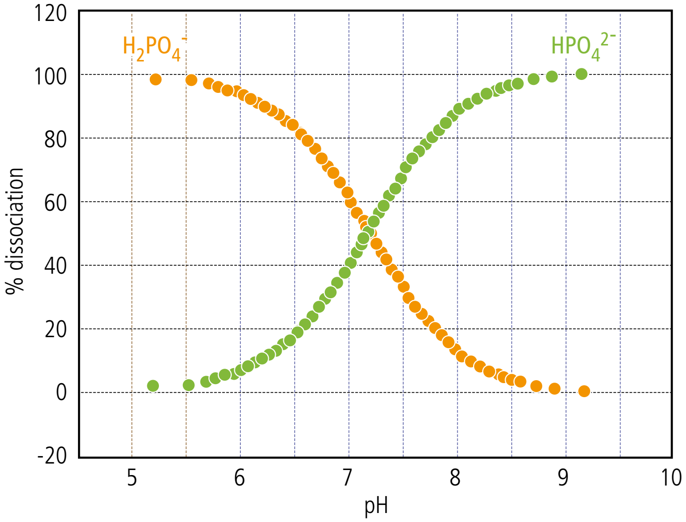

Figure 5.1. The relative concentration of the mono and divalent P ($H_2PO_4^-$: HPO_4^{2-}) ions as a function of soil solution pH (Based on the 2nd pK=7.2 of H_3PO_4).

5.2. Root excretion and P uptake

The roots of chickpea (*Cicer arientnum* L.) excrete acidic organic compounds while maize does not. It was shown that, when nitrate fertilizers are applied, the pH near the maize's roots increased to 6.5, while chickpea under the same conditions induced a reduction of pH from 5.0 to 3.9 near the roots (Marschner, 1995). This shows that by acidic root excretions, some plant species can derive P even from very low P concentration in the soil.

5.3. The effect of N fertilizers on P uptake

Ammonium uptake decreases root zone pH while nitrates increase it. It was demonstrated when P fertilizer was placed in bands with ammonium sulfate, it resulted in more than five times P uptake by maize than when it was placed with a nitrate source (Black, 1968). The combination of ammonium fertilizer (an acidic producing fertilizer) and a P fertilizer applied in bands enabled higher P uptake by young maize seedlings as compared with ammonium carbonate, a basic type of fertilizer (Figure 5.2) (Duncan and Ohlrogge, 1957). Further evidence for the preference of P uptake in the presence of ammonium was found by Imas *et al.* (1997a, 1997b) who also showed that ammonium uptake reduced the pH near the root surface and as a result increased P uptake.

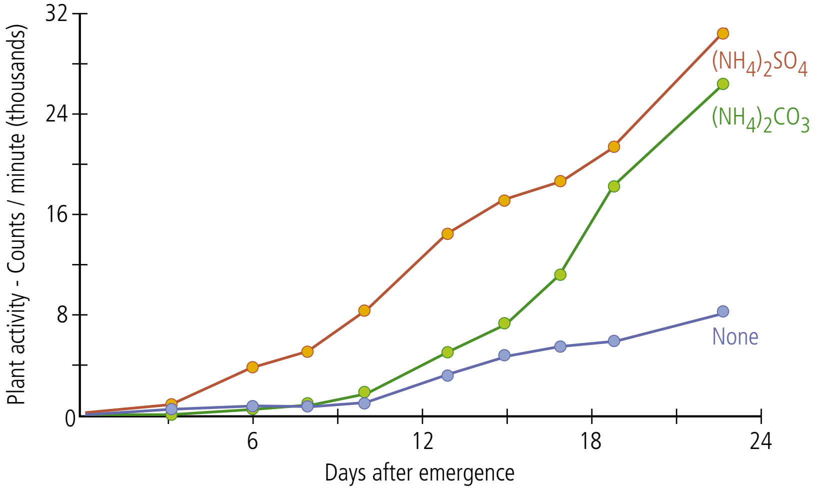

Figure 5.2. Maize uptake of radioactive P when placed in a band of acid or a basic nitrogen fertilizer (Redrawn from Duncan and Ohlrogge, 1957).

5.4. Phosphate movement in the soil from a dripper point

The rapid reactions of phosphate with Ca (lime rich soils) in basic soils, and with Fe and Al in acid soils restrict the distance of movement of applied P in the soil. The higher the clay content or $CaCO_3$ fraction of the soil, the shorter is the distance of movement of P from the dripper. Even in sandy soils (Ben Gal and Dudley, 2003), the distance traveled by P is quite limited as compared with the water (Figure 5.3).

However, when chicken manure is applied to the soil, organic complexes of P are formed (Kleinman *et al.*, 2005). As a result, the concentrations of P in the leached solution are unrelated to the water flow through the soil. This finding points out the importance of macropores in the soil as preferential flow pathways for P. When the P is complexed by organic compounds like in manures, it does not react with soil constituents, and, therefore, can travel to considerable distances from its point of application in the soil. The mechanisms governing the transport of P are poorly understood. The movement of P through soils has become an environmental issue. The leaching of P through the soil profile is commonly thought to occur only in coarsely structured soils due to the rapid infiltration of water and in sandy soils due to the absence of active sites for P sorption (Ozanne *et al.*, 1961; Mansell *et al.*, 1977; Peverill *et al.*, 1976; Sharpley *et al.*, 1993). A contrasting opinion is that, provided the soil reservoir of soluble P is unsaturated, P will not leach more than a few centimeters into a soil profile that contains significant amounts of clay due to the time-dependent adsorption and fixation processes occurring mainly at the surfaces of iron and aluminum oxides and calcium and magnesium carbonates (Rajan *et al.*, 1974; Rolston *et al.*, 1975; Bolt, 1976). Exceptions may occur in peat or in soils with high organic matter content where soluble organic matter can

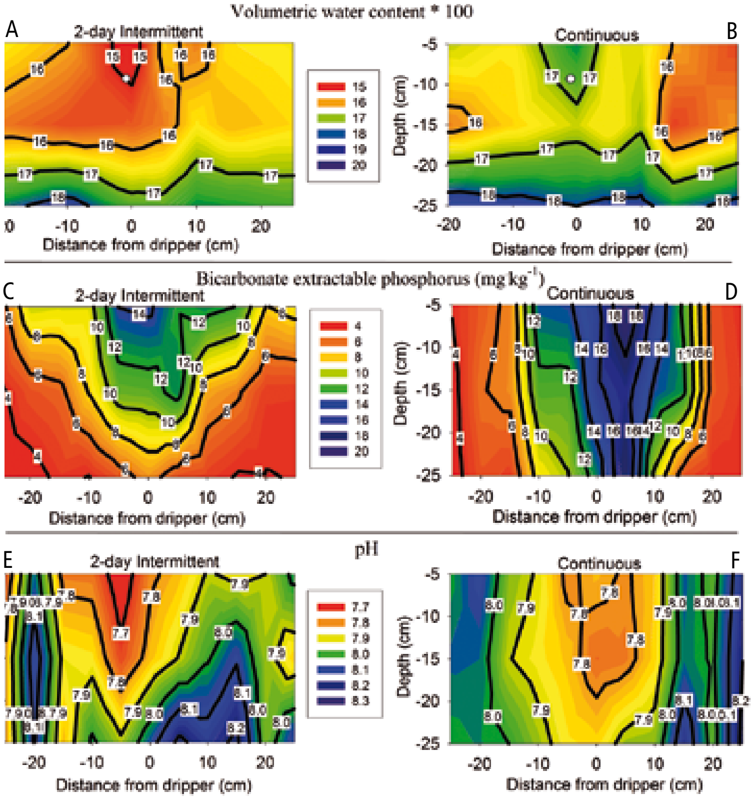

Figure 5.3. Measured gravimetric water content, bicarbonate extractable P and 2:1 water:soil pH distribution isocharts after 14 days of intermittent (A, C, E) and continuous fertigation (B, D, F) on a bare soil. Samples were taken in the middle of the two-days irrigation cycle (Ben-Gal and Dudley, 2003).

facilitate the transport of P in subsurface flow by coating the active sites for P adsorption (Pierzynski *et al.*, 1994). Kirkby *et al.* (1997), working on a pedological research on a catchment slope, demonstrated the deep percolation of P if the water can travel through macropore cavities in the soil.

5.5. Phosphorus fertilizers

P fertilizers used in fertigation must be fully soluble. Common types are potassium or ammonium salts of phosphoric acid, urea phosphate or industrial phosphoric acids. Soluble polyphosphate compounds are available in the phosphate industry, but their use as fertilizers is still limited.

Table 5.1. Characteristics of P fertilizers used in fertigation.

Name	Phosphoric acid (75%)[1]	Urea phosphate	MKP[2]	Acidulated MKP[3]	MAP ([4])
Formula	H_3PO_4	$(NH_2)_2CO·H_3PO_4$	KH_2PO_4	$KH_2PO_4+H_3PO_4$	$NH_4H_2PO_4$
pH (1% solution)	0	1.8	4.5	2.2	4.3-4.5
P_2O_5 (%)	52-54	44	51.5	60	61
K_2O (%)	0	0	34	20	0
N-NH_2 (%)	0	17.5	0	0	0
N-NH_4 (%)	0	0	0	0	12
Comments	Avoid metal parts	Avoid metal parts	Safe to metal parts	Avoid metal parts	Safe to metal parts

[1] Industrial green phosphoric acid

[2] MKP (Mono potassium phosphate)

[3] Acidulated MKP – a mixture of MKP and phosphoric acid

[4] MAP (Mono ammonium phosphate); fertigation grade

Note: In many liquid fertigation fertilizers, the P source is derived from one of the sources mentioned in Table 5.1.

5.5.1. Phosphoric acid

Phosphoric acid is usually used in industrial processes such as cleaning metal surfaces. It is supplied in plastic containers with a specific gravity of 1.6. In fertigation, phosphoric acid is used to clean fertigation lines from inorganic precipitates as well as opening clogs in drippers, and at the same time supplying P to growing plants. It is safer to handle as compared with concentrated nitric or sulfuric acids. However, as phosphoric acid is a concentrated acid, care in handling should still be taken such as wearing of goggles and gloves to protect from spills on skin and clothing. Since it is a highly concentrated P source, a separate delivery pump is used in the field.

5.5.2. Polyphosphate fertilizers

The term “poly” means that molecular structure of the substance contains more than one P atom. Compounds having only one P atom are termed “orthophosphates.” By heating and removing the water molecule, a P molecule containing two P atoms is produced, and is termed “pyrophosphate”, and when three and more P atoms are present in the molecule, the term used is “polyphosphate”. Pyrophosphate is the main form of condensed P in the liquid fertilizer ammonium polyphosphate (APP). When APP is applied to soil, the pyrophosphate is hydrolyzed to orthophosphate.

In the fertilizer industry, polyphosphate fertilizers are produced in the presence of ammonia to give concentrated liquid P fertilizers with compositions of 10-34-0 or 11-37-0. The relative high P concentration is an important parameter for transportation costs. However, the only form of P taken up by the plant is the anion $H_2PO_4^-$, which means that the polyphosphate fertilizer must revert to the mono P form before the plant can take it up. This reaction needs an acidic environment for the supply of H^+ ions (protons). The major supplier of protons is the root itself, which releases H^+ ions into the soil solution during the uptake of ammonium-N. This production of H^+ ions decomposes the polyphosphate and reverts it to mono-phosphate, which is available to the plant. In calcareous soil, the time needed to degrade 50% of the P (half life) was found to be 14-21 days (Khasawneh *et al.*, 1974 and 1979). This half life is very long since about five half life periods (i.e. 70-100 days) are needed for 90% of the material to revert to plant-available forms (McBeath *et al.*, 2006). In the soil, the pH varies and changes constantly over microscopic distances from the roots, so that the bulk pH as measured in the laboratory on air dried, then rewetted soil, does not necessarily describe the micro events near the roots. Lombi *et al.* (2004) compared liquid MAP to granular MAP fertilizer in a highly calcareous soil in Australia. The "liquid P" source enhanced P uptake and increased yield compared with granular P fertilizer, which was applied at the same rate. Their results indicated that P from liquid MAP diffused more rapidly and was more available than P supplied as granular MAP. Careful study of the MAP granules indicated that a significant percentage (12%) of the initial P remained in the granules even after five weeks of incubation in the soil. The enhanced P availability of liquid P source observed in the field trials as compared with granular forms could be a result of many differences in the dissolution, diffusion and reaction processes in soils.

In the USA, alfalfa was fertilized with liquid APP (10–34–0) as compared to solid MAP (11–52–0) fertilizer (Ottman *et al.*, 2006). In their study, the higher cost of liquid APP compared with granular MAP was not recovered by the slight increase in yield. However, they claim that at low P rates, APP solutions may be more economical than top dressed MAP due to its low application cost. Therefore, the cost of the fertilizer itself and its application costs are the main consideration in the choice. In fertigation via trickle line, it is possible to control P application with automatic remote control systems, which growers favor due to the savings in application cost. The fertigation technique supplies an easy solution to a practical problem.

5.5.3. Urea phosphate (UP) ($CO(NH_2)_2{\cdot}H_3PO_4$)

Urea phosphate is a chemical adduct between urea and phosphoric acid molecules. It contains a minimum of 17.5% N and 44% P_2O_5. It is used in the fertigation of soil-grown crops under neutral and alkaline conditions. Urea phosphate is easy to handle and safer to use, compared to liquid acids, as it is a free-flowing, dry acid in crystalline form. Furthermore, after dissolution, 6.3 mol H^+ per kg UP is released, which makes it a concentrated acidifier. Due to its acidic action, it helps to keep tank solutions clear and prevent clogging of the fertigation equipment. Urea phosphate reduces the pH of the irrigation water and soil, which improves nutrient availability and nutrient uptake efficiency. In calcareous sodic soils, UP reacts with calcium carbonate, the calcium ion replacing sodium from the soil complex, which improves the soil structure (less compaction). After flushing with sufficient water, sodium is washed out of the rooting zone. As a result, water infiltration is improved and sodium levels in the rooting zone are reduced (Ryan and Tabbara, 1989). The risk of N volatilization is reduced with UP (Mikkelsen and Bock, 1988). The use of UP has resulted in early flowering and yield

(Becker *et al.*, 2004). Earliness of yield is important for growers as, in general, prices are highest for those first to market.

5.5.4. Mono potassium phosphate (MKP) (KH_2PO_4)

Mono potassium phosphate is a soluble salt of potassium hydroxide and phosphoric acid. It contains 51.5% P_2O_5 and 34% K_2O. It is used in fertigation when daily supply of P is recommended, and in sand dune cultures. Due to its very low salt residues, it is especially suitable in saline water open field agriculture.

5.5.6. Acidulated MKP ($KH_2PO_4 + H_3PO_4$)

This is a new fertilizer introduced recently to increase the P concentration to 60% P_2O_5 and to increase acidity to prevent P precipitation and clogging of the irrigation lines when hard water (high Ca content) is the irrigation water source.

5.5.7. Mono ammonium phosphate (MAP) ($NH_4H_2PO_4$)

Mono ammonium phosphate fertilizer contains 61% P_2O_5 and 12% N in ammonium form. It is commonly used in fertigation field practices. In hydroponic systems, it can maintain acidic solution pH when ammonium is not toxic to the plants. Growers of crops sensitive to ammonium, like lettuce in hydroponic system, should take care when using ammonium in the solution. In substrate grown plants such as peat or soils, where nitrification prevails, this fertilizer is usually safe.

5.6. P uptake

Measured phosphorus demand in field grown crops are given in Table 5.2.

The patterns of P uptake by plants as shown in Table 5.2 demonstrate the differences in P demand at different physiological plant growth stages. Usually, the peak in P demand is during the early growth toward the differentiation of the generative organs. The cobs in maize demand high P transport so a high dose of P is given within 30-40 days after emergence. In tomato (for industry), most of the P is present in the fruit seeds, at 60-80 days after germination and, in a short period, all the harvested fruits are developed from the second flowering cycle. Trickle irrigation is the only method (Kafkafi, unpublished results) that can minimize P fixation, as it can be delivered when maximum P supply is needed by the plant, and by that, minimizing the time of contact of fertilizer P with the soil before being taken up by the plant. Using radioactive P supply at the middle of a row of cotton demonstrated that surface roots in the wet zone take up P immediately after its supply.

Table 5.2. Phosphorus uptake by various field and vegetable crops with respect to relative time of growth (Kafkafi and Kant, 2004).

Crop	Relative time of growth (%)					Total uptake (g plant^{-1})	Plants (no. ha^{-1})	Expected yield (t ha^{-1})
	0-20	20-40	40-60	60-80	80-100			
	Uptake* (g plant^{-1})							
Cotton	0.17 (5.2)	0.24 (7.7)	0.80 (25.8)	0.44 (14.2)	0.17 (5.2)	1.80 (11.6)	25,000	1.3**
Maize	0.07 (2.9)	0.30 (13.2)	0.28 (12.1)	0.25 (11.0)	0.10 (4.4)	1.00 (8.8)	60,000	8
Tomato	0.03 (1.1)	0.05 (1.8)	0.17 (6.2)	0.45 (16.5)	0.25 (9.0)	0.95 (7.0)	20,000	100
Sweet pepper	0.03 (1.5)	0.10 (5.0)	0.20 (10.0)	0.08 (4.0)	0.04 (2.0)	0.45 (4.5)	50,000	55
Potato	0.01 (0.5)	0.05 (2.5)	0.10 (5.0)	0.14 (7.0)	0.09 (4.5)	0.39 (3.9)	60,000	50
Muskmelon	0.02 (1.1)	0.08 (4.0)	0.20 (10.0)	0.32 (16.0)	0.20 (10.0)	0.82 (8.2)	25,000	50
Eggplant	0.03 (0.8)	0.12 (3.3)	0.18 (5.0)	0.42 (11.5)	0.35 (9.6)	1.10 (6.0)	20,000	40

*The numbers in parentheses are the daily amounts of phosphorus (mg P_2O_5 plant^{-1} day^{-1}) to be added with drip fertigation during the respective relative time of growth. This amount includes 10% additional P for root consumption.

**Seed cotton (lint) yield

6. Potassium (K) in fertigation

Potassium is an essential macronutrient and it is found in various parts of the plant. It is always present in the plant in the form of K^+ and never changes this ionic form. It moves in the xylem vessels as a cation, balanced mainly by nitrate (Ben Zioni *et al.*, 1971). In the leaf, nitrate is metabolized and K moves downward with the accompanying organic anions to the roots. This important characteristic of K was studied by Ben Zioni *et al.* (1971) and by Kirkby and Knight (1977).

6.1. Potassium interactions with soil particles: sorption, desorption and fixation

Potassium is present as a stable cation (K^+) in rocks, soils, and solution and has one positive active charge. The K^+ ion is a component of granite rocks and appears in the illite soil clay particles where its content is about 6% of the clay molecular weight. It is also found as an exchangeable cation on all clay particles, but its fraction is usually not more than 3% of the total CEC of the clay particle. Once the external concentration in the soil solution is increased by fertilizer additions, the K^+ ions split between three phases: (1) in soil solution, (2) in the clay pool of exchangeable cations and (3) in the inter clay particle space where it is "fixed." The rate of exchange between solution and adsorbed K^+ is high and an immediate equilibration is obtained. However, the "fixation" and "release" of K from the soil is slow and cannot match the rate of K^+ uptake by plant roots (Kafkafi *et al.,* 1978). Since the rate of K release from "fixed K position" is slower than the rate of K demand by a growing plant, additions of K in fertilizers are needed to match the plant K uptake during plant development. This is especially important when trickle irrigation is used, since the volume of soil occupied by the active root is small and not all the soil volume contributes K to the growing plant.

6.2. Types of K fertilizers in fertigation

There are four K fertilizers available for fertigation: potassium chloride (KCl) or muriate of potash (MOP), potassium sulfate (SOP), mono potassium phosphate (MKP) and potassium nitrate (KNO_3). The four fertilizers are arranged to represent increasing order of importance of their anion partner in the molecule in supplying the needs of plants for nutrients.

Potassium chloride is the most abundant K fertilizer in the world. It is soluble, dissolves quickly and is easily mixed with other N fertilizers. Reasons against its use usually point to the accompanying chloride (Cl^-) anion. The amounts of Cl supplied by the fertilizer might impact crops in sensitive to Cl like tobacco (Xu *et al.,* 2000), in which Cl interferes with the burning quality. In most other crops, KCl is an acceptable fertilizer. It is also used by producers of compound fertilizers as the cheapest source of K.

Potassium sulfate, K_2SO_4, is widely used under saline conditions. Due to the presence of $SO_{4,}$ it is used when the water available is low in Ca, i.e. only when "soft" water is available for irrigation. The presence of high Ca in the water can result in gypsum precipitation in the irrigation lines, clogging the drippers.

Mono potassium phosphate can be a source of K but it is more of a source for P in fertigation. Since the amounts of P needed by plants are only about 1/10 of the amount of K uptake, this fertilizer is considered mainly as a P source in fertigation.

Potassium nitrate is highly soluble in temperatures above 20 °C and presents an optimum ratio of K:N from a nutrient uptake viewpoint. At low night temperatures, this fertilizer can precipitate in the tank so special care must be taken when open field storage of KNO_3 containers are left overnight.

6.3. Advantages of fertigation with K

Trickle irrigated crops under strict water control usually develop restricted root volume. The amount of K present as exchangeable cation on clay surfaces or as K within the crystal lattice of illite clay particles in the soil might not be sufficient to completely meet plant needs for K. Since high K contents are present in harvested fresh vegetables, fruits, fresh leaves, tubers and root crops, large amounts of K are exported from the field. A continuous supply of K during fertigation is, therefore, required to ensure plant growth, quality and yield.

Lycopene content of tomato was increased by continuous supply of K to the tomato plant. The effect of K concentration in the soil solution on color was measured by Sosnitsky (1996) (Figure 6.1). Experimental tomato cv. 8687 showed that a gradual increase of K concentration in the recycled irrigation solution increased fruit quality and lycopene content without increasing total fruit yield. Because of the effect of K on product quality, it is important to include K in fertigation of field, garden and orchard crops.

6.4. Evaluation of anions of K fertilizers in fertigation

Nitrate is taken up by plants at almost equivalent amounts to K, and their concentration in the solution is expressed in mole L^{-1}. Since K:N weight ratio is 39:14, potassium concentration in plant tissues in mass units, as expressed in % by weight, is higher than that of N. However, from the viewpoint of the number of electric charges that enter the plant, N is about four times greater than K (Marschner, 1995). Sulfur (S) is essential to plants but its concentration in plant tissue is only about 6% of that of N. Sulfate is transported with K in the soil, but is left behind in the soil near the root surface (since

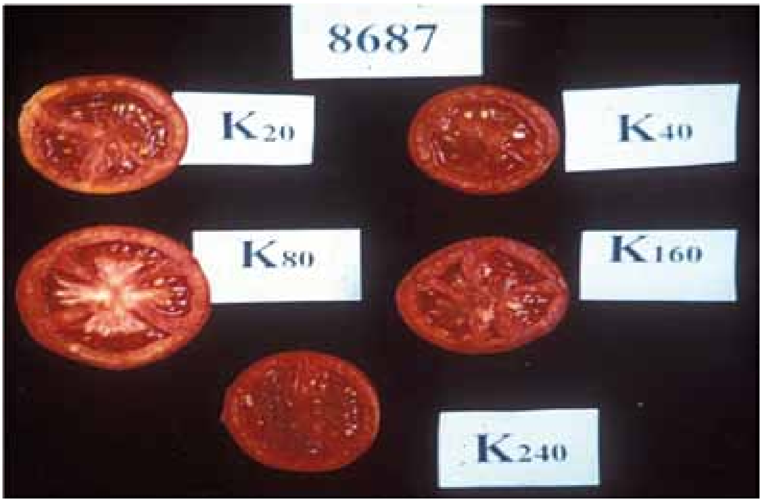

Figure 6.1. The effect of K concentration in the soil solution on color and lycopene of experimental processing tomato cv. 8687 (Sosnitsky, 1996).

the plant takes up much more K than sulfate). Chloride is an essential element but is needed by plant only in micro quantities (Marschner, 1995), yet if present in the solution around the root, it is taken up by the plants and competes with nitrate uptake (Xu *et al.*, 2000). Therefore, for high cash greenhouse crops and quality premium crops that are irrigated by drip irrigation, daily supply of KNO_3 fully satisfies the plant's need for K and partially satisfies the plant's need for N. When using sulfate or chloride-K fertilizers, an extra source of N should be supplied.

6.5. K movement from a dripper point

Mmolawa and Or (2000) made an in depth study of the dynamics of nutrient movements in the soil under drip irrigation. Bar-Yosef (1999) discussed K transport in the soil**.** In practice, the exact distribution of K in the soil from the drip point is of less importance since the roots can grow and find the K in the wet root zone. The efficiency of the plant roots to take up K is so high that whenever the root meets a K source it is easily taken up. In sand dunes with low soil K content, fertigation with daily supply of K and N is needed to ensure their supply to plants, particularly if there is restricted root volume. When the soil does not adsorb K due to low level of clay content, K distribution is typically larger than that of P distribution, but less than that of N. This was demonstrated in a fertigated field grown tomato on soil containing 95% calcium carbonate with low CEC (Kafkafi and Bar-Yosef, 1980).

6.6. K uptake

Table 6.1 shows K uptakes by different crops, converting the absolute number of growing days of each crop to a relative value as a % of the total time needed from seeding to harvest.

Table 6.1. Potassium uptake by various field and vegetable crops with respect to relative time of growth between seeding (0%) and harvest (100%) (Kafkafi and Kant, 2004).

Crop	Relative time of growth (%)					Total uptake (g plant^{-1})	Plants (no. ha^{-1})	Expected yield (t ha^{-1})
	0-20	20-40	40-60	60-80	80-100			
	Uptake* (g plant^{-1})							
Cotton	0.60 (20)	2.00 (65)	3.60 (117)	0.60 (20)	0.20 (7)	7.00 (45)	25,000	1.3**
Maize	0.25 (11)	1.83 (80)	1.00 (44)	0.33 (14)	0.08 (4)	3.50 (31)	60,000	8
Sugarcane	0.50 (11)	0.60 (13)	0.70 (15)	1.80 (40)	0.60 (13)	4.20 (19)	50,000	140
Tomato	0.70 (25)	0.80 (30)	3.50 (128)	7.00 (256)	4.50 (165)	16.50 (121)	20,000	100
Sweet pepper	0.50 (25)	2.00 (100)	1.40 (70)	1.40 (70)	0.40 (20)	5.70 (57)	50,000	55
Potato	0.20 (10)	0.80 (40)	1.80 (90)	1.50 (75)	0.40 (20)	4.70 (47)	60,000	50
Muskmelon	0.40 (20)	1.20 (60)	4.00 (190)	4.40 (220)	2.00 (100)	12.00 (120)	25,000	50
Eggplant	0.75 (21)	5.00 (138)	3.00 (82)	1.75 (48)	1.00 (28)	11.50 (64)	20,000	40

*The numbers in parentheses are the daily amounts of K (mg K_2O plant^{-1} day^{-1}) to be added with drip fertigation during the respective relative time of growth. This amount includes 10% additional K for root consumption.

**Seed cotton (lint) yield

7. Secondary nutrients in fertigation

The term secondary nutrients refers to nutrients such as calcium (Ca), magnesium (Mg) and sulfur (S), which are of secondary importance compared to the primary nutrients nitrogen (N), potassium (K) and phosphorus (P). However, the amount needed by some plants for Ca, Mg and S are similar or sometimes even greater to that of phosphorus. The typical amount of absorbed secondary nutrients by plants is presented in Table 7.1.

Table 7.1. Typical plant absorption of calcium, magnesium and sulfur.

Element	Symbol	Uptake form	kg absorbed t^{-1} DM*
Calcium	Ca	Ca^{+2}	5 (0.5%)
Magnesium	Mg	Mg^{+2}	2 (0.2%)
Sulfur	S	SO_4^{-2}	1 (0.1%)

*concentration sufficient for most plants (Marschner, 1995).

In most basic and less acid soils, the availability and transport of Ca and Mg to plant roots occurs via mass flow in the soil solution. The amounts of Ca and Mg that reach the plant roots by mass flow are usually more than the rate of uptake by the root, by a factor of several hundreds. As a result Ca and Mg accumulate near the plant roots (Barber, 1962). Some of the secondary nutrients are supplied through the application of macronutrient N, P and K fertilizers as shown in Table 7.2.

In soil applied macronutrient fertilizers used at pre-plant, sulfate and Ca are given in quantities greater than the N and P content in these fertilizers, while their uptake by the plant is less than that of N, such as in ammonium sulfate. Single superphosphate contains more Ca and S by weight than P. Therefore, the addition of Ca, Mg and S to agricultural crops is secondary in importance. However, the addition of Ca, Mg and S should be given first priority in acid soils where acute Ca deficiency and high fixation of P can often occur (Marschner, 1995).

Table 7.2. Secondary nutrients supplied with commonly used N, P and K fertilizers.

Fertilizer	Main nutrient content	Secondary nutrient supplied
Superphosphate simple	P_2O_5	Ca, SO_4, plus some micronutrients
Triple superphosphate	P_2O_5	Ca, plus some micronutrients
Ammonium sulfate	N	SO_4
Potassium sulfate	K_2O	SO_4

7.1. Calcium (Ca)

Calcium is unique in its behavior in the plant. It should be continuously supplied in the soil solution to the elongating roots. It moves in the plant one way only from the root to the top (Marschner, 1995), and it is the only element that does not move back in the phloem from the leaves to the roots or the developing fruits. Therefore, any shortage of Ca supply to the roots results in root cell death in the elongation zone. This is the main reason for restricted root growth in acid soils and the reason for adding calcium carbonate ($CaCO_3$) or limestone to lower soil acidity and promote root proliferation. In fertigation, calcium nitrate $5(Ca(NO_3)_2{\cdot}2H_2O){\cdot}NH_4NO_3$ is the main source of Ca. This fertilizer is essential when irrigation water is very low in Ca. In dry land and highly carbonate rich soil, additions of Ca in fertigation should be carefully checked since highly Ca rich water may clog the emitter by $CaCO_3$ precipitation if leftovers are not flashed at the end of the irrigation.

7.2. Magnesium (Mg)

Magnesium is an essential nutrient most well known for its central role in the structure of the chlorophyll molecule, which confers the green color on plant leaves. However, it has other important functions in plant metabolism including protein synthesis, the synthesis and activation of the high energy compound ATP and carbohydrate partitioning within plants (Marschner, 1995).

In basic soil conditions, the dominant clay type is montmorillonite, which contains Mg at about 6% of its lattice weight. Therefore, this clay can be a slow supply source of Mg to the soil solution.

Mg fertilizers are available in several forms:

- Kieserite ($MgSO_4{\cdot}H_2O$), a natural occurring mineral and used as a soluble Mg fertilizer in acid soils, dolomitic limestone, calcined magnesite, and fused magnesium phosphate (Loganathan *et al.*, 2005).
- Soluble Mg fertilizers: magnesium nitrate ($Mg(NO_3)_2{\cdot}6H_2O$) and magnesium sulfate ($MgSO_4{\cdot}7H_2O$) are used mainly in highly soluble formulations in fertigation practice.

Ammonium, when supplied via trickle irrigation, may compete with Mg^{2+} uptake and result in Mg deficiency (Kafkafi *et al.*, 1971). The competition between Mg and ammonium could be expected when trickle irrigation is used on sandy soils with very low clay content (Kafkafi, 1994).

7.3. Sulfur (S)

Sulfur is an essential element and is present in the plant in quantities close to those of P. Being an essential element, its supply (as sulfate ion SO_4^{2-}) in the irrigation water usually meets plant requirements. Its presence as the anion in potassium sulfate, ammonium sulfate and Mg fertilizers is able to supply all the plant's needs for S.

7.4. Water sources of Ca, Mg and S

The local concentrations of salts in the water and total salinity from a specific water source must be taken into consideration in fertigation. Water sources contain various concentrations of different elements (Harward, 1953). The range of Ca in various open river water sources in North California was only 6-9 mg L^{-1}, while in well water the range was 26-200 mg L^{-1}. Most abundant nutrients in irrigation water are: Ca with 26-200 g m^{-3}, Mg with 14-60 g m^{-3} and S-SO_4 from 21-599 g m^{-3}. With irrigation doses of 500 mm (1mm of water is equivalent to 10 tonnes of water per hectare), the amount of Ca supplied to a crop might range between 130-1000 kg Ca ha^{-1}. If all the Ca is supplied within the root volume, it might be sufficient for most crops. This example stresses the point that the use of trickle irrigation should take into account the nutrients already present in the irrigation water to prevent excess salt loading.

In fertigation, the natural concentration of a nutrient in the soil might be irrelevant to plant nutrient supply since the root volume might be restricted by the volume of the wetted soil (see section on water distribution from a point source) such that the plant cannot make use of the total nutrient elements present in the whole soil volume.

8. Micronutrients

8.1. Visual observations

Micronutrient deficiencies are first observed in the younger apex leaves, in contrast to macronutrient deficiencies (N, P and K), which first occur in the lower, mature leaves of the plant. The macronutrients in a growing plant are concentrated in the young developing tissues. When a shortage in macronutrients occurs in the plant, the meristems of the young developing plant mobilize the macronutrients from old tissue cells into the newly developing organs. In accordance with this explanation N deficient plants show yellowing (sometimes called chlorosis) of the lower, mature leaves while a deficiency of iron (a micronutrient) is evident from chlorosis in the upper, younger leaves of the apex.

8.2. Micronutrients in fertigation

Chemical elements that are present in plants in relatively small quantities compared to N, P and K are termed “micronutrients” (Harmsen and Vlek, 1985) or sometimes “trace elements” (Moran, 2004). The micronutrients that are taken up by plants as divalent cations are iron (Fe^{2+}), manganese (Mn^{2+}), copper (Cu^{2+}) and zinc (Zn^{2+}). The micronutrients taken up as anions are molybdenum as molybdate [MoO_4^{2}-] and boron as boric acid [$B(OH)_3$] or as borate [$B(OH)_4^-$].

8.3. Forms of micronutrient fertilizers used in fertigation

The micronutrients, Fe, Cu, Zn and Mn are very reactive with clay particles and other soil components and, therefore, when supplied to the soil as simple inorganic salts such as sulfates, their availability to the plant is significantly reduced and, most likely, very quickly rendered to unavailable forms. However, when added in a chelated form (Moran, 2004), keeping it available for plant uptake at the root surface, the metal element is released from the chelate (Chayney, 1988) and, when absorbed inside the plant, it may combine with an internal organic acid, e.g. citric acid to form citrate salts, which are translocated from the roots via the xylem in this complex form. There are a number of these complexing substances produced by plants to enable the uptake and translocation of specific micronutrients.

8.3.1. Boron (B)

Unlike the metal micronutrients discussed above, B is not present in any enzyme, but a shortage of B strongly depresses plant growth and development. For example, root elongation stops completely within 100 hours after transfer to a solution without B (Chapman and Jackson, 1974). Furthermore, B is absolutely critical for pollen germination, pollen-tube elongation and generative cell mitosis (Jackson and Linskens, 1978). Boron is also important for efficient calcium (Ca) metabolism and utilization by plants. In a pure fertigation solution, B is present as boric acid [$B(OH)_3$] or as the borate anion [$B(OH)_4^-$]. Inside the plant cytoplasm (at pH 7.5), more than 98% of the B is in the form of $B(OH)_3$ and, at pH 5.5, in the vacuole, 99.95% of the B is in the form of $B(OH)_3$ (Brown *et al.*, 2002). The pH around the root affects B uptake. The relative uptake as influenced by solution pH is shown in Figure 8.1. Above pH 8 there is a marked and fast decline in B uptake, suggesting that the form in which B is taken up is as $B(OH)_3$.

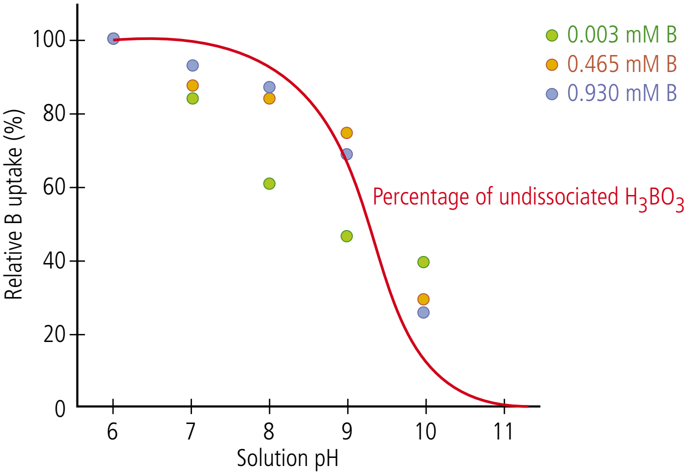

Figure 8.1. Relative uptake of boron as a function of solution pH. Uptake at pH 6 = 100% at each supply concentration (Adapted from Oertli and Grgurevic, 1975).

8.3.2. Chlorine (Cl)

Chlorine is considered to be an essential micronutrient (Shorrocks, 1994). It is required, however, in only minute amounts and most unlikely to be in short supply as the chloride anion (Cl^-) is taken up in relatively large quantities from the readily available supplies in soil solutions and irrigation waters. Chloride deficiency is found in areas far away from seas and oceans because the rainfall is free of marine-generated aerosols containing this essential micronutrient (Xu *et al.*, 2000). Inside plants, the chlorine is essential in water splitting during photosynthesis (Marschner, 1995) and is now known to be part of the Oxygen Evolving Centre (OEC) of Photosystem II along with Mn (Ferriera *et al.*, 2004). It also acts in ion charge balance during the uptake of nutrient cations and anions by the plants. In saline water, which can contain large amounts of Cl, toxicity may occur due to Cl accumulation in the leaves, causing edge necrosis in sensitive plants like avocado (Xu *et al.*, 2000; Bar, 1986) (Figure 8.2).

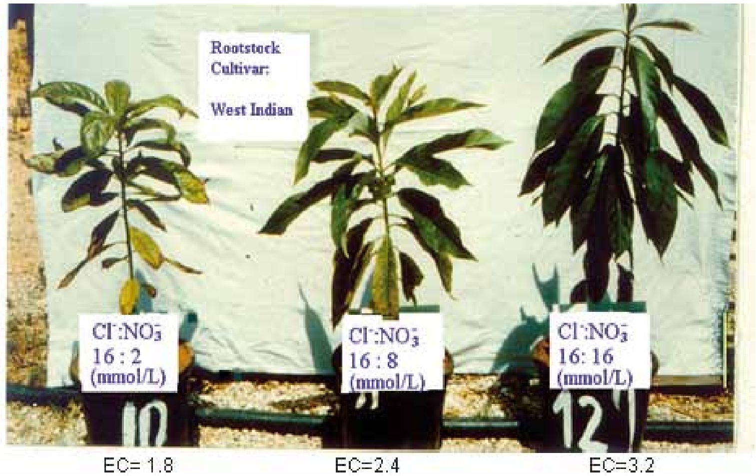

Figure 8.2. Relieving chloride toxicity in avocado leaves by increasing nitrate concentration in the irrigation water containing 16 mM Cl (Bar, 1986).

8.3.3. Copper (Cu)

Copper is an essential component in the chloroplasts of photosynthetic plant cells. Copper is a typical micronutrient needed by plants in relatively small amounts, but absolutely essential to drive photosynthesis. In the soil, Cu is sequestered by soil organic matter, which might limit its availability to plant roots, particularly at pH>7.0. However, in NFT (Nutrient Film Technique) systems and hydroponics, high levels of plant-available Cu above a few g m^{-3} can cause toxicity effects known as 'copper shock' (Marschner, 1995). Thus, careful control of Cu levels in fertigation solutions is essential.

8.3.4. Iron (Fe)

In general, in well-aerated soils, Fe is present in sparingly soluble forms such as ferric hydroxide [$Fe(OH)_3$]. When the pH near the roots is low, for instance when the plant take up N in ammonium form, there may be enough Fe naturally present to satisfy plant demand, even in soils containing 95% of their weight as calcium carbonate [$CaCO_3$], which normally reduces Fe availability (Kafkafi and Ganmore-Newmann, 1985). Once inside the plant, Fe is translocated and complexed with organic acids, such as in the form of Fe-citrate, to its site of specific activity in plant cells. The most common symptom of Fe deficiency is yellowing (chlorosis) of the younger leaves of the plant apex, particularly in calcareous soils with pH >8.0 where it is usually referred to as 'lime-induced' chlorosis. Sometimes, analysis shows that ample amounts of Fe are present in leaves even though deficiency still affects the plant and, therefore, its function in the leaf must be 'retarded' (Römheld, 2000).

The plant kingdom has developed two strategies to take up Fe (Marschner, 1995):

- Strategy I is found in all plants except grasses. The first stage is a reduction of Fe^{3+} to Fe^{2+}, which is carried out by a root plasma membrane–bound enzyme called Fe-chelate reductase. Then, the Fe^{2+} is transported across the root epidermal cell membrane. This was demonstrated early on for soybean by Chaney *et al.* (1972).
- Strategy II is only found in grasses. Compounds called phytosiderophores, which are Fe^{3+} specific ligands, are released by root cells of grasses in response to Fe deficiency.

In fertigation, most of the metal micronutrients such as Cu, Fe, Mn and Zn, are supplied in a chelated form, mainly as EDTA [ethylene-diamine-tetraacetic acid] (Moran, 2004). In this form, most of the metal-chelate compounds are stable below pH 7.0 (Lehman, 1963). Stable Fe chelates for alkaline soils (pH>7.5) are usually EDDHA [ethylene-diamine di ortho-hydroxyphenylacetic acid] based (Barak and Chen, 1982). Iron chelate compounds are indispensable to fertigation.

8.3.5. Manganese (Mn)

Manganese is an essential component of the Oxygen Evolving Centre (OEC) of Photosystem II (Ferreira *et al.*, 2004) in the photosynthetic apparatus of chloroplasts, where it has an essential function in the photolytic splitting of water molecules into electrons (e^-), protons (H^+) and oxygen (O_2) during photosynthesis. The electrons (e^-) are transported to produce energy in the form of ATP (adenosine tri-phosphate); the protons (H^+) are used to reduce carbon dioxide (CO_2) to carbohydrates (sugars) and in the reduction of nitrite-N to ammonium-N, which also takes place in the chloroplasts. Manganese, therefore, is fundamental to both carbohydrate and protein production in plant growth and development.

A number of problems can occur in Mn maintenance in soil solutions during fertigation. A rapid decrease (on a scale of seconds or minutes) of Mn concentration in the solution to a deficiency level was observed after addition of Mn(II) to plants (Sonneveld and Voogt, 1997; Silber *et al.*, 2005). This has been attributed to fast adsorption reactions on negatively charged surfaces or soil clay particles (Davies and Morgan, 1989; Morgan, 2005). The well-aerated conditions that characterize irrigated top soil layers may favor formation of oxidized Mn species – Mn(III) and Mn(IV) (Lindsay, 1979), so that formation of insoluble minerals might decrease Mn solubility further, to very low concentrations. Thus, the reaction kinetics must be taken into account when evaluating the relative importance of adsorption, precipitation and oxidation reactions (Morgan, 2005). Under fertigation management, the solubility of Mn(II) is predominantly controlled by pH-dependent reactions, i.e. adsorption and oxidation (Silber *et al.*, 2008). The role of precipitation, including formation of new solid phases of Mn(II)-P or Mn(II)-carbonates, as possible contributing factors to Mn(II) removal is probably less important. The solubility of Mn(II) on a time scale of seconds to a few hours after application is controlled by instantaneous adsorption process, but with passing time, the importance of biotic Mn(II) oxidation increases and becomes the predominant mechanism of Mn(II) removal (Silber *et al.*, 2008).

8.3.6. Molybdenum (Mo)

Molybdenum serves as a cofactor in the enzyme nitrate reductase (Sagi *et al.*, 2002). In this role, it is essential to the metabolism of nitrate by plants. In terms of uptake by the plant, about one molybdate anion enters the plant in comparison to one million nitrate anions (Lucas and Knezek, 1972). It is usually not included in any fertilizer formulas unless a specific demand is identified due to plant deficiency symptoms (Loue, 1986).

8.3.7. Zinc (Zn)

Zinc deficiency is frequently due to low availability of Zn rather than the absolute total Zn content of soils. High pH>7.5 and calcium carbonate content, poor levels of organic matter and low soil moisture are the factors predominantly responsible for low availability of Zn to plant roots (Kalayci *et al.*, 1999). Zinc is critical in the production of auxins for plant tissue elongation and expansion. Symptoms of Zn deficiency include stem and branch 'rosetting' and 'little-leaf' where leaves remain small and stunted.

8.4. Micronutrients availability as a function of soil pH

The soil pH range most suitable for effective micronutrient uptake by plants is presented in Table 8.1.

Table 8.1. Most suitable pH for micronutrient uptake by plants (Soil Fertility Manual, 2003).

Micronutrient	pH range for maximum availability
Iron	4.0-6.5
Manganese	5.0-6.5
Zinc	5.0-7.0
Copper	5.0-7.0
Boron	5.0-7.5
Molybdenum	7.0-8.5
Chlorine	Indifferent to pH

9. Water quality and fertigation

In fertigation management, fertilizer choice and irrigation water quality are the two most important considerations. The water characteristics influencing the fertigation operation are ion composition, water salinity level, pH, bicarbonate concentration and redox potential.

Two main aspects are of importance when water quality is considered in fertigation:

- The effect of water quality on plant nutrition;
- The fertilizer-water interactions in the irrigation system.

9.1. Effect on plant nutrition

Although the quality of water from all sources for irrigation can have effects on plant nutrition, the following two water sources are of increasing importance in irrigation projects:

- Saline water is characterized by high total salt concentration and potential specific ion toxicity due to sodium and chloride.
- Treated wastewater (TWW) is characterized by its nutrient content and high salt concentration.

9.1.1. Saline water sources

9.1.1.1. Total salt concentration

Saline irrigation water is common in arid and semi-arid climatic regions. The sensitivity of plants to solution salinity varies between plant species and cultivars. The sensitivity of crops to salinity has been a subject of many reviews and that of Maas (1985) is cited here. The electrical conductivity (EC) values beyond which plants reduce their growth varies widely. Sugar beet can tolerate EC of 7 dS m^{-1} (but not during seedling stage), while tomato starts to reduce yield with an EC of only 2.5 dS m^{-1}. Orange, depending on the root stock might suffer already at EC of 1.7 dS m^{-1}. Plant type, local soil and climatic conditions influence the plant's sensitivity to salinity. Calcium in saline water is usually present as $CaCl_2$. Calcium sulfate ($CaSO_4$) might also be detected in saline irrigation water but its low solubility (~0.1%) (0.24 g/100 mL = 0.24% w/v at 20°C, $CaSO_4 \cdot 2H_2O$) in the water restricts its use in counteracting salinity. In fertigation, the continued presence of nitrates in the irrigation feed at concentrations of 5-10 mM (70-140 g N m^{-3}), and Ca concentration in solution between 5-10 mM (200-400 g Ca m^{-3}), in the external solution can reduce salinity hazard to irrigated crops (Yermiyaho *et al.*, 1997; Bar, 1990).

9.1.1.2. Specific ions toxicity

Sodium (Na)

The sodicity of soils is expressed by the value SAR (Sodium Adsorption Ratio) (Richards, 1954). Soil structure deteriorates with increasing SAR. However, Na is not taken up in large quantities by most growing plants. High Na in the solution hampers root elongation (Kafkafi, 1991). Sodium competes with Ca^{2+} on specific adsorption sites in the cell walls at the elongation zones (Yermiyaho *et al.*, 1997). Increasing Ca^{2+} concentration alleviates the retarding effect of Na on root elongation. Yermiyaho *et al.* (1997) demonstrated that, in the range of 0-40 mM NaCl in the solution, Ca^{2+} competes with Na^+ to allow normal root growth despite high Na concentration in the solution around the roots. At higher Na concentrations, root growth declines due to excessive "osmotic" conditions (Figure 9.1).

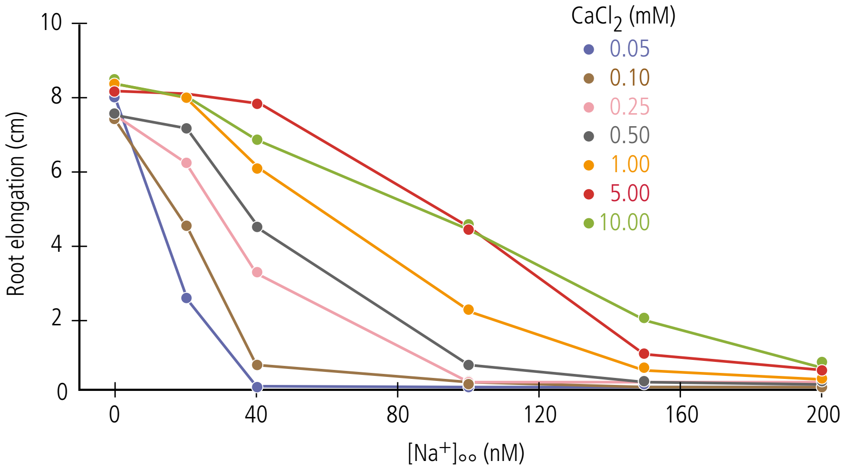

Figure 9.1. Na inhibition of root elongation and relieving Na effects by increase in Ca ions in the solution (Adapted from Yermiyaho *et al.*, 1997).

Chloride (Cl)

Aside from the salinity effects of Na^+, the chloride ion (Cl^-) is abundantly present in saline solution, and is taken up by all plants in large quantities. Certain components in some fertilizers can counteract the deleterious effects of water salinity. For instance, potassium nitrate (KNO_3), or calcium nitrate ($Ca(NO_3)_2$), when constantly applied in the saline solution, can reduce Cl^- uptake by plants (Xu *et al.*, 2000). Leaf Cl^- concentration increases with time during plant growth and can reach very high internal concentrations that might cause scorching and complete leaf death in extreme cases. Bar (1990) demonstrated that, by elevating the nitrate concentration in the nutrient solution, Cl uptake was reduced and even very sensitive plants to Cl^- such as avocado survived a concentration in irrigation solution of 568 g Cl^- per m^3 (16 mM). At 2 mM NO_3 (28 g NO_3 m^{-3}), the lower avocado leaves showed Cl accumulation and scorching symptoms (see Figure 8.2 in chapter 8). Increasing the nitrate concentration to 16 mM NO_3 (224 g NO_3 m^{-3}) in the solution, prevented Cl accumulation in the leaves.

9.1.2. Treated wastewater (TWW)

9.1.2.1. TWW re-use in agriculture

Treated wastewater is being used for irrigation in different parts of the world and in different climatic conditions like Arizona, California, New-Mexico, Pennsylvania, Mexico, Australia, Canada and Germany (Feigin *et al.,* 1991). EPA publication (EPA, 1992) presents the widespread use of TWW showing examples from Argentina, Brazil, Chile, Cyprus, India, Israel, Japan, Kuwait, Mexico, China, Peru, South Africa, Saudi Arabia, Singapore, Oman, Tunisia and the United Arab Emirates. The main motivations for increased use of TWW for irrigation are:

- In arid and semi-arid zones, TWW serves as an important water resource and improves the national and regional water budget;
- It provides a means of protecting human health and preventing environmental pollution.

The demand for potable water for human consumption is the driving force to use recycled or TWW for irrigation in agriculture. In Israel, drip irrigation or sub-surface drip irrigation (SDI) using TWW has been allowed for non-edible crops like cotton. The target has been to irrigate 70% of the total irrigated land with recycled water or TWW. The projected use of water in Israel for the period 1995-2020 is shown in Table 9.1.

Table 9.1. Water supply and demand – Israel 1995-2020 in million m^3 $year^{-1}$ (Forecasts by the Israel Water Commission, 2002).

Supply					
Year	Population (million)	Water sources			Total
		Natural replenishment	Treated wastewater	Desalination	
1995	5.6	1710	245	5	1960
2000	6.0	1720	360	20	2100
2010	7.0	1725	520	75	2320
2020	8.0	1740	780	160	2680
Demand					
Year	Urban sector	Agriculture			Overall total
		Natural	Treated wastewater	Total irrigation water	
1995	730	980	250	1230	1960
2000	850	900	350	1250	2100
2010	1060	760	500	1260	2320
2020	1330	600	750	1350	2680

Despite the widespread use of recycled water worldwide, it must be emphasized here that this practice should be carried out with caution before soil salinity reaches irreversible levels and results in excessive salt accumulation. The ultimate answer in dealing with saline water is desalination and returning the brine left over to the sea (Kafkafi, 2010).

9.1.2.2. Nutritional value of TWW

Treated wastewater contains plant nutrients that are not present in fresh water such as N, P, K and micronutrients. The N and P concentrations in TWW depend on the treatment level since their main source is organic, while the K concentration is not changed in all treatment levels, and its concentration reflects that of the origin of water. Nitrogen in sewage is mainly organic (protein, amide, amino-acid, urea). Therefore, the main N forms in TWW are organic and ammonium-N. Wastewater treatment plants use different treatment processes that may change the forms of N in TWW, and in the case of intensive aeration, nitrate-N is present as well. Phosphorus in sewage and effluent also originates from organic compounds and its concentration decreases with increasing treatment levels. Typically, 50 to 90% of the total P in TWW is in soluble form. Potassium in sewage and effluent is in ionic form and its concentration is not changed with all treatment levels. Table 9.2 illustrates the N forms and concentrations of P and K in sewage and effluent in different treatment levels. The N, P and K content of wastewater from domestic origin was estimated at 50, 10, and 30 g m^{-3}, respectively (Magen, 2002).

Table 9.2. Typical nutrient concentrations (mg L^{-1}) in TWW (Magen, 2002).

Water source	Typical domestic wastewater	Secondary treatment before SAT[1]	Secondary treatment after SAT[1]	Tertiary treatment	Filtered effluent	Secondary treatment
Nitrogen (total as N)	85					
NH_4-N		7	<0.02	0.55		30-60
NO_3-N		0.28	9.34	7.74	0.08-20.6	
Phosphorus (as P)	20	2.2	<0.05	1.6	3.8-14.6	6-15
Potassium (as K)		18	24	15.5	13-31.2	30-120
Source reference	FAO, 2002	Icekson-Tal *et al.*, 2003	Icekson-Tal *et al.*, 2003	Gori *et al.*, 2004	Asano, 1989	National Wastewater Survey, 2004

[1] SAT: Soil Aquifer Treatment

The nutritional value of effluents depends on the following factors:

- **Availability**: whether the plant can use the nutrient. Potassium is fully available, while the immediately available N are the mineral forms (ammonium and nitrate), and soluble P is orthophosphate. The organic forms of N and P are available to the plant but over a longer time scale.
- **Amount**: whether the total amount of the nutrients in the TWW can meet plant requirements and will not have negative "macro-micro" nutrient interactions. The amount of the nutrient in TWW can be estimated by multiplying its concentration by the amount of water applied. Too much P applied from the TWW can cause P accumulation in the soil, which can depress Fe and Zn uptake by the plant.
- **Timing**: whether nutrient concentration in TWW meets the specific plant growth stage requirements. Nutrient concentrations in effluents are difficult to control, in some cases are not needed or are too high, and this may cause problems to crops such as delaying fruit maturity in deciduous and citrus trees, color formation due to too much N, delayed leaf drop in cotton before harvesting due to N, and excess K may influence fruit acidity. However, when concentrations are lower than required, fertilizers have to be applied.

An example of the nutrient contents of two water sources, TWW and potable water were both used for growing roses in Israel, is presented in Table 9.3 (Berenstein *et al.*,

Table 9.3. Nutrient ion concentration in potable and TWW used for irrigation of roses (meq L^{-1}) (Berenstein *et al.*, 2006).

	Potable	TWW		Potable	TWW
Cations			Anions		
N-NH$_4$	0.03	3	N-NO$_3$	0.05	0.01
K	0.22	1.75	HCO$_3$	2.9	10
Ca	1.5	1.75	P	0.03	0.21
Mg	1.5	1.7	Cl	8.5	11.8
Na	5.6	12.9			
Sum of cations(+)	8.85	21.1	Sum of anions (-)	11.48	22.02
	Micronutrients in mg L^{-1}				
Fe	0.001	0.079			
Mn	0.0001	0.02			
Zn	0.04	0.05			
Cu	0.0001	0.003			
B	0.18	0.49			
Cd	0.0001	0.0009			
Ni	0.0001	0.016			
EC dS m^{-1}	1.1	2.5			
pH	7.4	7.7			

2006). There is a 100 fold increase in ammonium concentration, eight fold increases in K and seven fold increases in P in the TWW. However, these are all in a range of concentrations suitable for plant growth.

9.1.2.3. Variation in nutrient content in TWW

The TWW composition changes with season, source and water treatment processes before final usage. Sewage water is produced daily by urban populations, but irrigation demand is concentrated during the cropping season, which is also affected by winter rain accumulation in the soil before the irrigation season. As a result, large open surface reservoirs have to be built to accumulate the winter city effluent production.

Typically after secondary treatment, ammonium concentration in the water might vary between 10 and 50 g N m^{-3}. Since this ammonium is available to plants and comparable with N fertilizer, with supplemental 3000 m^{-3} water ha^{-1}, it can contribute a significant amount of 30 to 150 kg of N ha^{-1}. Depending on the soil initial concentration, N fertilization might be needed or the content in TWW can completely satisfy a good cotton crop. It is the local content of nutrients in the TWW that has to be measured at each location to make a decision about the need for additional fertilizers. In waste water treatment plants (WWTP), enhanced biological P removal treatment is employed to significantly reduce algal bloom in the system. A part of the P can be eliminated by chemical precipitation. In experiments with inactivated sludge containing relatively high concentrations of dissolved Ca (~ 1.5 mol m^{-3}) and P (~1 mol m^{-3}), a pH-sensitive and partly reversible precipitation of calcium phosphates was observed at below pH 8.0. The following reactions: (i) fully reversible precipitation of hydroxydicalcium phosphate (HDP) ($Ca_2HPO_4(OH)_2$ as an intermediate; (ii) formation of hydroxyapatite (HAP) ($Ca_5(PO_4)_3OH$) from HDP, have to be considered when P concentration in the TWW is an important issue (Maurer *et al.*, 1999).

In a study by Vangush and Keren (1995), for about 10 years after introduction of TWW to the aquifer, almost no change in water composition was observed. However, a continuous increase in Na, Cl, HCO_3, Ca, Mg and SO_4 was monitored; K hardly changed, and there was no P data available. The use of TWW in fertigation needs continuous monitoring and should take into account the variable amounts of plant nutrients found in the TWW before additional fertilization is made.

9.1.2.4. Salinity factors in recycled or TWW

The Na, Cl, and B contents of TWW (originating from household waste water sources) are the main considerations when using recycled water or TWW for agriculture. For example, high Cl levels were reported in palm dates irrigated with TWW (El Mardi *et al.*, 1998). Continuous use of TWW without monitoring can cause accumulation of Na in the soil and deterioration in soil structure. In citrus, leaf Na, Cl, and B concentrations were noticeably higher in plots using reclaimed water or TWW than in those of well water (Zekri *et al.*, 1994). However, in Central Florida, well-treated and managed waste water has been found to be a very safe and good option for additional water supplies. In well-treated wastewater, most nutrients are removed and thus, when used for irrigating field crops would demand additional fertilization.

The use of TWW as an alternative water source for irrigation of citrus in Spain was studied to evaluate its effect on different soils and crops (Reboll *et al.*, 2000). Young citrus trees were irrigated with TWW from a sewage treatment plant during three consecutive seasons and the growth, leaf mineral status and fruit quality were measured. Some differences were found between groundwater and TWW composition. Na, Cl, B and organic matter concentrations were always higher in the TWW. However, levels of Na, Cl, and B in the leaf tissue were below the toxic levels for citrus. Leaf N content was in the optimal range and no significant difference was observed between samples from trees irrigated with TWW and groundwater. Both growth and fruit quality parameters were unaffected by the high levels of Na, Cl, and B in the TWW. After three years of study, no detrimental effects were found on young citrus trees irrigated with TWW. High nitrate levels were found in groundwater, probably due to aquifer contamination. In all the seasons studied, the values of soil-plant nutrients analyzed were within the optimal ranges for citrus. Fertilizer rates could be lowered significantly without compromising yields or affecting leaf nutrient levels when using TWW. Reboll *et al.*, (2000) concluded that TWW appears to be a suitable alternative water source for citrus tree irrigation.

However, studies on the quality of wine as affected by the use of TWW for grapevine irrigation in Australia showed that the chemical composition of wines has been altered. Na and Cl levels in wines from TWW treatment were considerably higher than normal for Australian red wines. The higher concentrations of total N, P, K and Mg found in wines from vines receiving 135 liters of TWW per week (compared with 45 liters TWW per week or 135 liters fresh water per week), were not much above the range reported for Australian Shiraz wines (McCarthy and Downton, 1981).

The findings of intensive research on the use of recycled water have been published for grapevines (Prior *et al.*, 1992a, and 1992b; Walker *et al.*, 1996). Sensitivity of citrus trees on a variety of rootstocks was reported by Maas (1993) and for stone fruits by Catlin *et al.* (1993). In Australia, sensitivity has been recorded in pear trees (Myers *et al.*, 1995) and in peaches (Boland *et al.*, 1993). Sensitivity of vegetables to saline water was reviewed by Shannon and Grieve (1999). All natural salinity sources pose a long term threat due to accumulation of Na and Cl on the soil clay particles. The long-term use of city and industrial sewage water sources is dangerous because of accumulation of B and heavy metals to toxic levels. Future use of city recycled water will depend on preventing B contamination and accumulation of industrial and household chemicals in the sewage system and diluting it with de-ionized water before application to commercial agricultural irrigation systems.

Treated wastewater research demonstrates the intensive effort to adopt the use of TWW to agricultural production and, therefore, to monitor the long-term effects of its application to agriculture. One of the main hazards in continuous use of TWW is the accumulation of B that might reach toxic levels to plants. The source of B in the sewage water is household detergents and washing powders. In arid climate irrigated areas, B containing compounds should, therefore, be eliminated from the market since a low cost removal process of B from the water is not available. High Na in the water might, in the long run, cause destruction of soil structure. Calcium additions to the soil can alleviate Na hazard but not for long periods of irrigation. The organic compounds that are present in the recycled water can accumulate on soil surface and, after drying, can become hydrophobic in nature that might result in non-uniform soil wetting characteristics (Tarchitzky *et al.*, 2007). In the cases described above, the importance of long-term monitoring is indispensible. Accumulation or build-up of negative effects can be rather slow and can last for a few years, hence a longer period of observations and testing is needed.

9.2. Water quality and the irrigation system

Emitter clogging, which adversely affects the rate of application and the uniformity of water distribution, is one of the greatest problems in drip irrigation. Physical, chemical and biological substances in the water are the primary causes of clogging.

9.2.1. Iron (Fe^{2+}) containing water

Iron deposits appear as an amorphous gelatinous type of brown-reddish slime precipitate in water that contains soluble Fe. The Fe slime causes complete clogging of the emitters. This problem exists in areas where the groundwater aquifers are formed mainly on sandy soils or organic muck soils (very common in Florida) with well water pH below 7.0 and in the absence of dissolved oxygen. Such water contain ferrous iron (Fe^{+2}) which is water soluble and serves as the primary raw material for slime formation. Iron bacteria, like *Gallionella sp. leptolhris, Sphaerotihus*, *Pseudomonas* and *Enterobacter,* when present in the water, react with the ferrous iron through an oxidation process to form ferric iron (Fe^{+3}), which is insoluble. The insoluble ferric iron is surrounded by the filamentous bacterial colonies and creates the sticky Fe slime gel that is responsible for clogging the drippers.

Ferrous iron concentrations as low as 0.15-0.22 g Fe m^{-3} are considered potentially hazardous to drip systems (Ford, 1982). Between 0.2-1.5 g Fe m^{-3}, emitter clogging hazard is moderate, and Fe concentrations above 1.5 g Fe m^{-3} are described as severely hazardous to irrigation emitters (Nakayama and Bucks, 1991). Practically, any water that contains concentrations higher than 0.5 g Fe m^{-3} should not be used in drip systems unless they are treated chemically before introduction to the trickle lines.

Experiments in Florida indicate that chlorination successfully controls Fe slime formation when Fe concentrations were less than 3.5 g Fe m^{-3} and the pH was below 6.5 (Nakayama and Bucks, 1991). It was also stated that long-term use of water with a high level of Fe may not be suitable for drip irrigation. Water containing more than 4.0 g Fe m^{-3} was considered as a useless source for trickle irrigation as it needed a pond sedimentation process before pumping it back into the drip system. To overcome Fe clogging, due to biological activity inside the irrigation lines, the following succession procedure was proven successful in Florida: (i) injection of Cl gas online with the hydrocyclone containing filtering discs to achieve uniform mixture of the Cl gas in a small volume; (ii) sand filter to remove the oxidized Fe precipitates; and (iii) backup filters to secure final filtration and keep the irrigation water free of Fe precipitates. Such a system can be successfully operated on a daily basis and enables a safe usage of the water for fertigation.

9.2.2. Ca and Mg containing water

High concentrations of Ca, Mg and HCO_3 in irrigation water (high total hardness) increase the hazard of clogging, especially when P fertilizers are introduced to the system (see also 9.2.3). Precipitation of calcium carbonate is common in alkaline water (high pH) and rich in Ca and HCO_3. The scaling deposited in the irrigation system as the result of such water can cause clogging and malfunction of the system (Feigin *et al.*, 1991). The reaction is temperature and pH dependent. Scaling problems are more likely to occur with water pH > 7.5 and bicarbonate content > 5 mmol L^{-1}. Scale deposition increases with an increase in pH of applied fertilizers through the irrigation system.

9.2.3. Interaction between P, Ca and Fe in the irrigation water in fertigation

The use of P fertilizers in fertigation is very sensitive to water quality and its pH. Calcium concentration in the irrigation water is an important consideration, and low pH (acidic) in the irrigation water must be kept to prevent formation of Ca-P precipitates. Some water sources like shallow underground water (e.g. in Miami) sometimes contain divalent soluble iron (Fe^{2+}) (Bar, 1995). These two elements, Ca and Fe, quickly precipitate in the presence of P at pH values above 4 for Fe and above 5.5 for Ca. Therefore, P should not be introduced into the trickle lines if soluble Fe ions are present in the water. The precipitation problem is more acute in sub-surface drip lines, where the clogging is not observed until the poor performance of plants near the clogged emitters is evident.

Phosphate fertilizers might be corrosive, i.e. chemical reactions of P with metals in the water delivery system, which might produce precipitates. Early works with fertilizer tanks produced a thick iron phosphate paste (chocolate color) that blocked all filters and trickle lines (Malchi, 1986a and b).

Once iron phosphate precipitates occur, flushing the system with nitric acid to dissolve the chemical precipitates is the only way to restore the solution delivery in the irrigation lines. Because of such clogging hazards, phosphate fertigation should be made with caution and careful monitoring of water flow to prevent any development of filter and drippers clogging. Polyphosphate fertilizers, in certain concentrations also form gel suspensions with Ca and Mg, and clog emitters. Polyphosphate acids are polymers of orthophosphoric acid. Polyphosphate fertilizers mostly contain a mixture of compounds of varying chain length (Hagin *et al.*, 2002). The ammonium salt of polyphosphate can be used in fertilizer formulations. Polyphosphate fertilizers, in certain concentrations generate gel suspensions. However, specific concentrations of polyphosphates, induce sequestering of Ca ions and prevent gel formation (Noy and Yoles, 1979; Hagin *et al.*, 2002). The minimal concentrations of ammonium polyphosphate (APP) required to prevent gel formation in irrigation water with different Ca levels is presented in Table 9.4.

Table 9.4. Minimal concentrations of ammonium polyphosphate (APP) in irrigation water to prevent gel formation and clogging (Noy and Yoles, 1979).

Ca^{2+} in irrigation water (meq L^{-1})	Minimal APP concentration in irrigation water (%)
<2	< 1.0
2-5	1.0
5-8	2.5
8-11	4.0

10. Fertigation of field crops

10.1. Maize

Daily measurements of growth and consumption of nutrients by the maize plant was reported by André *et al.* (1978) at various physiological stages: vegetative, female and male flowering period and cob development. From seed development to male flower appearance, transpiration is at constant ratio with photosynthesis. During the male flowering period, transpiration exceeds photosynthesis. After silking (female flower), cobs and seed formation takes place with a continuous decline in daily water consumption. On day 62 of maize growth (maximum N uptake), a single plant consumes140 mg N and 254 mg K. The plant continues to take up N and K until harvest at about 20% of the maximum rate. Plant uptake fluctuates on a daily basis even if grown in a nutrient solution that is renewed daily during the entire experimental period. Plant demand for N is controlled by the internal plant metabolism of the various developing organs at any specific time.

The plant's physiological stages are important in planning for fertigation such that water and nutrients are supplied to the roots to meet plant demand. If the root volume is limited such as in containerized planting in greenhouses, the frequency of water and nutrient renewal must be kept daily. In field grown maize, it is important to follow the root volume distribution for irrigation timing and nutrient supply. In Figure 10.1, maize grown on sandy soil with daily fertigation, took up the entire N supplied without leaving

Figure 10.1. Micro-drip irrigated maize. The daily application of NPK fertilizers made exactly according to daily nutrient demand by the maize plants, as shown by the sharp boundary between complete and N deficient (front) treatments (Abura, 2001).

any excess N to neighboring plants as is evident from the sharp contrast between the complete and zero fertilized N treatments (Abura, 2001). The total daily water volume and nutrients were supplied according to the expected demand of the crop, from the work of André *et al.* (1978).

By silking (appearance of the female flower), 68 days from planting or at about half way through the growing period, 75% of the K, 66% of the N, and 43% of the P total uptake at harvest have already been attained, when values are expressed in grams per plant. Most of the P is taken up by the maize plant one month after silking and transported to the developing grains. Since most of the P is found in the upper soil layers, it is crucial to maintain soil moisture (by irrigation or by rain) up to about 40 days after silking to secure P uptake. Any period of dry soil within the five to six weeks after silking will reduce P uptake by the maize plant and may affect kernel formation.

It is clear that maize yield through the kernel (grain) exports substantial amounts of N and P away from the field but relatively little K (Table 10.1). On the other hand, silage maize exports considerably larger amounts of K.

Table 10.1. Average amounts of nutrients (kg) in above-ground plant material in 10 t ha^{-1} maize yield grown in the mid-western United States (Voss, 1993).

Element	Grain	Stover	Total	% in grain
	kg of nutrient in 10 t ha^{-1} yield			
N	49.5	28.1	77.6	63.8
P	10.3	4.3	14.6	71
K	16.8	43	59	28
Ca	0.3	15.6	15.9	1.9
Mg	3.5	12.3	15.7	22
S	3.1	3.4	6.5	47.7
Fe	0.05	0.9	0.91	5.5
Zn	0.08	0.08	0.16	50
Mn	0.02	0.12	0.14	14.3
Cu	0.01	0.04	0.05	20
B	0.02	0.06	0.08	25
Mo	0.002	0.001	0.004	50
Cl	1.8	32.7	34.5	5

The role of fertigation is to deliver plant nutrients from fertilizers with irrigation water to the root surface in sufficient quantities to prevent deficiencies during plant development. Supplying the right amounts of water and plant nutrients daily at the right time to meet plant needs is crucial in preventing excess supply of plant nutrients and seepage of nitrate salts to underground aquifers. Precise fertigation can prevent aquifer pollution and is less costly to farmers.

The timing of irrigation affects water and nutrient distribution in the soil. Ben-Gal and Dudley (2003) showed that in a sandy soil with very low P sorption capacity, the highest P concentration was found down to 10 cm below the dripper. With the same amount of water, but with continued application, P is found below 25 cm. Irrigation frequency also influences the water content and pH of the soil. It is to be expected that in heavy clay soils, the distribution of nutrients from a point source differ from that in sandy soil (Bar-Yosef, 1999). From the viewpoint of P uptake or dry matter production, the exact P distribution in the soil is not important as can be deduced from the data of Ben-Gal and Dudley (2003). As most of the P is taken up by maize during grain formation and maturity, late application of P with low N and K levels might secure high grain yield with low water application, but with daily P application in small quantities. Such a combination could save in water pollution and fertilizer wastage. An example of a planning table for nutrient application during 10-day intervals can serve as a guide to a practical field fertigation scheme (Table 10.2).

Table 10.2. Fertigation planning calculation for nutrient application based on 10-day intervals (André *et al.*, 1978).

Days	Daily plant N uptake (mg)	Nitrogen kg ha^{-1} day^{-1} for 100,000 plants	Daily plant P uptake (mg)	Phosphorus kg ha^{-1} day^{-1} for 100,000 plants	Daily K plant uptake (mg)	Potassium kg ha^{-1} day^{-1} for 100,000 plants
0-10	1.4	0.14	3.1	0.31	0	0
10-20	1.4	0.14	3.1	0.31	11.7	1.17
20-30	12.6	1.26	7.75	0.78	31.2	3.12
30-40	77	7.7	12.4	1.24	156	15.6
40-50	119	11.9	21.7	2.17	253.5	25.35
50-60	140	14	24.8	2.48	253.5	25.35
60-70	63	6.3	34.1	3.41	128.7	12.87
70-80	28	2.8	38.75	3.88	78.0	7.80
80-90	35	3.5	20.15	2.02	62.4	6.24
90-100	35	3.5	13.95	1.40	35.1	3.51
100-110	28	2.8	18.62	1.86	19.5	1.95
110-120	7	0.7	0	0	0	0

A total of approximately: *336 kg N ha^{-1} , 200 kg P ha^{-1}, 1000 kg K ha^{-1}*

The underline numbers mark the plant age with the highest demand for the specific element.

A detailed study on water uptake by maize with surface and subsurface drip irrigation was reported by Coelho and Or (1996), who found that root distribution follows water distribution in the soil in both irrigation systems.

10.2. Cotton

10.2.1. Cotton growth and irrigation

The benefits of irrigation have long been recognized in the cultivation of cotton. The crop is grown in many parts of the world, in hot climates with high precipitation. Cotton is a summer crop. Its development can be divided into three periods: (1) seeding to first flower appearance, about 60 days after seeding (DAS); (2) the main developing period: 60 to 110 DAS; and (3) maturity, 110-160 DAS: bolls maturing and lint development.

Until 1970, trickle irrigation was not used in cotton. The irrigation methods then employed were furrow (the most common system for cotton), sprinkler, border and level border or basin (Berger, 1969). Surface irrigation, which is used all over the world, requires deep soil with high water holding capacity. Using furrow might result in salt accumulation between ridges.

Drip irrigation of cotton mainly by subsurface drip irrigation (SDI) is increasing in the USA, mainly in California, where dry summers prevail (Robertson *et al.*, 2007). The benefit of trickle irrigation for cotton is the potential of growing the crop in arid, hot climate areas, where clouds do not interfere with boll development, and in areas with shallow soils, which are favorable for cotton production.

Trickle irrigation is applied in Israel using recycled wastewater, especially for non-food crops such as cotton and silage maize. Furthermore, cotton can tolerate saline and brackish water. From a public health standpoint, a safe method to deliver these needed amounts of recycled water is by trickle irrigation. In an irrigation trial in Arkansas, Robertson *et al.* (2007), using a new type of low pressure surface trickle irrigation system, reported 39% water saving on a per unit production calculation. As water shortage is an increasing problem all over the world, low pressure (gravity energy) surface applied trickle irrigation is a more utilized technique. However, this technology has not been studied using SDI.

10.2.2. Cotton nutrition

The total uptake or removal of nutrients by cotton plants is presented in Tables 10.3 and 10.4.

Typical rates of nutrient uptake (N, P, K, Ca, Mg and S) where water or nutrients are not limiting were described extensively by Mendes (1960) and are presented below:

Nitrogen (N)

N uptake by cotton as measured by chemical analysis reveals four linear uptake periods:

- 10-20 days: by the 20th day, 4.6% of the total N uptake at harvest is found in the tops of the plant;

Table 10.3. Cotton nutrient uptake/removal – macro- and secondary nutrients (IFA, 1992).

Country	Source	Yield of ginned cotton (kg ha^{-1})	(kg ha^{-1})					
			N	P_2O_5	K_2O	MgO	CaO	S
Brazil	Malavolta, 1987	(2 500)*	156	36	151	40	168	64
China**	An Yang, 1985	1 421	183	64	156	–	–	–
	An Yang, 1985	1 115	153	53	112	93	204	–
	An Yang, 1985	941	128	45	90	–	–	–
USA	Mullins & Burmester, 1988	per 100 kg lint	19.9	5.2	18.4			

* Seed cotton
** Nutrient uptake = all aerial parts plus part of roots

Table 10.4. Cotton nutrient uptake/removal – micronutrients (IFA, 1992).

Country	Source	Yield of ginned cotton (kg ha^{-1})	Fe	Mn	Zn	Cu	B
					(g ha^{-1})		
Brazil	Malavolta, 1987	(2 500)*	2 960	250	116	120	320
China	An Yang, 1985	1 115	5 000	254	397	71	205

* Seed cotton

- 20-60 days (from first leaf to square): the daily rate of uptake increases to 1.159% of the total uptake at harvest;
- 60-100 days (during flowering): this rate declines to 0.743% of total N uptake per day;
- 100-150 days: at the last period during maturation, which lasts about 50 days (about one third of the total growing period), only 20% of the total N is taken up by the cotton plant.

N uptake and its distribution in plant organs

The total amount of N taken up has been reported as about 240 kg N ha^{-1} (Halevy, 1976). The amount of N exported from the field in the seeds, however, is only about 40% of total N present in the whole cotton plant. This value is much lower than in maize, which removes 68% of the total N present in its dry matter. Cotton is thus, a much less N depleting crop than maize. During the first two months after seeding, the plant takes up only about 15 kg N ha^{-1}. During that time, an extensive deep root system is established (Adams *et al.*, 1942). In the following 55 days, 215 kg N ha^{-1} are taken up. This growth pattern suggests that the cotton plant develops its root system early in the season, which allows it to take up N during the vegetative and flowering stage from a larger soil volume. In deep clay alluvial soils, the supply of water and N early in the season affects the balance between vegetative and fruiting stages. Excess N at an early vegetative stage favors growth of leaves and branches and causes the shedding of bolls that have developed in the lower lateral buds (Yogev, 1986). As a result, only the late developed bolls are left to harvest. However, harvesting a late yield in the season might encounter early winter rains that might damage the lint. Keeping a rate of 1 cm per day increase in plant height was found to be the best main stem elongation rate to secure high yield of cotton (Yogev, 1986). Trickle fertigation allows the grower to control the vegetative growth rate by continuously monitoring cotton height and controlling it by the irrigation rate and intervals between irrigation as well as by N fertilizer concentration in the irrigation water. Timing of irrigation for early flower appearance in cotton is possible only under tight control of N, P and K fertigation. Since only about half of the soil volume is wet under trickle irrigation of cotton, additions of nutrients are needed to compensate for the decline in soil volume and hence available nutrients.

Phosphorus (P)

The relative fastest period of P uptake is also found between days 30 and 50 after germination, with a daily uptake rate of 0.993% of the total P at the end of growth. The second linear uptake rate period lasts from 50 to 120 days of plant development with a daily uptake rate of 0.746% of total P uptake. This is the maximum uptake potential from a nutrient solution with unlimited P availability to the root. The pattern of P uptake suggests that, in order to keep a constant P uptake rate under field conditions for such a long period, sufficient moisture and P content in the wet zone must be maintained to allow P diffusion to the root. Only 15% of the total P uptake occurs in the last month before harvest.

P uptake and distribution in cotton plant parts

About 44% of the P in the cotton plant is removed by the seeds, as compared with 80% in maize. It is clear that P is being taken up from the soil during the whole period of boll development and not from internal translocation. This pattern of P uptake is true for maize, cotton and potatoes. It is the late supply of P to the developing boll from the soil that is the challenge to cotton growers in arid climates. Since irrigation is stopped at least six weeks before mechanical harvest, the upper soil that is usually rich in P is dry and it might be possible that P becomes a limiting factor at the final stages of boll development in dry climates. Additions of P in trickle irrigation at the last month of growth might show some advantages. In subsurface trickle irrigation, there is no limitation to P application late in the season. However, using SDI, there is water saturation zone around the buried tube, as is evident from the root distribution around the SDI line (Figure 10.2) (Ben-Gal *et al.*, 2004). If the soil adsorbs the added P, fertigation would not be efficient and soil application of P prior to cotton seeding might be effective.

Figure 10.2. Roots exposed on soil profile perpendicular to vine row in vineyard after seven years of treatment in subsurface drip irrigation (SDI) (Ben-Gal *et al.*, 2004).

Potassium (K)

The rate of K uptake is fastest during leaf formation from days 25 to 47 after germination. During this period, K uptake accounts for 36.5% of total K that is found in the plant at harvest. Potassium continues to be taken up at a slightly slower rate during this longer period of 50 to 111 days after germination, when about 44% of the total K at harvest is taken up from the soil. Finally, during the last month of growth, only 10% of the total K in the plant at harvest is still being taken up but at a much slower rate.

K fertilization considerations

K is concentrated in the reproductive organs during plant development. Almost 40% of total K in the plant is present in the bolls, burs and seeds (Halevy, 1976; Mullins and Burmester, 1990). Only 25% of the total K in the plant is removed by the cotton seeds and lint, while the rest returns to the soil with soil preparation unless removed from the field. Cotton removes relatively more K than maize (in terms of kg ha^{-1} for average yields).

From field observations of plots with over 20 years of continuous cropping with cotton, irrigation is stopped about 6-8 weeks before harvest, leaving the upper 30 cm of soil devoid of water. Thus, K becomes a limiting factor and K deficiency symptoms appear on bolls and leaves. Addition of K to the last irrigation could prevent such deficiencies. This situation occurs due to the specific soil preparations needed prior to mechanical harvest that stops irrigation six weeks before harvest. After many years of continuous cotton growing, shortage of K in the deep soil layers develop. Deep plowing was used in the past to enrich the deep soil layers. With traditional mild soil treatments and sprinkle irrigation, symptoms of K deficiency appear while upper soil test values show sufficient K levels. When trickle irrigation on large areas becomes a routine, the limited root volume will most probably demand continuous application of nutrients with the trickle system.

Calcium (Ca)

Similar to K, Ca is taken up mainly during early canopy development from day 25 to day 50 with the square appearance at a daily rate of 1.53% of total uptake. At the end of flowering, the Ca uptake rate is reduced by half to 0.89% per day. During the last two months of boll formation, only 16% of all the Ca is taken up.

Magnesium (Mg)

Magnesium is taken up at a constant rate of 0.89% in the first 50 days, but from day 50 to the end of boll maturity, the rate of Mg uptake is almost constant at a rate of 0.66 % per day. Mg uptake rate is parallel with P during the first four months of cotton growth.

Sulfur (S)

Sulfur shows three distinct linear periods of uptake: from days 20 to 50, the rate is 1.36% per day, in tandem with K and Ca. It declines to 0.73% during days 50 to 90 (at the end of flowering) but is then taken up at a constant rate until harvest, at 0.38% per day.

Cotton in the USA is usually grown on large areas operated by mechanical seeders and cotton pickers and, due to heavy traffic, subsurface fertigation is the preferred system. In other parts of the world, annual drip lines are surface installed about one month after seeding, allowing the initial seedlings to develop based on soil moisture stored from the previous winter.

The dry matter accumulation and the cumulative nutrient uptake of cotton during the growing season were presented by Halevy (1976) (Table 10.5), who also described the absolute nutrient uptake and the nutrient distribution in the different plant organs.

Table 10.5. Relative dry matter (DM) accumulation and nutrients uptake in cotton along a growing season that lasted 156 days (Calculated from Halevy, 1976).

Season length (%)	DM (%)	N (%)	P (%)	K (%)
36	4	7	8	8
46	15	28	18	29
53	36	44	37	56
62	60	72	62	83
71	89	97	92	95
100	100	100	100	100

The main factor affecting cotton yield is shortage of light energy due to shading in dense plant stands (Eaton, 1955). Yogev (1986) checked the light interception on cotton using fertigation on cotton grown on scoria tuff (of volcanic origin) filled beds that prevented roots from penetrating deep into the soil. He checked the distance between rows of 0.5, 1 and 2 m with no restriction of water or nutrients. His results are presented in Table 10.6. When more plant parts were exposed to direct sun radiation (2 m between rows), total yield per plant increased by a factor of 10 and yield per unit area rose by a factor of 2.5 despite a reduction in total dry matter. If the same nutrition and irrigation is given with no restriction on root growth, vegetative growth exceeds cotton fiber development. The practical conclusion from this work is that restriction of vegetative growth of cotton in rain free summer areas is possible, thanks to trickle irrigation that can supply water and nutrients needed by the plants and by restraining vegetative growth. Trickle irrigation of cotton with 2 m between rows under desert conditions can offer a new cotton production system with minimal water input. This kind of treatment combined with fertigation experiments needs to be studied in the future.

Table 10.6. Yield parameters at harvest from raised-bed grown cotton at three different distances between rows (Yogev, 1986).

Plant parameters*	Distance between rows (m)		
	0.5	1	2
Plant height (cm)	173 c	145 b	120 a
Cotton 1st pick (g m^{-1})	91.4 a	435.6 b	828.4 c
Cotton 2nd pick (g m^{-1})	90.6 a	94.3 a	231.1 b
Cotton total (g m^{-1}) of row	182 a	529 b	1059 c
Total yield (seed+lint) (g m^{-2})	364 a	529 b	530 b
Earliness (%)	50 a	82 b	78 b
Total DM (g m^{-2})	1494 c	1116 b	889 a
Seed+lint /stem ratio	0.32 a	0.9 b	1.47 c

* data with the same letter are not significant at the 0.05 level.

Trickle fertigation of cotton in two crops per year system

Trickle irrigation, when applied in very small quantities with frequent applications, forces the cotton plant to limit the root volume in the soil thereby inducing a small but early flowering plant (Carmi *et al.*, 1992). The development of the shallow and restricted root system was characterized by a high fraction of thin roots (less than 1 mm per day), which comprised almost 90% of the root dry matter. Root proximity to the drippers and the limited amount of water in the rooted soil led to a sensitive and quick response of the plants to small amounts of irrigation. However, such a system fails if not accompanied by a complete nutrient solution applied daily, since the major nutrient reserves of the soil are far distant from the plant roots. The cotton yield per plant is reduced but the ratio of reproductive to vegetative organs increases. Restricted cotton root volume requires denser than usual seeding rate, and results in higher total lint yield than regular seeding. Such a sensitive field grown system allows double cropping per year: e.g. wheat for silage-seeding in November, harvest in mid-March and, on the dried soil after the wheat, seeding cotton with controlled trickle irrigation (northern hemisphere). Such a system is possible in relatively small plots where silage is needed on the farm. As silage, wheat removes about 500 kg K ha^{-1} (Kafkafi and Halevy, 1974), and seeding cotton immediately after removal of green wheat silage may induce deficiency of K. In order to prevent K and other mineral deficiencies, the cotton grown with restricted root volume should be supplied with complete NPK given from the first trickle irrigation. In acid soils, attention should also be given to Ca, Mg and S, if not present in the irrigation water.

11. Fertigation of fruit crops

11.1. Banana

A series of fertigation studies have been reported for banana in India and Brazil on acid soils. Banana is a huge consumer of N and K fertilizers. Reddy *et al.* (2002) and Badgujar (2004) in India stressed the benefits of fertigation for banana with N and K, at levels of 200 g N and K per plant day^{-1} ha^{-1}.

The Crawford Reid Memorial Award to Mr. B.H. Jain in 1997 was a significant achievement in the promotion of proper irrigation techniques and procedures that brought major advancement for irrigation systems as an infrastructure industry for his work on "Micro-irrigation for small holder banana growers of Jalgaon, India: A case study."

In Brazil, soil pH decreased with increasing N rates (Teixeira *et al.*, 2002). The reported decline in soil pH in tropical areas suggests that ammonium or most probably urea sources were the main N fertilizer source. Exchangeable K was significantly reduced due to crop exhaustion. Micro-sprinkler irrigation was used with rates of N (0, 200, 400 and 800 kg N ha^{-1}) and K (0, 300, 600 and 900 kg K_2O ha^{-1}). Irrigation caused a significant increase in fruit yield and the response being attributed to N and K fertilizers. Despite a high level of exchangeable K, a positive response to K application was observed on the banana yields in non-irrigated plants. A severe acidification of subsoil under banana plantation was also reported in Australia (Moody and Aitken, 1997) despite annual surface application of 2.4 t ha^{-1} of lime. Of all the crop systems they measured, banana was the major soil acidifier. They used ammonium fertilizers and this resulted in severe acidification and nitrate leaching due to excessive N application (Figure 11.1). The only practical way to increase the pH near plant roots is to use nitrate type fertilizers (see detailed explanation in Chapter 4).

In Spain (Canary Islands), fertigation of banana is by mini-sprinklers, using excess irrigation (Muñoz-Carpena *et al.*, 2002). Soil water balance showed that most of the drainage (18% of the total irrigation + rainfall) was produced during the crop highest water demand period and during the short rainy season when no irrigation was applied. Monitoring the soil solution revealed that very high nitrate concentrations (50–120 mg L^{-1} N-NO_3) are present throughout the experimental period. The high water fluxes and nitrate concentration in the lower part of the soil profile, produced a yearly loss of 48–52% of the total N applied (202–218 kg N ha^{-1} per year). Therefore, small, but more frequent applications of both N and water are recommended to reduce the environmental impact of the system.

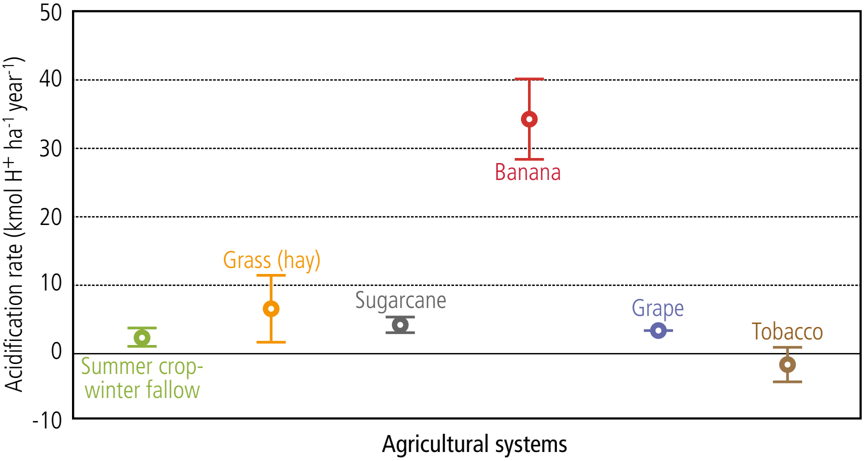

Figure 11.1. Mean and range (vertical bars) of the acidification rate of several agricultural systems of eastern Queensland (Moody and Aitken, 1997).

The monthly uptake of N by banana in the Canary Islands (Figure 11.2) shows two peaks a year: in January and August. Such information on plant uptake is essential to the grower to minimize N losses and to meet plant demand in the best possible way. The difference between the minimum and maximum demand is about 20 kg N per month. Figure 11.2 serves as an example for one location. The rate of appearance of banana leaves is about 1 leaf per 6 days. Each leaf contains about 100 g of N. Knowing the rate of leaf production can give the grower an estimate of the weekly N requirements.

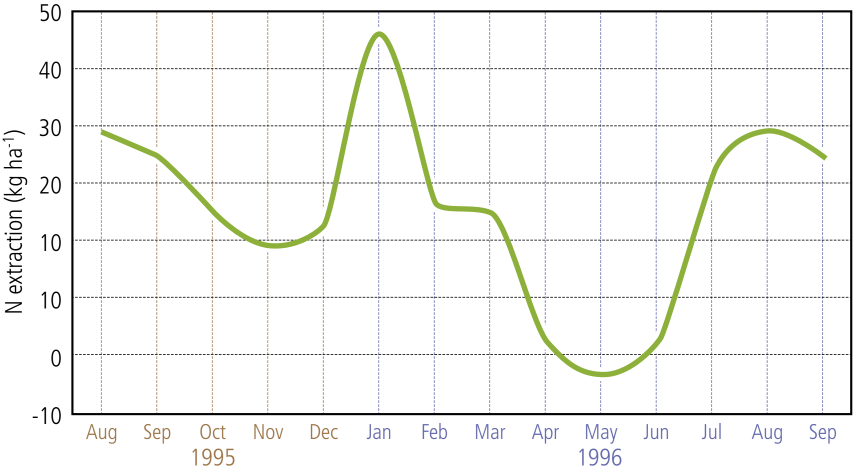

Figure 11.2. Nitrogen extraction from the soil by the banana crop in Canary Islands, Spain (Muñoz-Carpena *et al.*, 2002).

Fertigation of banana should follow the following principles:

- Apply N and K fertilizers according to plant demand. Demand varies with plant development and temperatures during the year.
- In acid soils, nitrate-N sources should be used to prevent further soil acidification which may result in aluminum toxicity.
- Monitoring leaf growth rate can help in determining the rate of N supply needed.

11.2. Vineyard

Trickle irrigation was first adopted by perennial plantations of vineyards and mature orchards (Elfving, 1982) without any reduction in plant yields. Early trials in the 1970s paved the way for worldwide acceptance of fruit tree fertigation for vines (Goldberg *et al.*, 1971), citrus (Bester *et al.*, 1974), apple (Groot Obbink and Alexander, 1977), pear (Black and Mitchell, 1974) and plum (Aljibury *et al.*, 1974). New vineyard plantations all over the world are now using trickle irrigation and fertigation (Figure 11.3).

Nitrogen (N) is the most common fertilizer nutrient applied to vineyards (Christensen *et al.*, 1978). The recommended timing of N applications varies from before bud break (Cahoon *et al.*, 1991) to between bud break and bloom (Bates, 2001). In a long season warm climate, application after harvest was useful (Conradie, 1986).

Grapevines efficiently absorb N from late-season applications in regions with long growing seasons. Chenin blanc vines in South Africa absorbed up to 34% of their total seasonal N uptake after fruit harvest (Conradie, 1980, 1991).

In California, vines absorb more of the N that was applied in July (mid season) and September (post harvest) than fertilizer applied at bud break in March (Peacock *et al.*, 1989). Late season or post-harvest applications are assumed to be less effective in

Figure 11.3. Trickle irrigation in a vineyard (hanging trickle line) (© SQM).

short-season regions where there is often a short period of active canopy following fruit harvest (Bates *et al.*, 2002).

Most new vineyards planted in Australia use trickle irrigation. Only N sources (urea, calcium nitrate or, in case of K deficient soils, KNO_3) are used in the fertigation scheme. Due to severe natural P deficiency in Australian soils, heavy application of P fertilizer is incorporated in the soil prior to vineyard establishment, while micronutrients are usually applied by leaf sprays (Robinson, 2000).

Many new vineyard plantations all over the world use fertigation. Initial fertigation experiments in Israel in all the vineyards that used trickle irrigation included P in the fertigation cocktails (Bravdo *et al.* 1984, 1985; Hepner and Bravdo, 1985). Bravdo and Hepner (1987) reviewed vineyard fertigation trials in Israel, while Bravdo and Proebsting (1993) reviewed vineyard fertigation practices worldwide. Trickle lines in the vineyard are either hung on the railing support below the canopy as shown in the picture (Figure 11.3), or are laid on the soil along the planted vines as shown in Figure 11.4. A detailed study of the method of leaf analysis, a common method to assess P status in vines was published by Atalay (1978).

A detailed plant analysis of 26 grape cultivars during the growing season was published by Christensen (1984) who compared leaf petiole and blade nutrient levels in 26 raisin, table and wine grape cultivars at five growth stages over three years. The cultivars were ranked according to total N, NH_4-N, NO_3-N, P, K, Zn and B. His detailed study suggest that each cultivar must be studied separately; blade and petiole analysis can serve in monitoring K and nitrate levels in the plants, but their values have to be calibrated separately for each cultivar. Once such a study is completed, leaf analysis could be used as a guide to vineyard fertilization.

Figure 11.4. Trickle irrigation in a vineyard (laid on the soil along the planted vines) (© Yara International ASA).

12. Fertigation of vegetable crops

12.1. Potato

The potato plant is propagated by vegetative tubers and the basic stages in crop development are profoundly affected by available water and N concentration in the root zone. The specific growth stages and demand for water and nutrients by the potato crop are as follows:

- Potato growth stages (see Table 12.1):
  - Above ground vegetative period- ends with flower appearance (initial)
  - New tuber development (developing to mid-season)
  - Foliage decline and tuber maturation (bulking to maturation)
- Duration of growth stages**:** Potato varieties have been grouped according to the length of their growth period (Bald, 1946; Jackson and Haddock, 1959):
  - Early (90-120 days)
  - Medium (120-150 days)
  - Late (150-180 days)

In most commercial potato fields, during the early stages after germination, the soil from both sides of the row is mounded to form a "hill" of loose soil medium where the future underground stolons develop and produce tubers. This operation means that trickle lines in potato can be established only after "hilling" is completed. The developing tuber must stay in a wet soil zone to secure Ca ions from the soil to allow tuber skin development without interruptions (Marschner, 1995). Thus, sprinkle irrigation is the most common and practical method of irrigation for large scale potato production.

12.1.1. Water demand

Tuber yield and quality are reduced by water deficit. Many tuber quality parameters are influenced by water stress (water shortage) such as tuber grade, specific gravity, heart necrosis, bruises, hollow heart, and more. Tuber grade is highly sensitive to irrigation management deficiencies. Irrigation timing based on amount of soil water depletion, soil water tension and crop evapo-transpiration are used to establish an irrigation schedule in a particular region (Susnoschi and Shimshi, 1985; Onder *et al.*, 2005). Water demand varies with the growing stage and climate (Shalhevet *et al.*, 1983) (Table 12.1). Increasing duration of water stress before tuber initiation reduces tuber set per stem (MacKerron and Jefferies, 1986).

Table 12.1. Water demand as a function of potato growth stage and climate (Shalhevet *et al.*, 1983).

Growth stage	Initial	Developing	Mid- season[1]	Bulking	Maturation
Duration (days)	20-30	30-40	40-60	20-35	
Crop water coefficient[2]	0.4-0.5	0.7-0.8	1.05-1.2	0.85-0.95	0.7-0.75

[1] Note: During flowering, water demand is larger than evaporation from free water surface.
[2] % of water evaporation from a class "A" pan.

12.1.2. Nutrient demand

Nutrient demand varies with time and growth stage.

Nitrogen (N)

Nitrogen needs of potato crops require careful management. High N supply during the initial growing period delays tuber formation and diverts growth to upper vegetative parts as seen in Table 12.2. The decision as to whether to apply N during the growing season is best achieved by plant tissue tests. Petiole testing is an effective tool for managing the N requirement of potatoes, especially in fine-tuning supplemental applications through fertigation. Potato petiole NO_3-N should be maintained at 25,000 parts per million (ppm) until tuber initiation and in the range of 13,000 to 15,000 ppm during the period of tuber bulking (Zhang *et al.*, 1996).

Table 12.2. Growth rate of potato tubers in relation to nitrate supply (Krauss and Marschner, 1982).

NO_3 (mM L^{-1})	N uptake (mM day^{-1})	Tuber growth (cm day^{-1})
0	0	3.89
1.5	1.18	3.24
3.5	2.10	4.06
7	6.04	0.44

Phosphorus (P)

High soil P concentration during the first stage of growth stimulates the number of initiated tubers (Jenkins and Ali, 2000). The plant takes up P during the whole period of tuber growth, from day 35 to day 95, at a constant daily rate of 51 mg P per plant (Figure 12.1; Carpenter, 1957). In traditional potato growing systems, P is usually applied with K as a basal dressing during soil preparation, mostly as various forms of organic manures (van Delden, 2001). This practice is preferred by growers as it minimizes the risk of nutrient shortages albeit the organic manures supply uncontrolled amounts of N that result in excessive vegetative growth and delay tuber formation.

To study P in trickle application, Papadopoulus (1992) used a constant concentration of 40 mg P L^{-1} in the trickle irrigation water throughout the growing period, and thus

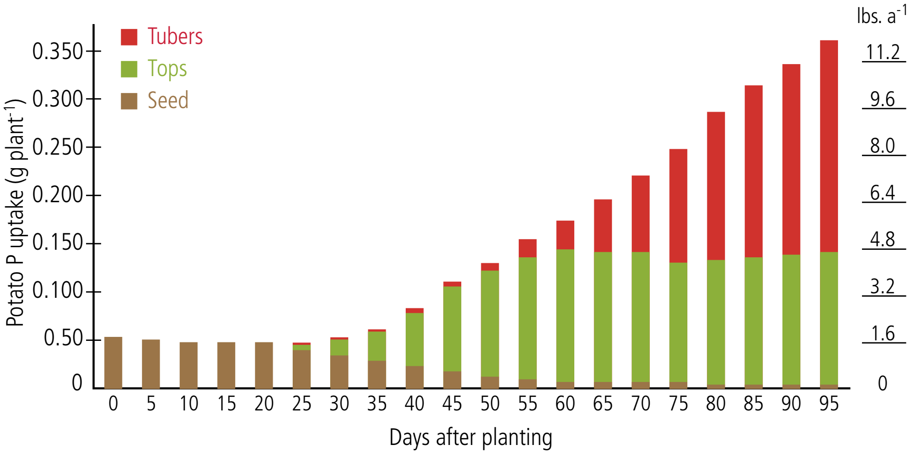

Figure 12.1. Phosphorus content of potato tops, tubers and seeds at various stages of growth (Carpenter, 1957).

maintained the level of P in the petioles and secured high yield of good quality. The tubers removed 22 kg ha^{-1} P from the soil.

Potassium (K)

Potassium mainly accumulates in the upper leaves and vines up to the end of growing stage II at a rate of 128 mg K per day. During growing stage III, the tuber absorbs K from the soil and imports K from the vine for tuber development at a rate of about 60 mg K per plant per day (Figure 12.2) (Carpenter, 1957). Potassium thus accumulates in the tuber during the entire growing period being supplied both from the vegetative parts and by direct uptake from the soil.

Calcium (Ca)

Calcium in tuber skin is obtained directly from the soil solution (Marschner, 1995), which implies that the growing tuber must be surrounded by moist soil at all times. Dry soil periods between irrigations result in shortage of Ca needed for the development of new skin tissues, leading to skin rupture and yield loss. With fertigation, it is possible to provide the wet condition of the soil mound that covers the tubers during the entire period of tuber growth. Thus, the location of the fertigation line should be on top of the ridge, above the depth of the developing tuber. Subsurface irrigation lines below the tuber might result in skin rupture and low quality mature tubers. Sprinklers, center pivot, and micro sprinklers are used in practice to control water and N application.

Sand and sandy loam are the most favored soils that allow better control of irrigation and N fertilization during the season as well as ease in tuber harvesting at the end of the season. Potatoes grown in clay soil are hard to manage and harvest, as mud may stick to the tuber, reducing tuber quality.

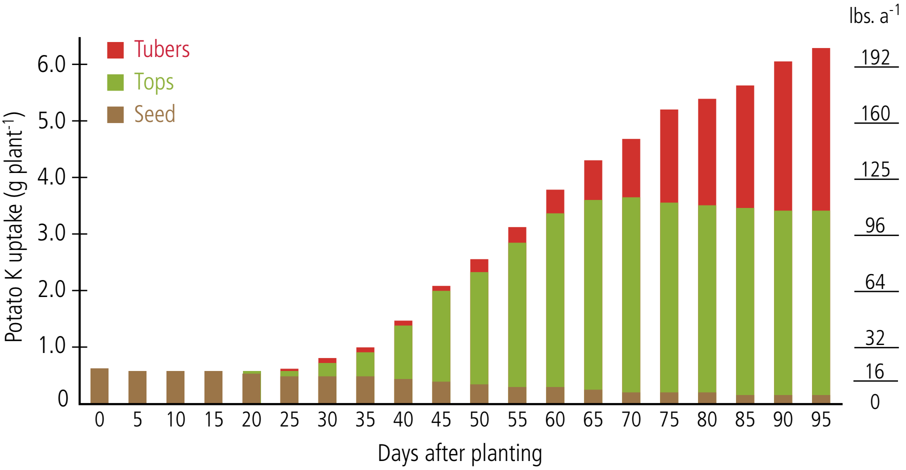

Figure 12.2. Potassium content of potato tops, tubers and seeds at various stages of growth (Carpenter, 1957).

The specific gravity of the tuber is the most important parameter for potato for industrial use. This was found highest with zero N application, when ammonium sulfate was applied in fertigation at rates of 35, 70 and 105 mg N L^{-1}. The increase in total yield observed with increasing N application was due to the increase in tuber size at the expense of specific gravity (Mohammad *et al.*, 1999).

12.1.3. Trickle irrigation systems in potato production in various countries

India: Gupta and Saxena (1976) found that the critical concentration of NO_3-N in petioles of 45-day old plants is from 9,100 to 9,600 ppm with the corresponding range in the midrib from 3,000 to 3,900 ppm. For PO_4-P, the critical concentration for petioles of 45-day old plants is 2,250 ppm. Testing nutrient contents of the leaves during the growing season is the most accurate method for determining nutrient status to enable a quick response to any needed addition of N fertilizers via the trickle line. In this respect, trickle irrigation is unique in that it is the only irrigation method that can be adapted to control the daily supply of nutrients when the plant demands it.

Israel: The earliest trickle irrigation studies to evaluate the effects of simultaneously varying moisture and N levels on potato plant development and assimilate partitioning in potato were conducted by Shalhevet *et al.* (1983), Shimshi and Susnochi (1985) and Susnochi and Shimshi (1985) in Israel on a loess soil. However, the most accepted method in 2007 was fertigation via micro sprinklers (U. Kafkafi, personal communication).

Spain: Fabeiro *et al.* (2001) used 10 drip irrigation treatments to examine the effect of the timing of irrigation deficits on potato yield and water use efficiency. Water shortage during mid- and late-season tuber bulking was particularly damaging to tuber yield. High yield was combined with high water use efficiency when irrigation deficits were restricted early in the season.

Syria: Potato fertigation in Syria was reported by Mussaddak (2007) where tuber marketable yield of fertigated spring potato was compared with furrow irrigation. At N fertilizer rates of 70, 140, 210 and 280 kg N ha^{-1} for the fertigated crop, tuber yield were increased by 4, 2, 31, and 13% for spring potato respectively, whereas, for fall potato with furrow irrigation, the comparative values were 13, 27, 20 and 35% respectively. This report demonstrates the delicate interaction between climatic conditions during potato growth and tuber yield at high N application rates. Drip fertigation improved field water use efficiency at the bulking and harvest stages. It also increased specific gravity of potato tubers compared to furrow irrigation, while higher N input decreased specific gravity of potato tubers under both irrigation methods as was also reported by Mohammad *et al.* (1999).

USA: Drip irrigation in potato was introduced only recently to the USA and is as yet used in only a very small proportion of total commercial potato production. Potato trickle irrigation trials failed to equal or surpass the yield and quality produced with sprinkler irrigation in the Pacific Northwest (Shock *et al.*, 1993). The Russet Burbank potato variety and difficulties in drip tube placement were responsible for the failure of the trickle irrigation system. Deep drip tape placement resulted in yield and grade reduction due to several reasons: poorer water supply to the shallow root system of potato, wetting deficiencies of the external tuber skin and overheating of the tuber at the relatively dry hill. Shallow drip tape placement in clay soils resulted in water savings, but also in difficulty in assuring tuber quality because of clay adherence to the tubers during mechanical picking. Sammis (1980) compared sprinkler, surface drip, subsurface drip and furrow irrigation for the production of potato in New Mexico. Subsurface drip irrigation (SDI) with a 20 kPa irrigation criterion was among the most productive irrigation systems. Shae *et al.* (1999) studied four options for managing drip irrigation of potatoes in North Dakota. Automation of irrigation based on a soil water tension irrigation criterion at 30 kPa had relatively high water use efficiency.

In Florida, Smajstrla *et al.* (2000) compared automated controlled SDI with conventional semi-closed seepage sub-irrigation. The need for a change in the old irrigation system is due to the problem of surface runoff and nutrient contamination of adjoining waterways. The SDI system as employed by Smajstrla *et al.* (2000) required more electrical energy but used 36% less water to obtain the same potato yield. Steyn *et al.* (2000) examined irrigation scheduling options for drip-irrigated potatoes. Sprinkler irrigation at different irrigation criteria was compared to surface drip and SDI with a range of fertilizer treatments, for potato yield and grade in Minnesota (Waddell *et al.*, 2000). Surface drip and SDI were among the most productive systems for total and marketable yield.

Drip irrigation or sprinkler irrigation reduced nitrate leaching compared to normal sprinkler irrigation (Waddell *et al.*, 1999). Simonne *et al.*, (2002) concluded that drip irrigation is an economically viable potato production method in the southeastern United States. Zartman *et al.* (1992) examined tape depth and emitter spacing on tuber yield and grade of Norgold Russet potato in Lubbock, Texas. Tape depth or emitter spacing did not influence potato yield, but the proportion of misshaped tubers was greater when the tape was buried at 0.2 m than with shallower placement. Soil temperature was greater with the tape at 0.2 m than at 0.1 m or 0.025 m. DeTar *et al.* (1996) found that the best location for irrigation tapes was at depths of 0.08 m (above the seed tuber) and 0.46 m (below the seed tuber). The experiments of DeTar *et al.* (1996) and that of Zartman *et al.* (1992) as well as the early experiment of Susnoschi and Shimshi (1985) in Israel, demonstrate the need for adaptation of water and fertilizer delivery systems for each soil type, potato cultivar and climate conditions.

Turkey: In the Capadocia region, the area under drip irrigation and fertigation increased from 500 hectare in 2003 to 4,000 ha in 2006, an indication that drip irrigation and fertigation are the prevailing irrigation systems in the region. The Capadocia results can be extrapolated to the light textured soils of Central Anatolia-Bolu region and the Agean Sea region, which are under nearly similar climatic conditions (FAO, 1990).

12.1.4. Outlook for potato fertigation

The complexity of potato crop maintenance under irrigation and the wide range of potato production techniques, e.g. for table consumption, against demands for industry and food chain stores, are slowing down the introduction of drip irrigation systems for potato production.

Maintaining uniform soil moisture around the tubers during development and, at the same time, adopting specific irrigation techniques to specific soil types, soil preparation methods and climate conditions are major considerations in potato production. In sandy light textured soils, micro sprinklers and fertigation are used with applications of frequent, even daily or several times a day, small doses of water and nutrients. On heavy clay soils, sprinkler irrigation lines are used with either basal fertilization only during soil preparation or splitting the N application with the irrigation schedules until flowering. Potassium and P fertilizers are usually given during soil preparation, part as organic manures and part as inorganic fertilizers.

The complexity of potato management under field conditions and the diversity of the world market dictate the need for site specific solutions to achieve the best possible commercial yield. Potato cultivars vary differently in their performance under drip irrigation (Shock *et al.*, 2003). Adopting trickle irrigation and fertigation for potato is, therefore, a tedious and continuous work that becomes economical only when large areas and good market exists and when a shortage in water becomes a limiting factor. However, fertigation using micro sprinklers on sandy soils is an acceptable method. Nitrogen fertilizer supplied via center pivot irrigation system is also a common practice using only three to four applications.

12.2. Tomatoes

12.2.1. Greenhouse-grown tomatoes

Greenhouse tomato is trimmed to grow on only one stem. The pattern of growth is: nine leaves and a truss as the first strata, then three leaves and a truss, which theoretically can proceed endlessly as long as the apical dominance is kept alive (Figure 12.3). Such a system is kept throughout the growing period of the plant in the greenhouse. The rate of uptake of the major nutrients slowly increases in the first three months after seeding. Once the first nine leaves and a truss are obtained, an almost constant uptake rate pattern of N, P, K and Ca is observed.

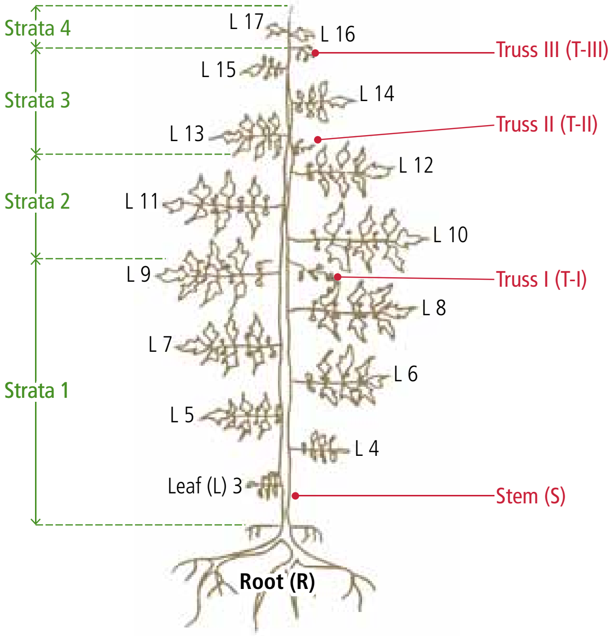

Figure 12.3. Diagram of a tomato plant (After Tanaka *et al.*, 1974).

De-topping the growing tip of the plant (broken lines; Figure 12.4) stops plant elongation and nutrient uptake. During the time of linear uptake rate, N uptake reached 4 kg N ha^{-1} per day.

The distribution pattern of nutrients in the vegetative and fruit parts (Figure 12.5) demonstrates the internal control of the plant on mineral distribution inside the plant (Tanaka *et al.*, 1974). 62% of all N taken up by the tomato plant is found in the fruits. The comparative figure for P is almost 70%, most of which is in the seeds. Potassium is evenly distributed between fruit and vegetative parts, while less than 5% of the Ca enters the fruit (Figure 12.4).

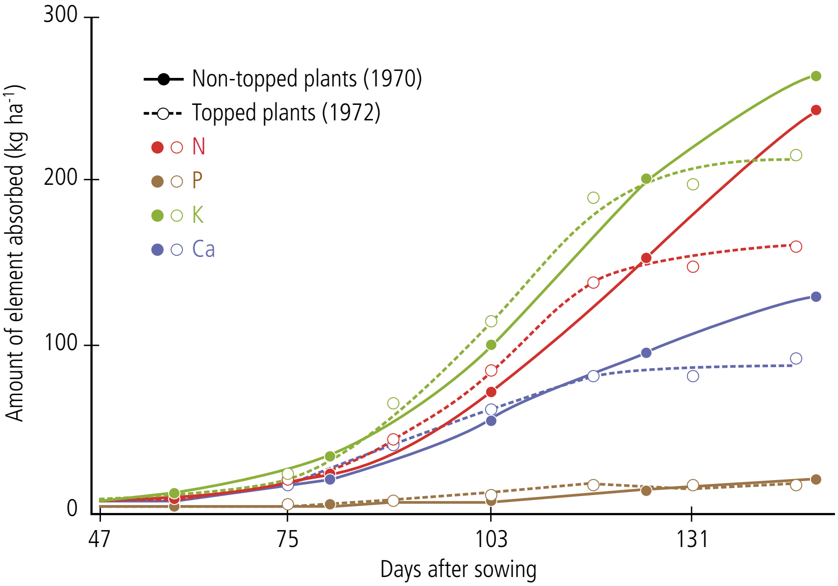

Figure 12.4. Amount of N, P, K and Ca absorbed by the topped and non-topped plants (Adapted from Tanaka *et al.*, 1974).

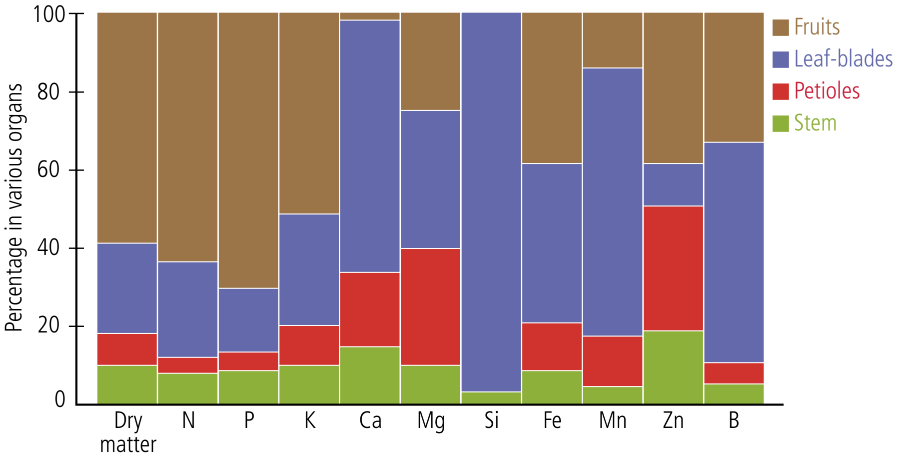

Figure 12.5. Distribution of mineral elements in the tomato plant parts (Adapted from Tanaka *et al.*, 1974).

A daily supply pattern of N, P and K for greenhouse tomato grown in sand is summarized in Table 12.3 (Bar-Yosef *et al.*, 1992).

Table 12.3. Daily nutrients supply by fertigation for greenhouse grown tomato*.

Days after planting	kg N (ha^{-1} day^{-1})	kg P (ha^{-1} day^{-1})	kg K (ha^{-1} day^{-1})
1- 10	1	0.1	2
11- 20	1	0.1	4
21- 30	1	0.1	3.5
31- 40	2	0.2	3.5
41- 50	2.5	0.4	5.5
51- 60	2.5	0.6	5.5
61- 70	2.5	0.3	6
71- 80	2.5	0.3	4
81- 90	1.5	0.3	6
91-100	1.5	0.1	0.1
101-110	1	0.1	0.1
111-120	1	0.1	1
121-130	1.5	0.2	1
131-150	1.5	0.35	1.3
151-180	4	0.5	3.8
181-220	2	0.3	3
Total (kg ha^{-1})	450	65	710

*cv F-144 (Daniela, planted Sept. 25, at 23,000 plants ha^{-1}, yielded 195 t ha^{-1} (Bar-Yosef *et al.*,1992).

Greenhouse tomato can be grown in culture media made from a mixture of organic sources (i.e. peat and compost) and mineral sources (i.e. perlite, rock and glass wool, tuff or sand) as well as in hydroponics and nutrient film techniques (NFT). Such systems expose the roots to the internal greenhouse temperatures. Greenhouses in cold climates are warmed up and kept heated during the night. In warm climates, greenhouses might be overheated, where the roots are exposed to higher temperatures than the leaves since evaporation cools the leaves but the roots cannot escape the greenhouse heat. This factor is very important in choosing the N form in fertilizers.

The nitrate ion (NO_3^-) is transported to the leaves as nitrate, where it is transformed to and assimilated as ammonia. The ammonia is immediately bound to sugar that is also produced in the leaf by photosynthesis, and both produce amino acids. Ammonia is a toxic substance in the cell and is eliminated during the production of amino acids, a mechanism that keeps the plant growing (Marschner, 1995). Ammonium-N is metabolized in the root to amino acids using the sugar present in the root cells. The sugar in the root depends on transport from the leaves. When root temperature increases, root respiration increases and consumes sugar in parallel but independent of N metabolism. These two metabolic processes, respiration and ammonium metabolism, strongly compete for sugar in the root. When the sugar is totally consumed by respiration, ammonia production during ammonium metabolism becomes toxic to cell organs and impairs root growth and death of the root cells is observed (Ganmore-Newmann and Kafkafi, 1985) (Figure 12.6). The metabolism of ammonium or nitrate inside a plant was reviewed by Britto and Kronzucker (2002). They covered the complete metabolic cycle in different plant families, sensitive and tolerant to ammonium nutrition. The sensitivity of crops grown to ammonium or nitrate should, therefore, be considered to select the best N form for a specific crop and climatic conditions.

Figure 12.6. Glasshouse tomato (tomato cv. Money Maker): right - only nitrate sources; left - increasing levels of ammonium in the recycled nutrient solution (Kafkafi, 1964).

12.2.2. Salinity

The relationship between fruit dry matter, water transport to the fruit and salinity was studied by Ho *et al.* (1987), who showed that the total entry of water into the fruits is much lower in high salinity treatments resulting in low fruit fresh weight. Since the size of the tomato fruit is very much dependent on water availability, growers can control entry of water into the fruit according to the specific target market. Small fruits with high TSS (Total Soluble Solids) usually contain higher concentration of sugar than large fruits of the same cultivar grown in the same location but that received higher water applications. Both table and industrial tomatoes respond in the same way to irrigation and salinity levels. Total soluble solids in tomato rises with increase in salinity and the ratio between ammonium and nitrate in the fertilizer solution as demonstrated by the work of Flores *et al.* (2003) and the data presented in Table 12.4 adapted from Ben-Oliel (2004).

Table 12.4. Effect of the N source and salinity on yield and fruit quality parameters in tomato cv. 'R144'.

*NH_4^+ (mM)	MY[1] (g $plant^{-1}$)	BER[2] (g $plant^{-1}$)	TY[3] (g $plant^{-1}$)	BY[4]	MFW[5] (g)	TSS[6] (%)	FSEC[7] (dSm^{-1})	TA[8] (%)	pH	LAI[9] (m^2 $plant^{-1}$)
NaCl - 0 mM										
0	5480b	158d	6084b	322b	141a	5.3b	5.3c	0.51b	4.07a	1.8ab
1	5980a	236c	6814a	368a	143a	5.4b	5.3c	0.48b	4.04a	2.1a
2	5160b	247c	5906b	325b	140a	5.5b	5.5c	0.53b	4.00a	1.8ab
4	4430c	356c	4927b	256c	126b	5.2b	5.1c	0.46b	4.04a	1.6b
NaCl - 45 mM										
0	2700e	763c	3663e	267c	82d	7.3a	6.9ab	0.67a	4.02a	1.25d
1	3820d	821bc	4840d	334b	103c	6.9a	7.2a	0.64a	4.00a	1.7b
2	2810e	954ab	3914e	282c	89d	7.2a	7.2a	0.64a	3.96a	1.5c
4	1670f	1183a	2919f	201d	87d	6.9a	6.4b	0.43b	3.98a	1.05e

*Concentration of NH_4^+ out of total 8 mM N.
[1]MY – marketable yield;
[2]BER – blossom end rot;
[3]TY – total yield=MY+BER+ developing fruits;
[4]BY – brix yield;
[5]MFW – mean fruit weight;
[6]TSS – total soluble solids;
[7]FSEC – fruit serum electrical conductivity;
[8]TA – titratable acidity as citric acid;
[9]LAI – leaf area index.
Within each column, means followed by the same letter do not significantly differ at $P< 0.05$.

The effects of increasing ammonium in the nutrient solution at the expense of nitrate (total 8mM N) with and without sodium chloride, on the growth and fruit quality parameters of tomato plants was investigated in a greenhouse experiment (Table 12.4). The plants were grown in 10 L containers filled with perlite (a sponge like siliceous material) and supplied by a constant stream of the nutrient solution that was drained continuously. It is clear that high ammonium levels raised the incidence of blossom end rot (BER) regardless of the presence or absence of NaCl in the nutrient solution. However, the incidence was much greater in the saline treatment. While the total yield was severely depressed by high ammonium and high salinity, the TSS value of the fruits of the saline treated plants increased. Salinity decreased the mean fruit weight (MFW). As a result, fruit sweetness (sugar concentration) was higher in the small fruits under salinity due to higher concentration of TSS.

12.2.3. Fertigation of tomato for processing

The tomato industry reformed its system of payment by weight of tomato (Santos, 1996). At present, grower reward is based on the percent level of fruit dry matter. That decision alone induced significant changes in the management of processing tomato irrigation systems, with a need to emphasize the technological quality of the marketable product. Optimization of dry matter production, expected revenues and seasonal applied water were studied by Santos (1996). The critical factor controlling profit was identified as yield distribution uniformity of fruit quality. Decreases in fruit dry matter resulted from increasing levels of seasonally applied water. The optimal irrigation level for high fruit dry matter production is always lower than that required for maximum fresh yield. Such interaction suggests an inverse relationship between profit and water applied to tomato for processing. While TSS yield per ha is the result of the multiplication of fresh tomato yield per ha by the TSS concentration, lack of water may become the limiting factor for plant growth, causing reduction of fresh yield, which cannot be compensated by higher TSS concentrations. The introduction of subsurface trickle irrigation allows accurate irrigation without overflow controlling the yield quality.

A field study comparing various forms of irrigation and fertigation of field grown tomato in India was carried out by Hebbar *et al.* (2004). Fertigation with 100% water soluble fertilizers increased fruit yield significantly (79.2 t ha^{-1}) over subsurface drip fertigation (76.55 t ha^{-1}). Fertigation recorded a significantly higher number of fruits per plant (56.9) and higher fertilizer use efficiency (226.48 kg yield kg^{-1} NPK) compared to drip- and furrow-irrigated controls. Since nutrient doses in fertigation are given in small daily amounts as plant demand increases with growth, lesser leaching of NO_3-N and K to deeper soil layers was observed.

Fertigation schedules used in the USA for processing tomato are given in Tables 12.5 and 12.6 (Snyder and Thomas, 2007).

The main trickle irrigation methods used in the USA is subsurface at a depth of 15-20 cm to secure the irrigation lines from being damaged by mechanical harvesters.

Table 12.5. Suggested fertigation schedule for transplanted tomatoes in Mississippi, using all fertilizers via fertigation (14-week schedule)*.

Total (lb a^{-1})		Growth stage	No. of weeks fertigated	Injection rate (lb a^{-1} week^{-1})	Total injected at stage (lb)
N	K_2O	vegetative	2	6	12
		bloom	3	8	24
120	120	fruit set	7	10	70
		fruit set ended	1	8	8
		maturation	1	6	6
Total			14		120

*Note: P fertilizer is not mentioned in these tables because all P should be applied at pre-plant and not fertigated.

Table 12.6. Suggested fertigation schedule for transplanted tomatoes in Mississippi, using 20 percent of N and K_2O pre-plant (12-week schedule)*.

Total ($lb\ a^{-1}$)		Growth stage	No. of weeks fertigated	Injection rate ($lb\ a^{-1}\ week^{-1}$)	Total injected at stage (lb)
N	K_2O	vegetative	2	0	0
		bloom	3	7	21
96	96	fruit set	7	9	63
		fruit set ended	1	7	7
		maturation	1	5	5
Totals			12		96

*Note: P fertilizer is not mentioned in these tables because all P should be applied at pre-plant and not fertigated.

12.2.4. Tomato industrial quality

Red color intensity and sugar or TSS is directly related to the lycopene content and quality of tomatoes. The relationship between K concentration of the lower leaves and lycopene yield is presented in Figure 12.7 (Sosnitsky, 1996) (See also Figure 6.1).

Between day 50 and 65, the main flowering cycle occurs that is marked by minimum K consumption. Immediately at the end of flowering, fruit development peaks during two weeks. The supply of K by fertigation must secure enough K in the active root zone before the peak periods, i.e.: (i) base K application to secure early growth; (ii) increasing

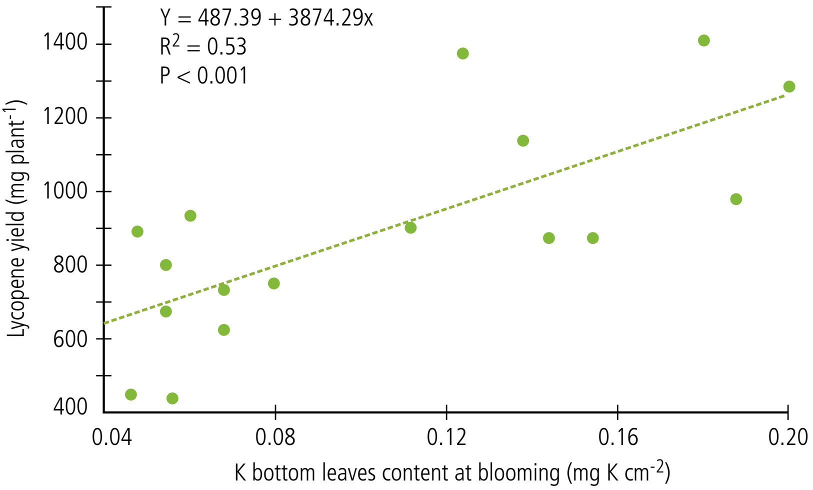

Figure 12.7. Tomato fruit lycopene content as a function of lower leaf K concentration on day 40 after transplant (Sosnitsky, 1996).

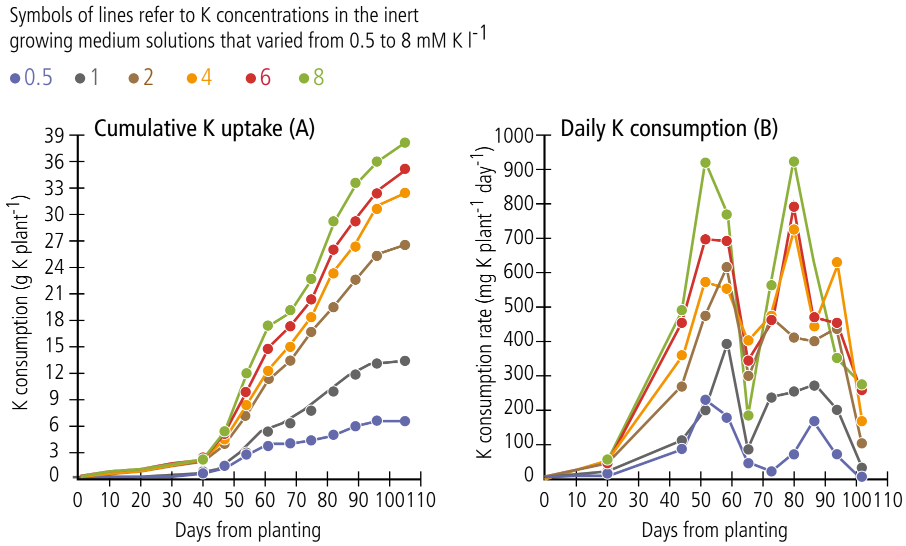

Figure 12.8. Cumulative K uptake (A) and daily K consumption (B) during the growing season of tomato cv. 8687 (Sosnitsky, 1996).

quantities to secure first fruit wave; and (iii) increasing levels up to 1 g K per plant day^{-1} to secure final K supply (Figure 12.8 A and B).

The results of the fertilization experiment by Sosnitsky (1996) with processing tomato elucidate the major principles of fertigation of processing tomato:

- Base application of P fertilizer should supply all plant demand on seeding day.
- Initial high N levels reduce plant growth rate by competing with P uptake.
- K application is needed during all the growing season, mainly starting at first bloom.

Table 12.7 demonstrates that during the early growing stages after direct seeding on day 37 and day 81, ammonium fertilizer applied before seeding, delayed the vegetative growth by about 25% relative to the control plots.

The effect of large basal application of P fertilizer (Table 12.8) on processing tomato is very positive on plant development and fruit yield. Phosphorus increases the number of tomato flowers, and an initial large amount of P applied during soil preparation increases fruit yield. In a period of 40 days, the fruit dry matter increases four times while the vegetative part increases only by about 50%. This procedure is employed in the USA, where P fertilizers are avoided in subsurface fertigation (Snyder and Thomas, 2007).

During the last six weeks of field grown tomato, the entire N taken up from the soil is diverted to the developing fruit. The vegetative parts lose N in the control plots in favor of the developing fruit, starting 40 days before harvest. The initial amount of N in the soil in the control plots was enough for the first 37 days of growth but could not supply the yield potential of the tomatoes. Therefore, in general the total amount of P can be applied during soil preparation, while N should be split during the last 10 weeks of growth, with its quantity steadily increasing with plant growth (Table 12.9).

Table 12.7. Dry matter yield of field growing tomato affected by N fertilization (Feigin, A., personal communication).

Plant parts	Accumulated dry matter yield (kg ha^{-1})				
	$(NH_4)_2SO_4$ (kg N ha^{-1})	27 May 37 DAS*	11 July 81 DAS	30 July 100 DAS	19 Aug 120 DAS
Fruits	0	0	905	2429	4143
	60	0	1000	2762	4286
	120	0	1095	2905	4000
	180	0	619	3352	3905
Vegetative shoot	0	166	2143	2619	3000
	60	119	2095	2524	3810
	120	95	2048	2905	3619
	180	72	1905	2571	3381
Total	0	166	3048	5048	7143
	60	119	3095	5286	8095
	120	95	3143	5810	7619
	180	72	2524	5924	7286

*DAS- days after seeding

Table 12.8. Dry matter yield of field growing tomato affected by P fertilization (Feigin, A., personal communication).

Plant parts	Accumulated dry matter yield (kg ha^{-1})				
	Superphosphate (kg P ha^{-1})	27 May 37 DAS	11 July 81 DAS	30 July 100 DAS	19 Aug 120 DAS
Fruits	0	0	714	2190	3619
	80	0	905	2648	4000
	240	0	1238	3619	5095
Vegetative shoot	0	48	1667	2571	3143
	80	114	1952	2476	3857
	240	190	2286	2905	3381
Total	0	48	2381	4762	6762
	80	114	2857	5124	7857
	240	190	3524	6524	8476

Table 12.9. Accumulated N uptake affected by N fertilization (Feigin, A., personal communication).

Plant parts	Accumulated N uptake (kg N ha^{-1})				
	$(NH_4)SO_4$ (kg N ha^{-1})	27 May 37 DAS	11 July 81 DAS	30 July 100 DAS	19 Aug 120 DAS
Fruits	0	0	22	53	94
	60	0	28	76	112
	120	0	34	97	109
	180	0	25	90	118
Vegetative shoot	0	7	52	47	37
	60	5	58	53	59
	120	5	60	62	59
	180	4	58	69	65
Total	0	7	74	100	131
	60	5	86	129	171
	120	5	94	159	168
	180	4	83	160	182

The effect of P on N uptake is obvious during the early growth stage. In that period, plant N uptake due to high P application is six times greater than the control. This early "jump start" of seedling is reflected in the final N in the fruit (Table 12.10).

Table 12.10. Accumulated N uptake affected by P fertilization (Feigin, A., personal communication).

Plant parts	Accumulated N uptake (kg N ha^{-1})				
	Superphosphate (kg P ha^{-1})	27 May 37 DAS	11 July 81 DAS	30 July 100 DAS	19 Aug 120 DAS
Fruits	0	0.0	2.2	8.2	11.7
	80	0.0	4.2	10.6	14.7
	240	0.0	5.4	11.7	16.9
Vegetative shoot	0	0.1	3.3	4.5	4.2
	80	0.3	4.8	4.4	5.0
	240	0.6	4.1	4.8	4.7
Total	0	0.1	5.6	12.6	16.0
	80	0.3	8.9	15.0	19.8
	240	0.6	9.5	16.5	21.6

K uptake follows plant and fruit growth. When an initial high dose of N, as ammonium sulfate (as used in the study) is applied, a decline in plant growth is reflected in the small amount of K uptake (Table 12.11). As shown for the four tomato cultivars (Figure 12.9), K in the fruit juice is linearly related to the total fruit dry matter of processing tomato.

Table 12.11. Accumulated K uptake as affected by N fertilization (Feigin, A., personal communication).

Plant parts	Accumulated K uptake (kg ha^{-1})				
	$(NH4)_2SO_4$ (kg N ha^{-1})	27 May 37 DAS	11 July 81 DAS	30 July 100 DAS	19 Aug 120 DAS
Fruits	0	0	48	112	187
	60	0	57	127	212
	120	0	58	146	187
	180	0	42	167	206
Vegetative shoot	0	5	56	52	67
	60	4	53	46	77
	120	3	56	58	67
	180	2	50	62	63
Total	0	5	104	163	254
	60	4	110	173	288
	120	3	113	204	254
	180	2	92	229	269

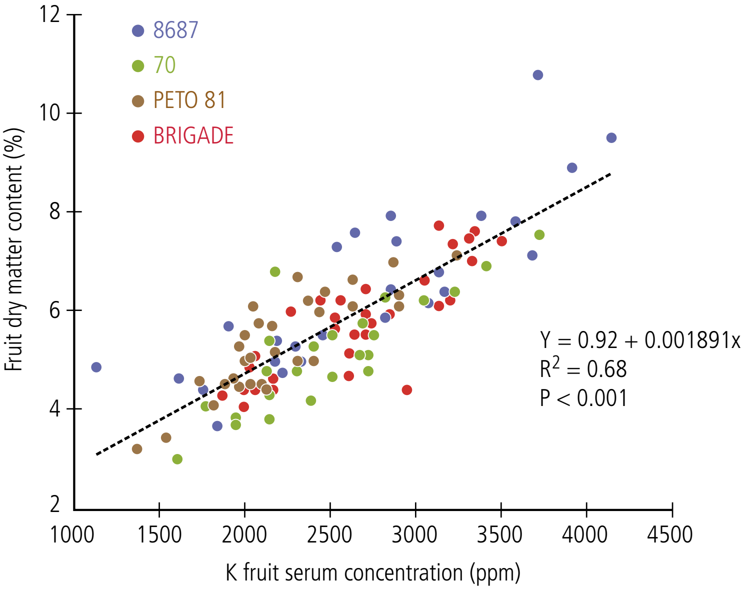

Figure 12.9. Potassium in the fruit juice (fruit serum) of four processing tomato cultivars.

13. Fertigation in flowers and ornamental plants grown in soil

“Floriculture for Food Security” is promoted by FAO (Baudoin *et al.*, 2007), as flower biodiversity is being perceived as a potential income source for developing countries. In most cases, trickle irrigation and fertigation are the methods used to secure production of these delicate plant species.

Flowers endemic to various parts of the world have developed unique adaptation to local soil and climatic conditions so that their transfer to commercial culture usually involves problem responses to culture media and nutrient compositions. Australian native flowers in particular are sensitive to increase in soil P. Addition of NPK and micronutrient fertilizer or raising only P concentration in growing one such species, Safari Sunset, increased total fresh weight and improved plant growth. Clusters of proteoid roots (dense clusters of rootlets of limited growth) (Watt and Evans, 1999) developed when very low P was present in the nutrient solution; and no proteoid roots developed in treatments with P present (Silber *et al.*, 1998).

13.1. Impatiens

Production of high-quality plants demands optimal nutrient supply during growth, especially with respect to the total N concentration and the ratio between N sources provided. Impatiens (*Impatiens wallerana Hook. F.*) is one of the most important horticultural crops in the United States. A detailed study on the suitable ratio between nitrate (NO_3^-) and ammonium (NH_4^+) in the fertigation of this species (Romero *et al.*, 2006) suggested that shoot fresh and dry weights and flower bud number were at a maximum with a nitrate to ammonium ratio of 1:3 at a total N concentration of 10.5 mmol L^{-1}. Since the media used for plant growth are site-specific, the actual ratio of nitrate to ammonium in the solution will be affected by the buffer capacity of the particular growth medium used. As mentioned in Chapter 4, the ratio of nitrate to ammonium is the main tool used to control the pH of the root media in growing plants.

13.2. Roses

Roses are the most common flower produced and grown in many parts of the world. Trickle irrigation on volcanic scoria (tuff) bedding, or on other artificial media are commonly used (Paradiso *et al.*, 2003). The pH near the root (around pH 6.5) is usually measured daily in the drainage water and is maintained within a narrow range by controlling the nitrate to ammonium ratio in the feed. The root pH is also affected by plant age, radiation and growing stage of the plant. A typical composition of a recirculating nutrient solution for roses is presented in Table 13.1 (Lykas *et al.*, 2006).

Table 13.1. The initial mineral composition of a recirculating nutrient solution for roses (Lykas *et al.*, 2006).

Element	Concentration (ppm)
Nitrogen – as N-NO_3	172
Nitrogen – as N-NH_4	14
Phosphorus – as P-H_2PO_4	31
Sulfur – as S-SO_4	24
Potassium (K)	250
Calcium (Ca)	160
Magnesium (Mg)	24
Iron (Fe)	1.3
Boron (B)	0.28
Copper (Cu)	0.6
Molybdenum (Mo)	0.027
Manganese (Mn)	0.50
Zinc (Zn)	0.23

In a recirculating nutrient solution system, N uptake by greenhouse 'Royalty' rose plants was studied in relation to irradiance and the developmental stage of the crop (Cabrera *et al.*, 1995). The rate of N uptake followed a cyclical pattern that was related to shoot development and harvest, but independent of transpiration rate. The rate of N uptake varied four- to five-fold during a single cycle of flower shoot growth in the range of 29–146 mg N per plant day^{-1}. Following a flower harvest, the N uptake rate decreased even as the new flower shoots began to develop. The lowest N uptake occurred when the shoot elongation rate was at its maximum. Thereafter, uptake rates increased, with the highest rate occurring as the flower shoots reached commercial maturity. K, Ca, Mg and P followed the same pattern of uptake as observed for N. Irradiance did not control the periodicity of the N uptake cycles but did affect average daily plant N demand. Uptake rates in summer days reached 60–70 mg N per plant day^{-1}, about twice of those in winter (about 30 mg N per plant day^{-1}). The total annual plant N uptake was 16.8 g N per plant year^{-1}.

13.3. Carnations

Changing the concentrations and rates of nutrients in the soil media can affect quality of flowers. Calyx splitting and high percentage of stem brittle disorder in carnation (*Dianthus caryophyllus* L.), cv. Standard White Candy, grown under fertigation on a sandy loam soil, in the coastal plateau of Israel, 18 km east, was treated by increasing K (K_2SO_4 and KNO_3) and the NO_3^-:NH_4^+ ratio in the fertigation medium (Yermiyahu and Kafkafi, 2009). The increase in K levels in the fertigation media was reflected in the content of K in the plant dry matter (DM). The beneficial effects of the KNO_3 treatment probably resulted because of the absence of NH_4-N in the fertigation media. These beneficial effects were expressed in the form of a 17% increase in flower yield and a reduction in calyx splitting. When compared to the ammonium-containing fertilizer in the irrigation water, flower quality - as measured by stem brittle - was improved by the highest level of K supply, irrespective of the K fertilizer form, KNO_3 or K_2SO_4. The findings suggested that maintaining a continuous supply of K at a much higher concentration in the soil solution above the "sufficient" level for maximum yield, may be regarded as an "insurance cost" against detrimental effects of unexpected climatic events of cold nights followed by sunny days, which are the main cause of the disorder.

14. Fertigation of crops in soilless culture and growth media

Plants growing in containers differ from field growing plants in several respects. Containers limit root volume development and as a consequence, the requirements for water, oxygen and nutrients are more intensive. Growers and agronomists use various natural and artificial growth media to suite specific local conditions, taking into account the required physical and chemical properties of the media and the plant grown. However, the depletion of nutrients from the limited rooting zone in soilless culture necessitates the continuous replenishment of nutrient reserves. Silber *et al.* (2003) suggested that the yield reduction obtained at low frequency irrigation (and fertigation) resulted from nutrient deficiency, rather than water shortage, and that high irrigation frequency can compensate for nutrient deficiency. Frequent fertigation improved the uptake of nutrients through two main mechanisms: continuous replenishment of nutrients in the depletion zone at the vicinity of root interface and enhanced transport of dissolved nutrients by mass flow, due to the higher averaged water content in the growth media. The fertigation frequency, the nutrients concentration and the ratio between them, the irrigation water pH after the fertilizer injection have to be suited to the growth media characteristics.

In the following sections growth media will be defined, the physical and chemical characteristics related to nutrient supply and fertigation management will be described.

14.1. Definition of growth media

The expression "growth media" is applied to any solid material, different from the soil in situ, natural or synthetic, or a residue of an industrial production process, mineral or organic, that is introduced into a container, alone or in a mixture, which allows the anchoring of the plant root system. The "growth medium" can participate (be chemically active) or not (be inert material) in the complicated process of nutrient supply to the plant (Abad Berjón *et al.*, 2005).

14.2. Growth media used in containers to grow plants

Abad Berjón *et al.* (2005) classified the growth media according to the material of origin.

14.2.1. Mineral growth media

- **Natural media:** obtained from rocks or minerals without treatment or by simple physical treatment like sieving (e.g. sand, gravel, volcanic scoria).
- **Treated or transformed by physical or chemical treatments:** expanded clay, perlite (derived from a siliceous volcanic rock heated to about 1000°C), vermiculite (hydrated magnesium aluminum silicate), rockwool (obtained from a mixture of basaltic rocks, limestone and coal fused together at 1600°C).
- **Residues or industrial by-products:** crushed bricks, coal from blast furnace.

14.2.2. Organic growth media

- **Natural sources:** peat of different botanic origin, peat-moss sphagnum, true moss (Bryalers Broilers), sedges, pine litter, leaf moulds and woody plants.
- **Synthetic:** organic polymers, non biodegradable, obtained by chemical synthesis (expanded polystyrene, urea-formaldehyde and polyurethane foams).
- **Residues or by-products of domestic, industrial or agricultural activity:** (most have to be composted before use in order to obtain a stable material) rice husk, wood bark, manure, sawdust, coconut fiber, cork residues, municipal solid waste, treated sewage sludge, etc.

14.3. Characteristics of growth media

Chen and Inbar (1985) summarized the desired characteristics of growth media for optimal plant growth (Poole *et al.*, 1981; Hanan *et al.*, 1978; Hartmann and Kester, 1975; Richards *et al.*, 1964; Wilson, 1984).

14.3.1. Physical characteristics

- High water retention for easily available water to the plant
- High air content already at low water tension
- Particle size distribution that allows conditions (a) and (b)
- Low bulk density to secure light weight growth media
- High porosity to allow aeration
- High hydraulic conductivity to allow efficient drainage
- Provide the plant with stable anchoring ability
- Constant volume, minimizing the growth media changes in time due to shrinking, and compacting

14.3.2. Chemical characteristics

- High cation exchange capacity
- Reasonable level of nutrients and ability of supplying these to the plant
- Buffer capacity and preserving a uniform pH level
- Low soluble salt content
- Organic growth media should have low C/N ratio, stable with very low decomposition rate

Some of these characteristics are not typical for all growth media but there is the possibility to introduce some of them by proper irrigation and fertilization. Plants can be grown in a growth medium composed of a single substrate but, more usually, it is composed of two or more components that complement each other. As a result, the final growth media is more effective than its individual components and its characteristics are balanced.

14.4. Chemical characteristics and nutrient content

14.4.1. C/N ratio and N concentration

Fresh organic matter is decomposed by microorganisms. Microorganisms use N to decompose the organic material. The C/N ratio in the microorganism bodies is in the range 5-30 (Chen and Inbar, 1985). When this range is in the growth medium, it is considered relatively stable to decomposition. Microbial breakdown of materials with higher C/N ratios induces N fixation by the microorganisms, thereby decreasing the N available to plants in the growth media. Different growth media have different C/N ratios (Table 14.1).

Table 14.1. C/N ratio in different organic growth media (Verdonck, 1983).

Material	C/N ratio
Fresh bark	75-110
Composted hard-wood bark	30-40
Composted soft-wood bark	30-40
Peat	±50
Pine litter	±25
Sewage sludge	50-80

14.4.2. Cation exchange capacity (CEC)

The Cation exchange capacity (CEC) is the total amount of exchangeable cations that a particular material or soil can adsorb at a given pH. This property plays an important role in the nutrient reserves available to plants. The adsorbed ions are protected from leaching and can be released to become available to the plant. The CEC is expressed in terms of meq per unit weight. The CEC of organic growth media varies with the pH of the medium. The CEC of humic substances in organic growth media increases by 0.30 meq g^{-1} when the solution pH increases by one unit. In comparison, the clay CEC increases only by 0.044 meq g^{-1} (Helling *et al.*, 1964). Abad *et al.* (2005) defined the optimal CEC for growth media according to the fertigation frequency. Under continuous fertigation (one or more times a day), the CEC of growth media has no significant effect, thus, inert growth media can be used. In intermittent fertigation, it is convenient to utilize growth media with a moderate or high CEC, always higher than 0.20 meq g^{-1}.

Table 14.2. Cation exchange capacity in different growth media (modified from Chen and Inbar (1985) and Verdonck (1983)).

Growth media	Cation exchange capacity (meq 100 g^{-1} dry matter)
Peat – Sphagnum fuscum	140
Peat – Sphagnum papillosum	110
Peat – Sphagnum cuspidatum	90
Peat – Sphagnum sedge	110
Peat – Sphagnum	130
Peat – Sedge	80
Black peat	160
Vermiculite	150
Montmorillonite	100
Perlite	1.5
Fresh bark	40-50
Composted hard-wood bark	70-75
Composted soft-wood bark	70-80
Peat	120-140
Pine litter	70-80
Coconut fiber dust	
Fresh	107
3-4 months old	120
3-4 years old	150

14.4.3. pH

Plants can grow over a wide pH range (4-8) in the growth media without development of physiological disorders. However, plant growth and development is depressed in extreme acid or alkaline conditions. The pH of the medium influences nutrient availability, CEC and total biological activity. Plants growing in growth media generally require intensive management. Under these conditions, a limited pH range is recommended. The optimal saturated extract pH range for ornamental plants is 5.2-6.3, and for vegetables 5.5-6.8. At high alkaline pH (higher than 7.5-8.0), the availability of P, Fe, Mn, B, Zn and Cu for plant uptake decreases. In contrast, at lower pH (lower than 5.0) deficiencies of N, K, Ca, Mg and other nutrients might be found in the plant. Increased solubility of metal oxides at low pH can result in phytotoxic symptoms (Roy *et al.*, 2006). The pH value of different commercial growth media is presented in Table 14.3.

Some special considerations are needed in the pH management of growth media. The pH of new (unused) rockwool might be high (7-8). This condition should be corrected before planting by using acidified nutrient solutions (pH= 5.0-5.5). Thereafter, a slightly higher pH (5.5-6.5) is appropriate for many crops (FAO, 1990).

Organic growth media have a higher pH buffer capacity than mineral and inert substrates (Penningsfeld, 1978). When the pH of an organic medium is not at an appropriate pH level, adjustment is needed. Ground limestone or dolomite can be used to increase the pH for acid growth media while sulfur is used to decrease high pH in substrates. The quantities to be applied depend on the initial pH, the final pH to be achieved and CEC of the growth media. When neither limestone nor dolomite is present in the growth media, a substitute source of calcium and magnesium is required if the concentration of these two nutrients in the irrigation water is not high enough (Benton Jones, 2005).

The neutral or high pH in inert growth media can be regulated by acidifying the irrigation solution. The acid dose added to the solution depends on the water quality or specifically the carbonate and bicarbonate concentration in the irrigation water.

Table 14.3. pH of different growth media (modified from Verdonck (1981) and Verdonck (1983)).

Growth media	pH
Pine litter	3.9-5.5
Bark	6.0-6.8
Perlite	6.5-7.2
Rockwool	±7.0
Vermiculite	±7.0
Fresh bark	5.5
Composted hard-wood bark	6.5
Composted soft-wood bark	6.7
Peat	4.0-5.0
Sewage sludge	7.3-7.6
Pine litter	5.0-5.5
Coconut fiber dust	
Fresh	5.8
3-4 months old	6.0
3-4 years old	6.0

14.5. Application of fertigation

As described earlier, growth media can differ widely in their chemical and physical properties. Their chemical properties are the most important consideration when establishing the fertigation regime since inert inorganic and active organic growth media have very different requirements.

Inert growth media are characterized by an almost zero CEC, have no buffer capacity and are unable to provide nutrients. The fertigation system for this type of growth media must be very similar to hydroponic solutions, providing all the essential nutrients absent in the irrigation water. This regime is possible only using fertigation tools and is a major advantage in comparison to traditional fertilization. However, as the fertigation system has to supply all nutrients accurately in the amounts needed throughout growth - and this is critical - any mistake or malfunction in the system can cause crop damage. The fertilizer used for inert growth media must be carefully chosen considering the water quality (mainly bicarbonate concentration). Similarly the desired pH of the media solution must be selected because of lack of buffer capacity of the media. High concentration of acid fertilizers reduces the pH. Calculations which depend on water composition can be made to determine the maximum concentration of acid fertilizer allowed before induction of an undesirable pH drop in the media solution. Alternatively, values can be determined directly under field conditions by titration of the water with the fertilizer to be used in the fertigation program. The ratio of nitrate- to ammonium-N in the fertilizer formula must also be taken in account. Ammonium-N decreases the pH during growth as a consequence of both uptake by the crop and by nitrification in the media; nitrate-N increases the pH during uptake. The advantage of these growth media combined with the fertigation is the possibility of being able to manage the growth media solution almost to the ideal requirements of any specified crop. However, together with this great potential advantage, lurks in the background the hazard of failure in irrigation and fertigation systems because lack of buffer capacity can change rapidly to extreme conditions to cause irreversible damage to the crop.

On the other hand organic growth media present the very opposite properties: high CEC, high buffer capacity with media pH, usually much more stable. Interactions between the irrigation water and the growth media determine the composition of the media solution. As a result, there is only partial control on the solution composition. However, this can also be an advantage, as organic growth media are more able to maintain appropriate nutrient concentrations and pH during failures in the fertigation system than are the inert growth media.

Generally, a mixture of materials is used in soilless culture so that individual chemical properties are used to advantage in the preparation of growth media suitable for crop needs in combination with fertigation.

15. Monitoring water, soil and plant in fertigation

Fertigation is an advanced tool that provides the grower with a precise instrument for fertilization and irrigation according to plant requirements and soil or growth media conditions. In order to take advantage of the agro-technical benefits of fertigation, very close monitoring of irrigation water, soil and growth media, drainage and crop is recommended.

15.1. Monitoring the quality of irrigation water

The objectives of sampling and analyzing the irrigation water are to:

- Evaluate its suitability for a specific crop, soil, irrigation method, filtration degree and other necessary chemical treatments;
- Determine salinity level and concentration of toxic elements in the water to assess their effects on crops;
- Determine sodium concentration and sodium absorption ratio (SAR) to assess the potential long-term effect on soil structure and water infiltration;
- Determine the nutritional value in order to take into account the nutrients in the water that is used in the fertigation programme.

Salinity in irrigation water is defined as the total sum of dissolved inorganic ions expressed in units of mol per liter or total weight of salt in grams per liter of water. The main components of salinity are the cations calcium (Ca), magnesium (Mg) and sodium (Na), and the anions chloride (Cl^-), sulfate (SO_4^-) and bicarbonate (HCO_3^-). Nitrate (NO_3) and potassium (K) are usually minor components of salinity. Boron (B) and other dissolved micronutrients are negligible in assessing the salinity of irrigation water. Salinity is simply measured by determining the electrical conductivity (EC) of the water.

Sodicity or Na hazard of irrigation is related to soil dispersion, soil structure breakdown, potential for water infiltration problems, and accumulation of Na in plants. The most common procedure to evaluate the potential damage by Na is the Sodium Adsorption Ratio (SAR). The presence of HCO_3^- reduces the activity of Ca in the solution and, therefore, taking its concentration into the calculation of cation activities in the water gives a better assessment of the reduction in Ca concentration in the soil solution by changes imposed on the solubility of Ca compounds.

Element toxicity problems in the irrigation water are different from those of the salinity problem, and normally occur when certain ions are being taken up by the plants during transpiration and accumulated in the leaves to a level that result in leaf damage.

The degree of damage depends on the concentration in the irrigation water, time, amount, crop sensitivity and crop-water consumption. The most commonly observed toxic elements are Cl, B and Na.

Usually, in most surface and groundwater sources, P and K are present in negligible amounts. The nitrate content of groundwater can reach considerable levels and, therefore, its concentration in the irrigation water should be considered in planning for fertigation.

Laboratory determinations recommended to evaluate the quality of irrigation water are listed in Table 15.1. Not all these determinations are essential for all samples and for all sampling times. It is important, however, to keep records of the results of analysis for specific water sources and dates and times of sampling such that determination can be avoided, or the frequency of analysis reduced for some elements. Data have been included in Table 15.1 to illustrate the concentration ranges in secondary treated wastewater. However, these data can vary somewhat between countries and regions depending on factors including: the potable water supplied to the population, industrial and agricultural sewage inputs, and the processes in the wastewater treatment plants.

An additional monitoring method is to sample the irrigation solution flowing from the irrigation emitters (dripper, micro-jet or sprinkler). This solution represents the water quality and the fertilizers added during fertigation. Fertilizer injection by the different fertigation devices is not continuous but receives pulses of fertilizer with concentrations higher or lower than the programmed concentration in the irrigation water. Momentary sampling of only part of the water when the irrigation is running thus gives a misleading result, higher or lower than the expected average concentration. In order to avoid this problem, it is recommended that collection of samples of water emitted by an irrigation device should be made during a complete fertigation cycle. The vessel to collect the solution must be adapted to the device discharge and the period of irrigation. Nutrient and salinity factors can be determined in the laboratory, but some field analysis can also be performed. If the grower knows the electrical conductivity (EC) of the irrigation water and the contribution of the fertilizers added to the EC, the overall EC of the irrigation water collected at the emitter can be used to evaluate the performance of the fertilizer injector and to control the amount of fertilizer that is injected into the irrigation line.

The increasing use of treated wastewater (TWW) raises the importance of the assessment of water quality to avoid salinity and sodicity damage, nutrient accumulation in the soils and crops, and to consider the nutrient value in the water. Sampling and testing TWW is also performed to evaluate the organic matter content and the presence of pathogens.

Instructions for collecting TWW for analyses, which are in use by The Israeli Extension Service (Ministry of Agriculture and Rural Development) are as follows (Tarchitzky and Eitan, 1997):

- For most physical and chemical analyses, a volume of 1 liter is sufficient. It is recommended to rinse the bottle with the sample water before filling it. All the necessary details should be written on a sticker attached to the bottle.
- If the sample is taken directly from the irrigation system, the valve should be turned on to allow water to flow for about 20-30 seconds (depending on pipe diameter). This

Table 15.1. Recommended laboratory determinations (marked in *) to evaluate irrigation water quality (Modified from Westcot and Ayers, 1985 and Feigin *et al.*, 1991).

Water parameter	Symbol	Unit	Treated wastewater		Fresh water
				Typical range	
Electrical Conductivity	EC_w	$dS\ m^{-1}$	*	0.62-1.71	*
Calcium	Ca^{2+}	$mg\ L^{-1}$	*	20-120	*
Magnesium	Mg^{2+}	$mg\ L^{-1}$	*	10-50	*
Sodium	Na^+	$mg\ L^{-1}$	*	50-250	*
Carbonate	CO_3^{2-}	$mg\ L^{-1}$	*	–	*
Bicarbonate	HCO_3^-	$mg\ L^{-1}$	*	–	*
Chloride	Cl^-	$mg\ L^{-1}$	*	40-200	*
Sulfate	SO_4^{2-}	$mg\ L^{-1}$	*	–	*
Boron	B	$mg\ L^{-1}$	*	0-1	*
pH			*	7.8-8.1	*
Sodium Adsorption Ratio	SAR[1]	$[meq\ L^{-1}]^{1/2}$	*	4.5-7.9	*
Biochemical Oxygen Demand	BOD	$mg\ L^{-1}$	*	10-80	
Chemical Oxygen Demand	COD	$mg\ L^{-1}$	*	30-160	
Total Suspended Solids	TSS	$mg\ L^{-1}$	*	10-100	
Nitrate-nitrogen	NO_3-N	$mg\ L^{-1}$	*	0-10	*
Ammonium-nitrogen	NH_4-N	$mg\ L^{-1}$	*	1-40	
Organic-nitrogen	Org-N	$mg\ L^{-1}$	*	–	
Total nitrogen	Total-N	$mg\ L^{-1}$	*	10-50	
Potassium	K	$mg\ L^{-1}$	*	10-40	
Ortophosphate-phosphorus	PO_4-P	$mg\ L^{-1}$	*	–	
Total phosphorus	Total-P	$mg\ L^{-1}$	*	6-17	
Residual chlorine	Cl_2	$mg\ L^{-1}$	*	–	
Trace elements[2]		$mg\ L^{-1}$	*	–	

[1] Sodium, calcium and magnesium concentrations need to be transformed to $meq\ L^{-1}$ units in order to calculate the SAR ratio

[2] Aluminum, arsenic, barium, cadmium, chromium, copper, fluoride, iron, lead, lithium, manganese, mercury, nickel, selenium, silver, vanadium and zinc

is done in order to ensure that the sample does not include water that has been in the pipe for a long period and may possibly have changed in composition. Samples should be collected from the control filter and from irrigation emitters (sprinklers, micro-jet or drippers). Sampling of water should be done only when the fertigation system is not operating (to avoid fertilizers in the sample).

- The samples should be sent as soon as possible to the laboratory. The samples must be kept in cold picnic boxes (4°C) for nitrogen, Biochemical Oxygen Demand (BOD) or bacteriological analyses.

The same principles can be employed for fresh water sampling.

Two methods can be used when the collection of TWW is made directly from the reservoirs and not through the irrigation system:

- Use of an automatic sampler.
- Use of a bottle connected to a heavy object (this system is limited to 1 meter depth).

Samples should be collected away from the reservoir banks to avoid the accumulation of wind-blown fats and oils. In collecting TWW, it is recommended that sampling should be carried out as close as possible to the pumping point. If a bottle is used rather than an automatic sampler, the following points should be taken into account. The bottle should have a narrow neck, be connected to an extension stick, be tied with a rope and attached to a heavy object. The bottle should be immersed usually to a depth of one meter and should be sunk very quickly to ensure minimum collection of surface water.

Types of sampling

Changes in composition may occur often during the day or the week due to supply from different potable water sources or additions during sewage formation. It is therefore recommended to use one of the two procedures below, the choice depending on the information required:

- Occasional sampling is done arbitrarily. The results represent the situation at the time of sampling. When it is known that the source varies with time, sampling at suitable intervals can illustrate the extent, frequency and duration of those variations (Standard Methods for the Examination of Water and Wastewater, 1998);
- Composite samples are obtained from collected samples over a period of time, depth, or at different sampling points, at specific times of the day or night (24 hours). Composite samples are achieved by using one of the following procedures:
  - Separate samples are taken, each of equal volume and all the samples are then mixed together;
  - By using automatic sampler, samples are mixed together to obtain one composite sample.

15.2. Monitoring in soil and growth media

15.2.1. Soil

For crops grown in soils, soil sampling and testing are essential tools to manage soil salinity and in determining nutrient supply. By means of soil tests, deviation between prevailing and optimum concentrations can be determined and corrective measures undertaken to restore required concentrations in the soil. Monitoring nutrient status in soils can be achieved by two approaches (Bar-Yosef, 1992). The first involves soil sampling at a reference position in the root zone and extraction to determine soluble and sorbed nutrient concentrations in the soil. The second, for NO_3^- and Cl^- only, is to sample the soil solution directly by means of vacuum cups inserted permanently in the soil and to analyze the collected solution.

Frequency of sampling depends on the soil type, water quality and crop growth rate. In orchards, sampling twice during the year can be enough but, if relatively high salinity water is used, sampling should be done every 3-4 weeks in order to monitor soil salinity and to decide about leaching dose applications. In intensive crops like vegetables, the soil should be sampled frequently (every 2-3 weeks) in order to monitor both the nutrient concentration in the soil and salinity, and eventually to correct the fertilization programme or to leach accumulated salts. Instructions for soil sampling of the Israeli Extension Service (Tarchitzky and Eitan, 1997) are as follows:

- **Drip irrigation:** The sample is taken along the drip lateral, at a distance of 10 cm from the dripper, to depths of 0-30, 30-60, 60-90 cm. About 20 random samples are taken from a plot of 2000 m^2.
- **Sprinkler and micro-jet:** The distance of sampling from irrigation accessories is selected according to the discharge and water distribution of the emitter, i.e. distance of 70-100 cm from a micro-jet or 100-120 cm from a mini-sprinkler or a sprinkler. Samples are taken from depths of 0-30, 30-60, 60-90 cm, with about 20 random samples from a plot of 2000 m^2.

In general, all the samples from the same depth are mixed well in order to obtain a representative composite sample. Each composite sample of a certain depth is placed in a separate bag, and about 1 kg is sent to the laboratory. Identification of the sample includes name, address, plot number, crop, depth and date of sampling.

The extraction methods are specific for nutrient and the soil characteristics (Hagin *et al.*, 2002). Water-soluble nutrients are usually determined in saturated-paste soil extracts and sorbed nutrients by specific extractants (Bar-Yosef, 1992). Some methods are based on mild acid extractions. Potassium is often measured by the extraction of the exchangeable fraction or some expression that relates to the soluble K and divalent cations to the exchangeable phase as Potassium Adsorption Ratio (PAR). The analyses have to be calibrated with results from field experiments on crop response.

Soil tests for estimation of the "available P" present in the soil are used as a guide in decision making on P fertilizer additions via the trickle lines. Because of the immense variability in the estimation of available P by soil testing methods and the different extraction methods used by soil test laboratories all over the world, each location has developed its own method of estimation of soil available P. Intensive vegetable and glasshouse production systems usually disregard the levels of P detected in soil tests and use a complete nutrient solution during the whole growing period to make sure that deficiency is avoided.

Plant analysis is preferred in intensive growing under trickle irrigation, where only part of the soil is wet and the root volume represents only a small fraction of the total soil volume.

15.2.2. Growth media and drainage monitoring

Knowledge of the nutritional status of all the components of a soilless culture system is important for two reasons: (i) it is a means by which the grower can judge the success of the fertigation management practices; whether the planned fertilizer programme's objectives are followed in terms of nutrient availability; and (ii) it helps to diagnose nutrient deficiency and correct symptoms that may occur (Johnson, 2008). The methods used in the analysis of available nutrients in growth media are based on the equilibration of a sample of the growth media with an extracting solution. Some typical extracting solutions are: DTPA, ammonium acetate and water (Bunt, 1988). The extraction is performed during a standard time and with different mass-to-volume ratios of the growth media to the extractant (1:1.5; 1:5; 1:10). Growth media samples are obtained from the root zone by taking a representative number of sub-samples and mixing them prior to their analysis. Growth media solution can be obtained by extracting a prescribed volume of the substrate in the laboratory or in the field by measuring nitrate-N, K and P using field kits. Solution samples from rockwool or similar substrates can be extracted by a medical syringe or a syringe connected to a manometer to extract the solution at a specific tension.

In nutrient solution circulation systems, it is easy to sample and control nutrient composition on-line or to obtain a sample for laboratory analysis. In containerized growth systems, without recycling, the irrigation regime includes a high component of leached nutrients necessary to avoid any salt accumulation. All the excess nutrients are drained away from the system through drain holes in the base of the containers. By installing a solution collecting device below some of the containers, randomly distributed in the entire greenhouse, these drainage samples can be collected for analysis or sent to a laboratory for testing. The relative nutrient loss can then be calculated.

15.3. Monitoring the plants

Visual nutrient deficiency symptoms are used as a diagnostic tool (Scaife and Turner, 1983; Winsor *et al.*, 1987). A high level of expertise is a prerequisite for a valid diagnosis. A disadvantage of such observation is that, by the time the symptoms appear, damage to the plant has already been established and the deficiency might be serious, and correction of it is too late to avoid yield decrease.

Plant tissue analysis shows the nutrient status of the plants at the time of sampling, whether nutrients supplied to the root solution are adequate or may confirm visual deficiency symptoms. Toxic levels also may be detected. Plant tissue analysis allows correction of present nutritional problems or can act as a tool for a future fertilization programme.

Dry matter and nutrient content determination in plant tissues is tedious, destructive and needs laboratory facilities. In annual and short growing season crops, like field crops, vegetables and flower plantations, the analyses need to be done very quickly. To be effective in correcting current deficiencies, the analyses must be completed within two to three days after plant sampling.

In fruit trees or evergreen, leaf analysis is a common tool for nutritional guidance, the plant tissue analysis is used to prepare a future fertilization programme, and a longer time period is available to complete the analyses in the laboratory. Deducing fertilizer recommendations from plant tissue analyses data is not always straightforward. Concentrations of plant nutrients in tissues change with the physiological age of the tissue. Air humidity, temperature and soil moisture affect the concentration of nutrients by influencing transpiration and solute transport in the plant as well as the plant growth rate. Very strict standardization of plant tissue sampling is therefore necessary (Hagin *et al.*, 2002). However, comparing samples from both a "good" and a "bad" area any time in the growing season often helps in taking corrective actions.

The parts of plants to sample depend on the plant and its growth stage. Tissue sampling techniques for selected field crops, vegetables, ornamentals and flowers and fruit and nut trees are presented in tables 15.2 – 15.5 respectively (Flynn *et al.*, 1999). The following nutrients can be determined in a plant sample: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), copper (Cu), zinc (Zn), boron (B), sodium (Na), chloride (Cl) and other micronutrients. The leaf or whole plant samples have to be taken at optimal periods according to the specific plant standards. Instructions for petiole or leaf sampling may differ.

Table 15.2. Tissue sampling techniques for field crops (Flynn *et al.*, 1999).

Field crops			
Crop	When to sample	Where to sample	Number to sample per plot
Cotton	Full bloom	Recently mature leaf from main stem	40-50
Sunflower	Before heading, on recently mature leaf	Before heading, recently mature leaf	20-30

Table 15.3. Tissue sampling techniques for vegetable crops (Flynn *et al.*, 1999).

Vegetable crops			
Crop	When to sample	Where to sample	Number to sample per plot
Asparagus	Maturity	Fern, 18-30 inches above ground line	10-30
Bean	Seedling stage or before or at bloom	All above-ground portions Recently mature leaf	20-30
Broccoli	Before heading	Recently mature leaf	12-20
Brussels sprout	Midseason	Recently mature leaf	12-20
Celery	Midseason	Outer petiole of recently mature leaf	12-20
Cucumber	Before fruit set	Recently mature leaf	12-20
Head crop (cabbage, cauliflower)	Before heading	Recently mature leaf at center of whorl	12-20
Leaf crop (such as lettuce, spinach)	Midseason	Recently mature leaf	12-20
Melons	Before fruit set	Recently mature leaf	12-20
Pea	Before or at bloom	Leaves from 3rd node from top	40-60
Pepper	Midseason	Recently mature leaf	25-50
Potato	Before or at bloom	3rd to 6th leaf from growing tip	25-30
Sweet potato	Midseason or before root enlargement	3rd to 6th leaf from tip center or mature leaves	25-35
Root/bulb crop (such as carrot, beet, onion)	Midseason before root or bulb enlargement	Recently mature leaf	20-30
Tomato (field)	Midbloom	3rd to 4th leaf from growing tip	15-20
Tomato (trellis or indeterminate)	Midbloom from 1st to 6th cluster stage	Petiole of leaf below or opposite top cluster	12-20

Table 15.4. Tissue sampling techniques for ornamentals and flowers (Flynn *et al.*, 1999).

Ornamentals and flowers			
Crop	When to sample	Where to sample	Number to sample per plot
Carnation	Newly planted Established	4th to 5th leaf pair from base 5th to 6th leaf pair from base	20-30
Chrysanthemum	Before or at bloom	Top leaves on flowering stem	20-30
Ornamental tree and shrub	Current year's growth	Recently mature leaf	30-70
Poinsettia	Before or at bloom	Recently mature leaf	15-20
Rose	At bloom	Recently mature compound leaf on flowering stem	25-30
Turf	Active growth	Leaf blades (Avoid soil contamination)	2 cups

Table 15.5. Tissue sampling techniques for fruits and nuts (Flynn *et al.*, 1999).

Fruit and nut crops			
Crop	When to sample	Where to sample	Number to sample per plot
Apple, pear, almond, apricot, cherry, prune, plum	Midseason (June-July)	Leaves from current season's non-fruiting, non-expanding spurs	50-100
Peach and nectarine	Midseason (June-July)	Mid-shoot leaflets/leaves	25-100
Grape	At bloom	Petioles or leaves adjacent to basal clusters at bloom	50-100
Pecan	Midseason	Mid-shoot leaflets/leaves	25-60
Pistachio	Mid- to late season (August)	Terminal leaflets from non-fruiting shoots	25-60
Raspberry	Midseason	Recently mature leaves from laterals of primocanes	30-50
Strawberry	Midseason	Recently mature leaves	25-40
Walnut	(June-July)	Terminal leaflets/leaves from non-fruiting shoots	25-40

16. Future trends in fertigation

Fertigation was first developed for field and horticultural crops, and later used on tree plantations. In later stages, small gardens and the potting trade adopted the use of fertigation with automatic scheduling of irrigation cycle for home and city gardens. Fertigation today is used in any system, small or large scale, all over the world.

The shortage of water worldwide for use in agriculture and increased urbanization has forced agricultural development to new locations, less suitable to old flood or canal irrigation methods. While large flat areas use center pivot systems and combine it with N fertilizers, new plantations on hilly terrains have become more and more fashionable for vineyards and tree plantations. Under these growing conditions, complete nutrient feed is expected to dominate since soil volume available for tree growth is small compared to the old system of deep soil plantations.

In arid areas, the shortage of potable water and increase of population is driving agricultural growers to use any available water source. Two main avenues of development are possible, the use of recycled city sewage water and desalination of either sea or recycled water. Desalination of recycled water can prevent the accumulation of salts in the tilth layer, but energy cost limits its use. Sodium chloride accumulation in the irrigated area under recycled water is the main problem, as long period of usage of such water source can degrade soil productivity. Bringing arid lands into cultivation can be sustainable only if good quality water is available for agricultural production.

Trickle irrigation and fertigation will continue to expand and slowly replace traditional flood irrigation wherever population demand for fresh water will put pressure on water resources. This will free a significant amount of water to be used by the urban population.

Labor costs are also an important factor in the transformation from flood or canal irrigation to permanent fertigation systems. As agriculture progresses from subsistence to commercial viability, the shift to fertigation is inevitable.

We believe that the basic topics on the combined use of plant nutrients with irrigation as discussed in this publication will be of benefit to growers all over the world for the efficient use of water and fertilizers in agricultural production systems.

Bibliography

Abad Berjón, M., P. Noguera Murray, and C. Carrión Benedito. 2005. Sustratos para el cultivo sin suelo y fertirrigación. Cap. In: Fertirrigación- Cultivos Hortícolas, Frutales y Ornamentales. Ed.: C. Cadahía. Ed. Mundi-Prensa. Madrid. 8 pp. 299-354.

Abura, L. 2001. Growth curves as a tool to understanding maize production in Uganda. M. Sc. Thesis, The Hebrew University of Jerusalem, Faculty of Agriculture, Rehovot.

Adams, F., F.J.Veihmeyer, and L.N. Brown. 1942. Cotton irrigation investigations in San Joaquin Valley, California, 1926 to 1935. California Agr. Exp. Sta. Bull. 668.

Aljibury, F.K., M. Gerdts, A. Lange, J. Huntamer, and G. Leavitt. 1974. Performance of plants with drip irrigation. In: Proc. 2nd Intern. Drip Irrigation Congr. San Diego California, Univ of California, Riverside. pp 497-502.

Andre, M., D. Massimino, and A. Daguenet. 1978. Daily pattern under the life cycle of a maize crop II. Mineral nutrition, root respiration and root excretion. Physiol. Plant. 44:197-204.

Asano, T. 1998. Wastewater reclamation, recycling, and reuse: An introduction. In: Wastewater Reclamation and Reuse (T. Asano, Ed.). Water Quality Management Library. Vol. 10. Technomic Publishing Co. Inc. Lancaster – Basel.

Assouline, S. M. Moler, S. Cohen, M. Ben-Hur, A. Grava, K.Narkis and A. Silber. 2006. Soil-Plant system response to pulsed drip irrigation and salinity: Bell pepper case study. Soil Sci. Soc. Amer. J. 70:1556-1568.

Atalay, I.Z. 1978. The petiole and the leaf blade relationships for the determination of phosphorous and zinc status of vineyards. Vitis 17:147–157.

Badgujar, C.D., S.S. Deshmukh, S.M. Dusane, and S.S. Shide. 2004. Influence of 'N' and 'K' fertigation and different plant densities on yield of banana cv. Grand-Naine. South Indian Horticulture 52: 22-28.

Bald, J.G. 1946. A plan of growth, maturity and yield of the potato plant. Emp. J. Exp. Agric. 14:43-48.

Bar, Y. 1995. Iron control system for drip irrigation. Proceedings of the Fifth International Micro-irrigation Congress. Orlando, Florida, USA. pp. 239-247.

Bar, Y. 1990. Chloride nitrate interaction in avocado rootstocks. M.Sc. Thesis, Faculty of Agriculture, The Hebrew University of Jerusalem.

Barak, P. and Y.Chen 1982. The evaluation of iron deficiency using a bioassay type test. Soil Sci. Soc. Am. J. 46:1019-1022.

Barber, S.A. 1962. A diffusion and mass flow concept of soil nutrients availability. Soil Sci. 93:39-49.

Bar-Yosef, B. 1992. Fertilization under drip irrigation. In: Fluid Fertilizer, Science and Technology. Ed. by D.A. Palgrave. Marcel Dekker, New York. pp. 285-329.

Bar-Yosef, B. 1999. Advances in Fertigation. Adv. Agron. 65:1–77.

Bar-Yosef, B. and U. Kafkafi. 1972. Rates of growth and nutrient uptake of irrigated corn as affected by N and P fertilization. Soil Sci. Soc. Am. J. 36:931-936.

Bar-Yosef, B. and M.R. Sheikolslami. 1976. Distribution of water and ions in soils irrigated and fertilized from a trickle source. Soil Sci. Soc. Am. J. 40:575 582.

Bar-Yosef, B., E. Matan, I. Levkovich, A.Assaf, and E. Dayan. 1992. Response of greenhouse tomato (CV F-144) to irrigation and fertilization. ARO, Ministry of Agriculture., Bet Dagan Israel (Hebrew).

Bates, T.R. 2001. Vineyard nutrient management. Lake Erie Grape Research, Cornell University, New York. http://lenewa.netsync.net/public/Bates/NutrientRec.htm#Chart

Bates, T.R., R.M. Dunst, and P. Joy. 2002. Seasonal dry matter, starch, and nutrient distribution in 'Concord' grapevine roots. HortScience 37:313-316.

Baudoin, W.O., C. Bester, D. Chemonidou, N. Laws, M. Mohktari, and E. Ozzambak. 2007. Proc. XXnd Intl. Eucarpia Symp. (Sect. Ornamentals) on Breeding for Beauty (Vol II). Eds. A. Mercuri and T. Schiva. Acta Hort. 743:25-32. ISHS 2007.

Becker, S. J., A. Kania, G. Neumann, and V. Römheld. 2004. Effects of urea phosphate and monoammonium phosphate fertilizers on plant earliness in vegetable production. Institute of Plant Nutrition (330), University of Hohenheim, D-70599 Stuttgart.

Ben-Gal, A. and L.M. Dudley. 2003. Phosphorus availability under continuous point source irrigation. Soil Sci. Soc. Am. J. 67:1449-1456.

Ben-Gal, A., N. Lazarovitch, and U. Shani. 2004. Subsurface drip irrigation in gravel filled cavities. The Vadose Zone Journal. 3:1407-1413.A204.

Ben-Oliel, G., S. Kant, M. Naim, H.D. Rabinowitch, G.R. Takeoka, R.G. Buttery, and U. Kafkafi. 2004. Effects of ammonium to nitrate ratio and salinity on yield and fruit quality of large and small tomato fruit hybrids. Journal of Plant Nutrition. 27(10): 1795-1812.

Benton Jones Jr., J. 2004. Hydroponics: a practical guide for the soilless grower. 2nd ed. CRC Press, Boca Raton, USA. Benton Jones, J. Jr.1983. A guide for the hydroponic and soilless culture grower. Timber Press. Portland, Oregon, USA.

Ben-Zioni, A., Y. Vaadia, and S.H. Lips. 1971. Nitrate uptake by roots as regulated by nitrate reduction products in the shoot. Physiol. Plant. 24:288-290.

Berenstein, N., A. Bar-Tal, H. Fridman, P. Snir, I. Rot, A. Chazan, and M. Ioffe. 2006. Application of treated wastewater for cultivation of roses (Rosa hybrida L.) In: Soilless culture. Scientia Hortic. 108: 185-193.

Berger, J. 1969. The world's major fibre crops: their cultivation and manuring. Centre d'etude de l'azote Monographs No. 6. Zurich.

Bester, D.H., D.C. Lötter, and G.H. Veldman. 1974. Drip irrigation on citrus. In: Proc. 2nd Intern. Drip Irrigation Congress, San Diego, California, University of California, Riverside. pp 58-64.

Black, C.A. 1968. Soil-plant relationships. J. Wiley. New York. USA.

Black, J.D.F. and P.D. Mitchell. 1974. Changes in root distribution of mature pear trees in response to trickle irrigation. In: Proc. 2nd Intern. Drip Irrigation Congress, San Diego, California, Univ. of California, Riverside. pp 437-438.

Boland, A.M., P.D. Mitchell, and P.H. Jerie. 1993. Effect of saline water combined with restricted irrigation on peach tree and water use. Austr. J. Agric. Res. 44:799-816.

Bolt, G. H. 1976. Adsorption of anions by soil. In 'Soil Chemistry'. Eds: G. H. Bolt and M. G. M. Bruggenwert. Elsevier Scientific Publishing Co. New York.

Bravdo, B. and E.L. Proebsting. 1993. Use of drip irrigation in orchards. Hortechnology 3:44–49.

Bravdo, B. and Y. Hepner. 1987. Irrigation management and fertigation to optimize grape composition and vine performance. Acta Hort. 206:49–67.

Bravdo, B., Y. Hepner, C. Loinger, S. Cohen, and H. Tabacman. 1984. Effect of crop level on growth, yield and wine quality of a high yielding Carignane vineyard. Am. J.Enol. Vitic. 35(4):247–252.

Bravdo, B., Y. Hepner, C. Loinger, S. Cohen, and H. Tabacman. 1985. Effect of crop level and crop load on growth, yield, must and wine composition and quality of Cabernet Sauvignon. Am. J. Enol. Vitic. 36:125–131.

Bresler, E. 1977. Trickle-drip irrigation: Principles and application to soil-water management. Advances in Agronomy 29:343-393.

Britto, D.T. and H.J. Kronzucker. 2002. NH_4^+ toxicity in higher plants: a critical review. Journal of Plant Physiology. 159:567-584.

Brown, P.H., N. Bellaloui, M.A. Wimmer, E.S. Bassil, J. Ruiz, H. Hu, H. Pfeffer, F. Dannel, and V. Römheld. 2002. Boron in plant biology. Plant Biol. 4: 205-223.

Bunt, A.C. 1988. Media and mixes for container-grown plants: a manual on the preparation and use of growing media for pot plants. 2nd Edition. Unwin Hyman, Ltd, London, 309p.

Burt, C., K. O'Connor, and T. Ruehr. 1998. Fertigation. Irrigation Training Center, California Polytechnique State University, San Luis Obispo, CA, USA.

Cabrera R.I., R.Y. Evans, and J.L. Paul. 1995. Cyclic nitrogen uptake by greenhouse roses. Scientia Horticulturae 63:57-66.

Cahoon, G., M. Ellis, R. Williams, and L. Lockshin. 1991. Grapes: Production, Management, and Marketing. Extension Bulletin 815. The Ohio State University, Columbus.

Carmi, A., Z. Plaut, B. Heuer, and A Grava. 1992. Establishment of shallow and restricted root systems in cotton and its impact on plant response to irrigation. Irrig. Sci. 13:87-91.

Carpenter, P.N. 1957. Mineral accumulation in potato plants. Maine Agric. Exp. Sta. Univ. of Maine, Orono, Bul. 562, September.

Catlin, P.B., G.J. Hoffman, R.M. Mead, and R.S. Johnson. 1993. Long term response of mature plum trees to salinity. Irrig. Sci. 13:171-176.

Chaney, R. L., J. C. Brown, and L. O. Tiffin. 1972. Obligatory reduction of ferric chelates in iron uptake by soybeans. Plant Physiol. 50:208-213.

Chapman, K.S.R. and J.F. Jackson. 1974. Increased RNA labelling in boron-deficient root-tip segments. Phytochem. 13:1311-1319.

Chen, Y. and Y. Inbar. 1985. Growth media: properties and characterization. Faculty of Agriculture, Hebrew University of Jersualem (In Hebrew).

Chio, T.F. and C. Bould. 1976. Effect of shortage of calcium and other cations on 45-Ca mobility, growth and nutritional disorder of tomato plant. J.Sci. Food Agric. 27: 969-977.

Christensen, L.P., A.N. Kasimatis, and F.L. Jensen. 1978. Grapevine nutrition and fertilization in the San Joaquin Valley. Publication 4087. Division of Agricultural Sciences, University of California, Berkeley.

Christensen P. 1984. Nutrient level comparisons of leaf petioles and blades in twenty-six grape cultivars over three years (1979 through 1981), Am. J. Enol. Vitic.,. 35: 124-133.

Coelho, P.E., and D. Or. 1996. A parametric model for two-dimensional water uptake intensity in corn roots under drip irrigation. Soil Sci. Soc. Am. J. 60:1039-1049.

Conradie, W.J. 1980. Seasonal uptake of nutrients by 'Chenin blanc'in sand culture: I. nitrogen. S. Af. J. Enol. Vitic. 1:59-65.

Conradie, W.J. 1981. Seasonal uptake of nutrients by Chenin blanc culture: II. phosphorus, potassium, calcium and magnesium. S.Afr. J. Enol. Vitic. 2:7-18.

Conradie, W.J. 1986. Utilization of nitrogen by the grapevine as affected by time of application and soil type. S. Af. J. Enol. Vitic. 7:76-83

Conradie, W.J. 1991. Translocation and storage of nitrogen by grapevines as affected by time of application. In Proceedings of the International Symposium on Nitrogen in Grapes and Wine. J.M. Rantz (Ed.). American Society for Enology and Viticulture, Davis, CA. pp. 32-42.

Court, M.N., R.C. Stephen, and J.S. Waid. 1962. Nitrite toxicity arising from the use of urea fertilizer. Nature 194:1263-1265.

Dasberg, S. and D. Or. 1999. Drip irrigation. Springer Verlag, Berlin.

Davies, S.H.R., Morgan, J.J. 1989. Manganese (II) oxidation kinetics on metal oxide surfaces. Journal of Colloid and Interface Science 129: 63 -77.

DeTar, W.R., G.T. Browne, C.J. Phene, and B.L. Sanden. 1996. Real-time irrigation scheduling of potatoes with sprinkler and subsurface drip systems. In Proc Int Conf. on Evapotranspiration and Irrigation Scheduling, eds. C.R. Camp, E. J. Sadler, and R.E. Yoder, 812-824. ASAE, St. Joseph, Michigan.

Duncan, W.G. and A.J. Ohlrogge. 1957. Measuring fertilizer uptake in growing plants with the Geiger counter. Agron. J. 49:57-58.

Eaton, F.M. 1955. Physiology of the cotton plant. Ann. Rev. Plant Physiol. 6:299-328.

EFMA.(European Fertilizer Manufacturers Association). 2004. Understanding nitrogen and its use in agriculture (Karl-Friedrich Kummer and Chris Dawson, editors). Published by EFMA, Brussels, Belgium.

Elfuving, D.C. 1982. Crop response to trickle irrigation. In: Horticultural Reviews. J. Janick ed. AVI publishing Co. Inc. Westport Conn. USA. pp.1-48.

El-Mardi, M.O., S.B. Salama, E.C. Consolacion, and M. Al-Solomi. 1998. Effect of treated sewage water on the concentration of certain nutrient elements in date palm leaves and fruits. Commun. Soil Sci. Plant Anal. 29:763-776.

EPA (Environmental Protection Agency). 1992. Guidelines for water reuse. Washington DC, United States Environmental Protection Agency, EPA/625/r-92/004.

Epstein, E.1999. Silicon. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50:641-665.

Fabeiro, C., F. Martín de Santa Olalla, and J.A. de Juan. 2001.Yield and size of deficit irrigated potatoes. Agricultural Water Management 48:255-266.

FAO (Food and Agriculture Organization of the United Nations). 2002. Wastewater treatment and use in agriculture – FAO irrigation and drainage paper 47. ISBN 92-5-103135-5. Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations). 1990. Soilless culture for horticultural crop production. FAO Plant production and protection. Paper 101. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www-naweb.iaea.org/nafa/news/crop-drop-turkey.html

Feigin, A., I. Ravina, and J. Shalhevet. 1991. Irrigation with treated sewage effluent. Management for Environmental Protection. Advances Series in Agricultural Sciences 17. Pub. Springer-Verlag. Berlin, Heidelberg, New York.

Ferreira, K.N., T.M. Iverson, K. Maghlaoui, J. Barber, and S. Iwata. 2004. Architecture of the Photosynthetic Oxygen-Evolving Center. Science 303 (5665):1831-1838.

Flores, P., J.M. Navarro, M. Caravajal, A. Cerada, and V. Martinez. 2003. Tomato yield and quality as affected by nitrogen source and salinity. Agronomie 23:249-256.

Flynn, R., S.T. Ball, and R.D. Baker. 1999. Sampling for plant tissue analysis. Guide A-123. College of Agriculture, Consumer and Environmental Sciences New Mexico State University

Ford, H.W. 1982. Iron ochre and related sludge deposits in subsurface drain lines. Circular 671 Florida Cooperative Extension Service, I.F.A.S, University of Florida, Gainesville.

Frith, G.J.T. and D.G. Nichols. 1975. Nitrogen uptake by apple seedlings as affected by light, and nutrient stress in part of the root system. Physiologia Plantarum 34:129–133.

Ganmore-Newman, R. and U. Kafkafi. 1983. The effect of root temperature and NO^-_3/NH^+_4 ratio on strawberry plants. I. Growth, flowering and root development. Agron. J. 75:941-947.

Ganmore-Newman, R. and U. Kafkafi. 1985. The effect of root temperature and NO^-_3/NH^+_4 ratio on strawberry plants. II. Nutrient uptake and plant composition. Agron. J. 77:835-840.

Goldberg, S.D., M. Rinot and N. Karu. 1971. Effect of trickle irrigation intervals on distribution and utilization of soil moisture in vineyard. Soil Sci. Soc. Am. Proc. 35: 127-130.

Goodwin, P.B. 1983. Nitrogen, phosphorus, potassium and iron nutrition of Australian native plants. *In* Proc National Technical Workshop on Production and Marketing of Australian Wild-flowers for export. Univ. Ext., Univ. West., Nedlands. pp 5–97.

Groot Obbink, J., and D.M. Alexander. 1977. Observations of soil water and salt movement under drip and flood irrigation in an apple orchard. Agr. Water Management. 1:179-190.

Gupta, A. and M.C. Saxena. 1976. Evaluation of leaf analysis as a guide to nitrogen and phosphorus fertilization of potato (Solanum tuberosum L.). Plant and Soil 44: 597-605.

Hagin, J. and A. Lowengart. 1996. Fertigation for minimizing environmental pollution by fertilizers. Fert. Res. 43:5-7.

Hagin, J., M. Sneh, and A. Lowengart-Aycicegi. 2002. Fertigation – Fertilization through irrigation. IPI Research Topics No. 23. Ed. by A.E. Johnston. International Potash Institute, Basel, Switzerland.

Halevy, J. 1976. Growth rate and nutrient uptake of two cotton cultivars grown under irrigation. Agron. J. 68:701-705.

Hanan, J.J., W.D. Holley, and K.L. Goldsberry. 1978. Soils and soil mixtures. Greenhouse management, Springler-Verlag, pp. 255-322.

Harmsen, K. and P.L.G. Vlek. 1985. The chemistry of micronutrients in soil. Fertilizer Research 7:1-42.

Hartmann, H.T. and D.E. Kester. 1975. Propagation structure. Media, fertilizers, soil mixtures and containers plant propagation, principles and practices. 3rd ed. Prentice-Hall Inc., Englewood Cliffs, N.J. pp. 17-55.

Harward, C.S. 1953. Determination of total dissolved solids in water analysis. Ind. Eng. Chem. 5:4-6.

Haynes, R. J. 1990. Movement and transformations of fertigated nitrogen below trickle emitters and their effects on pH in the wetted soil volume. Nutrient Cycling in Agroecosystems 23:105-112.

Haynes, R.J. 1985. Principles of fertilizer use for trickle irrigated crops. Fertilizer Research 6:235-255.

Hebbar, S.S., B. K. Ramachandrappa, H. V. Nanjappa, and M. Prabhakar. 2004. Studies on NPK drip fertigation in field grown tomato (Lycopersicon esculentum Mill.). European Journal of Agronomy 21:117-127.

Helling, C.S., G. Chester, and R.B. Corey. 1964. Contribution of organic matter and clay to soil cation-exchange capacity as affected by the pH of the saturating solution. Soil Sci. Soc. Amer. Proc. 28:517-520.

Henry, L.T. and C. D. Raper, Jr. 1989. Cyclic variations in nitrogen uptake rate of soybean plants; ammonium as a nitrogen source. Plant Physiol. 91:1345-1350.

Hepner, Y. and B. Bravdo. 1985. Effect of crop level and drip irrigation scheduling on the potassium status of Cabernet Sauvignon and Carignane vines and its influence on must and wine composition and quality. Am. J. Enol. Vitic. 36:140–147.

Ho, L.C., R.I. Grange, and A.J. Picken. 1987. An analysis of the accumulation of water and dry matter in tomato fruit. Plant Cell and the Environment 10:157-162.

Hofman, G.J., J.D. Rhoades, and J. Letey. 1990. Salinity Management. In: Management of farm irrigation systems. Edited by G.J. Hofman, T.A. Howell, and K.H. Solomon. The American Society of Agricultural Engineers. Michigan. U.S. pp. 667-715.

Hofman, G.J. and O. Van Cleemput. 1995. Ammoniakvervluchtiging uit kunstrnest. Landbouwkundige Uitgeverij G.C. van den berg (ed.). Waddinxveen, The Netherlands, 27 pp.

Hofman, G.J. and O. Van Cleemput. 2004. Soil and plant nitrogen. International Fertilizer Industry Association (IFA), Paris, France.

Hu, H. and P.H. Brown. 1997. Absorption of boron by plant roots. Plant and Soil 193:49-58.

Huck, M.G. and D. Hillel. 1983. A model of root growth and water uptake accounting for photosynthesis, respiration, transpiration and soil hydraulics. In: Advances in Irrigation, Vol. 2 (D. Hillel Ed.).Academic Press New York. pp. 273-333.

Huck, M.G. 1970. Variation in tap root elongation rate as influenced by composition of the soil air. Agron. J. 62:815-818.

Icekson-Tal, N., Avraham O., Sack J., Cikurel H. 2003. Water reuse in Israel - the Dan Region Project: evaluation of water quality and reliability of plant's operation. Water Science & Technology: Water Supply 3:231-237.

IFA. 1992. World Fertilizer Use Manual. W. Wichman (editor) Cotton. 457-471. http://www.fertilizer.org./ifa/Home-Page/LIBRARY/World-Fertilizer-Use-Manual/by-type-of-crops.

Imas, P., B. Bar-Yosef, U. Kafkafi and R. Ganmore-Neumann. 1997a. Release of carboxylic anions and protons by tomato roots in response to ammonium nitrate ratio and pH in solution culture. Plant and Soil, 191: 27-34.

Imas, P., B. Bar-Yosef, U. Kafkafi and R. Ganmore-Newmann. 1997b. Phosphate induced carboxylate and proton release by tomato roots. Plant and Soil 191:35-39.

Israel Water Commission. 2002. National Water Plan 2002-2010. http://www.water.gov.il

Jackson, J.F. and H.F. Linskens. 1978. Evidence for DNA repair after ultraviolet irradiation of *Petunia hybrida* pollen. Molecular and General Genetics 161,117-120.

Jackson, R.D. and J.L. Haddock. 1959. Growth and nutrient uptake of Russet Burbank potatoes. Amer. Potato J. 36:22-28.

Jenkins, P.D. and H. Ali. 2000. Phosphate supply and progeny tuber numbers in potato crops. Annals of Applied Biology 136:41–46.

Johnson, H. 2008. Soilless culture of greenhouse vegetables. UC Davis, Vegetable Research and Information Center. http://vric.ucdavis.edu/pdf/hydroponics_soillesscultureofgreenhouse%20vegetables.pdf

Kafkafi, U. 1979. Measurements of available nutrients in the soil for prediction of fertilizer requirements by crops in the Mediterranean region. In: Soils in Mediterranean type climate and their yield potential. Proc. 14th Colloq of International Potash Institute, Sevilla, Spain. pp. 225-236.

Kafkafi, U. 1991. Root growth under stress: Salinity. In: Plant Roots. The Hidden Half.. Y. Waisel, A. Eshel and U. Kafkafi (Eds.). Marcel Dekker, Inc., New York. pp 375-391.

Kafkafi, U. 1994. Combined irrigation and fertilization in arid zones. Israel J. Plant Sci. 42:301-320.

Kafkafi, U. 2005. Global aspects of fertigation usage. Fertigation Proceedings, International Symposium on Fertigation Beijing, China. 20-24 September 2005. pp. 8-22.

Kafkafi, U. 2010. Chlorides in TWW and their effects on plants. In: Use of treated wastewater in agriculture: impacts on crop and soil environment. Editors: G.J. Levy, P. Fine and A. Bar-Tal (editors) Publisher: Wiley Blackwell (In print).

Kafkafi, U. and B. Bar-Yosef. 1980. Trickle irrigation and fertilization of tomatoes in high calcareous soils. Agron. J. 72:893-897.

Kafkafi, U. and R. Ganmore-Newmann. 1985. Correction of iron chlorosis in peanut by ammonium sulfate and nitrification inhibitor. J. Plant Nutr. 8:303-310.

Kafkafi, U. and J. Halevy. 1974. Rates of growth and nutrients consumption of semidwarf wheat. Trans. Int. Congr. Soil Sci., 10th (v. 4): 137-143.

Kafkafi, U. and S. Kant. 2004. Fertigation. In: Encyclopedia of Soils in the Environment, (Hillel, D.; Rosenzweiz, C.; Powlson, D.; Scow, K., Singer, M. and Sparks, D. Eds.), Elsevier Ltd., Oxford, UK, Vol. 2: 1-9.

Kafkafi, U., B. Bar-Yosef, and A. Hadas. 1978. Fertilization decision model. Soil Science. 125:261-268.

Kafkafi, U., G. Xu, P. Imas, H. Magen, and J. Tarchitzky. 2001. Potassium and Chloride in Crops and Soils: The role of potassium chloride fertilizer in crop nutrition. Research Topics, No. 22. International Potash Institute, Basel, Switzerland.

Kafkafi, U., I. Walerstein, and S. Feigenbaum. 1971. Effect of potassium, nitrate and ammonium nitrate on the growth, cation uptake and water requirement of tomato grown in sand soil culture. Israel J. agric. Res. 21:13-30.

Kalayci, M., B. Torun, S. Eker, M. Aydin, L. Ozturk, and I. Cakmak. 1999. Grain yield, zinc efficiency and zinc concentration of wheat cultivars grown in a zinc-deficient calcareous soil in field and greenhouse. Field Crops Research 63:87-98.

Keller, J. and R.D. Bliesner. 1990. Sprinkle and trickle irrigation. Van Nostrand Reinhold. New York.

Khasawneh, F.E., E.C. Sample, and I. Hashimoto. 1974. Reactions of ammonium ortho- and polyphosphate fertilizers in soil, I. Mobility of phosphorus. Soil Sci. Soc. Am. J. 38:446–450.

Khasawneh, F.E., I. Hashimoto, and E.C. Sample. 1979. Reactions of ammonium ortho- and polyphosphate fertilizers in soil, II. Hydrolysis and reactions with soil. Soil Sci. Soc. Am. J. 43:52–58.

Kirkby E.A. and A.H. Knight. 1977. Influence of the level of nitrate nutrition on ion uptake and assimilation, organic acid accumulation and cation-anion balance in whole tomato plants. Plant Physiol. 60:349-353.

Kirkby, C.A., L. J. Smythe, J. W. Cox, and D. J. Chittleborough. 1997. Phosphorus movement down a top sequence from a landscape with texture contrast soils. Aust. J. Soil Res., 35:399-417.

Kleinman, P.J.A., M.S. Srinivasan, A.N. Sharpley, and W.J. Gburek. 2005. Phosphorus leaching through intact soil columns before and after poultry manure application. Soil Science 170:153-166.

Krauss, A. and H. Marschner. 1982. Influence of nitrogen nutrition, day length and temperature on content of gibberellic and abscisic acid and on tuberization in potato plants. Potato Res. 25:13-21.

Kremmer, S. and Kenig E. 1996. Principles of drip irrigation. Irrigation & Field Service. Extension Service, Ministry of Agriculture and Rural Development, Israel (in Hebrew).

Lamont, B.B. 1972. The effect of soil nutrients on the production of proteoid roots by *Hakea* species. Aust. J. Bot. 20:27–40.

Lamont, B.B., G. Brown, and D.T. Mitchell. 1984. Structure, environmental effects on their formation, and function of proteoid roots in *Leucadendron laureolum* (Proteaceae). New Phytol. 97:381–390.

Lehman, D.S. 1963. Principles of chelation chemistry. Soil Sci. Soc. Amer. J. 27 : 167-170.

Lewis, D. G. and J.P. Quirk. 1965. Diffusion of phosphate to plant roots. Nature 205: 765–766.

Lindsay, W.L. 1979. Chemical Equilibria in Soils. Wiley, New York, 449 pp.

Loganathan, P., A.D. Mitchell, J.A. Hanly, and T.M. Aye. 2005. An improved procedure for determining magnesium fertilizer dissolution in field soils. Communications in Soil Science and Plant Analysis. 36:2121-2128.

Lombi, E., M.J. McLaughlin, C. Johnston, R.D. Armstrong, and R.E. Holloway. 2004. Mobility and lability of phosphorus from granular and fluid mono-ammonium phosphate differs in a calcareous soil. Soil Sci. Soc. Am. J. 68:682-689.

Loué A. 1986. Les oligo-elements en agriculture (in French). La Nouvelle librairie – ISBN2.86479.943.X

Lucas, R.E., and B.D. Knezek. 1972. Climatic and soil conditions promoting micronutrient deficiencies in plants. In: Micronutrients in Agriculture. Mortvedt, J.J., Giordano, P.M. and Lindsay, W.L. (eds.). Soil Sci. Soc. America, Madison, p. 265-288.

Lykas, C., N. Katsoulas, P. Giaglaras, and C. Kittas. 2006. Electrical conductivity and pH prediction in a re-circulated nutrient solution of a greenhouse soilless rose crop. Journal of Plant Nutrition, 29:1585–1599.

Maas, E.V. 1985. Crop tolerance to sprinkling water. Plant and Soil 89: 373-354.

Maas, E.V. 1993. Salinity and citriculture. Tree Physiol. 12:195-216.

MacKerron, D.K.L., and R.A. Jefferies. 1986. The influence of early soil moisture stress on tuber numbers in potato. Potato Res. 29:299-312.

Magen, H. 2005. Potential development of fertigation and its effect on fertilizer use. International Potash Institute (IPI) International Symposium on Fertigation: Optimizing the utilization of water and nutrients, Beijing, September 2005. http://www.ipipotash.org/udocs/Potential%20development%20of%20fertigation.pdf

Magen, H. and P. Imas. 2003. Fertigation – The Global View. 4th Fertigation Training Course, NWSUAF, September 2003. International Potash Institute, Basel, Switzerland.

Malchi, I. 1986a. Iron in irrigation water "Hassadeh", Vol. 66 (Hebrew).

Malchi, I. 1986b. Personal and internal information, (Netafim Irrigation Inc. U.S.A.)

Mansell, R. S., H.M. Selim, P. Kanchanasut, J.M. Davidson, and J.G.A. Fiskell. 1977. Experimental and simulated transport of P through sandy soils. Water Resources Research 13:189-194.

Marschner H. 1995. Mineral nutrition of higher plants. 2nd ed. AP London.

Martinez Hernandez, J.J., B. Bar-Yosef and U. Kafkafi. 1991. Effect of surface and subsurface drip fertigation on sweet corn rooting, uptake, dry matter production and yield. Irrig. Sci. 12: 153 159.

Mattos Jr. D, D. Donald, A. Graetz, and A.K. Alva. 2003. Biomass distribution and nitrogen-15 partitioning in citrus trees on a sandy entisol. Soil Science Society of America Journal 67: 555-563.

Maurer, M., D. Abramovich, H. Siegrist, and W. Gujer. 1999. Kinetics of biologically induced phosphorus precipitation in waste-water treatment. Water Research 33:484-493.

McBeath, T.M., R.J. Smernik, E. Lombi, and M.J.McLaughlin. 2006. Hydrolysis of pyrophosphate in a highly calcareous soil: A solid-state phosphorus-^{31}NMR study. Soil Sci. Soc. Am. J. 70:856-862.

McCarthy, M.G. and W.J.S Downton. 1981. Irrigation of grapevines with sewage effluent. II. Effects on wine composition and quality. Amer. J. Enology and Viticulture 32:197-199.

Mendes, H.C. 1960. Nutriçao do algodoeiro. Baragantia, 19:435-458.

Mikkelsen, R.L and B.R. Bock. 1988. Ammonia volatilization from urea fertilizers. In: TVA Bulletin p. 175-189.

Millard P. and G.H. Neilsen. 1989. The influence of nitrogen supply on the uptake and remobilization of stored N for the seasonal growth of apple trees. Annals of Botany 63: 301-309.

Mmolawa, K. and D. Or. 2000. Root zone solute dynamics under drip irrigation: A review. Plant and Soil 222:163-190.

Mohammad, M.J., S. Zuraiqi, W. Quasmeh, and I. Papadopoulos. 1999. Yield response and nitrogen utilization efficiency by drip-irrigated potato. Nutrient Cycling in Agroecosystems 54:243-249.

Moody, P.W. and R.L. Aitken. 1997. Soil acidification under some tropical agricultural systems. 1. Rates of acidification and contributing factors. Aust. J. Soil Res. 35:163-173.

Morgan, J.J. 2005. Kinetics of reaction between O_2 and Mn(II) species in aqueous solutions. Geochimica et Cosmochimica. Acta 69: 35-48.

Moran, K. 2004. Micronutrient product types and their development. Proceedings No. 545, International Fertilizer Society, York, UK. 1-24.

Moritsugu M. and Kawasaki T. 1983. Effect of nitrogen sources on growth and mineral uptake in plants under nitrogen restricted culture solution. Berichte de Okayama Instituts fur landswirtschafliche Biologie, Okayama Universitat 18:145-158.

Moritsugu M., T. Suzuki, and T. Kawasaki. 1983. Effect of nitrogen sources on growth and mineral uptake in plants under constant pH and conventional culture solution. Berichte de Okayama Instituts fur landswirtschafliche Biologie, Okayama Universitat 18:125-144.

Mullins, G.L. and C.H. Burmester. 1990. Dry matter, nitrogen phosphorus, and potassium accumulation by four cotton varieties. Agronomy J. 82:729-736.

Muñoz-Carpena, R., A. Ritter, A.R. Socorro, and N. Pérez. 2002. Nitrogen evolution and fate in a Canary Islands (Spain) sprinkler fertigated banana plot. Agricultural Water Management, 52:93-117.

Mussaddak, J. 2007. Efficiency of nitrogen fertilizer for potato under fertigation utilizing a nitrogen tracer technique. Communications in Soil Science and Plant Analysis. 38:2401–2422.

Myers, B. A., D.W. West, L. Callinan, and C.C. Hunter. 1995. Long term effects of saline irrigation on the yield and growth of mature "Williams" pear trees. Irrig. Sci. 16: 35-46.

Nakayama, F.S. and D.A. Bucks. 1986. Trickle irrigation for crop production, Elsevier Science Publishers B. V. (383 p.).

Nakayama F. S., and D.A. Bucks. 1991. Water quality in drip/trickle irrigation: A review. Irrigation Science 12: 187-192.

Primary Industry: Agriculture. 2000. Horticultural fertigation-techniques, equipment and management. Industry and Investment, New South Wales, Australia. http://www.dpi.nsw.gov.au/agriculture/resources/water/irrigation/crops/publications/fertigation

Nichols D.G., D.L. Jones, and D.V. Beardsell. 1979. The effect of phosphorus on the growth of *Grevillea* 'Poorinda Firebird' in soil-less potting-mixtures. Scientia Hortic. 11:197–206.

Noy, J. and D. Yoles. 1979. Precipitates formed by APP 11-37-0 in irrigation water. Hassadeh 59:2129-2130 (In Hebrew).

Oertli, J.J. and E. Grgurevic. 1975. Effect of pH on the absorption of boron by excised barley roots. Agronomy J. 67:278-280.

Onder, S., M.E. Caliskan, D. Onder, and S. Caliskan. 2005. Different irrigation methods and water stress effects on potato yield and yield components. Agricultural Water Management. 73:73-86.

Ottman, M.J., T.L. Thompson, and T.A. Doerge. 2006. Alfalfa yield and soil phosphorus increased with top dressed granular compared with fluid phosphorus fertilizer. Agron. J. 98:899-906.

Ozanne, P. G., D.J. Kirton, and T.C. Shaw. 1961. The loss of P from sandy soils. Australian Journal of Agricultural Research 12:409-423.

Papadopoulos, I. 1992. Phosphorus fertigation of trickle-irrigated potato. Nutrient Cycling in Agroecosystems 31:9-13.

Paradiso, R., G. Raimondi, and G. De Pascale. 2003. Growth and yield of rose in a closed soilless system on two inert substrates. Proc. 6th IS on Protected Cult. Eds: G. La Malfa et al. Acta Hort 614:193-198. ISHS 2003.

Peacock, W.L., L.P. Christensen, and F.E. Broadbent. 1989. Uptake, storage, and utilization of soil-applied nitrogen by 'Thompson Seedless' as affected by time of application. Am. J. Enol. Vitic. 40:16-20.

Penningsfeld, F. 1978. Substrates for protected cropping. Acta Horticulturae 82:13-22.

Peverill, K. I. and L.A. Douglas. 1976. Use of undisturbed cores of surface soil for investigating leaching losses of S and P. Geoderma 16:193-199.

Pierzynski, G. M., J.T. Sims, and G.F. Vance. 1994. Soils and Environmental Quality. Lewis Publishers: Boca Raton, FL.

Poole, R.T., C.A. Conover, and J.N. Joiner. 1981. Soils and potting mixtures. Foliage plant production. J.N. Joiner (ed.). Prentice-Hall, Inc., Englewood Cliffs, N.J., pp. 179-202.

Primary Industries: Agriculture. 2005. Horticultural fertigation- techniques, equipment and management. Industry and Investments. New South Wales, Australia. http://

www.dpi.nsw.gov.au/agriculture/resources/water/irrigation/crops/publications/fertigation

Prior, L.D., A.M. Grieve, and B.R. Culis. 1992a. Sodium chloride and soil texture interaction in irrigated field grown Sultana grapevines I. yield and fruit quality. Austr. J. Agric.Res. 43:1051-1066.

Prior, L.D., A.M. Grieve, P.G. Slavich, and B.R. Culis, B.R. 1992b. Sodium chloride and soil texture interactions in irrigated field grown Sultana grapevines. 3. Soil and root system effects. Aust. J. Agric. Res. 43:1085-1100.

Rajan, S.S S., K.W. Perrott, and W.M.H. Saunders. 1974. Identification of phosphate reactive sites of hydrous alumina from proton consumption during phosphate adsorption at constant pH values. Journal of Soil Science 25:438-447.

Reboll, V., M. Cerezo, A. Roig, V. Flors, L. Lapena, and P. Garcia-Agustin, 2000. Influence of wastewater vs. groundwater on young citrus trees. J. Sci. Food and Agric. 80:1441-1446.

Reddy, B.M.C., K. Srinivas, P. Padma, and H.B. Raghupathi. 2002. Response of Robusta banana to N and K fertigation. Indian J. of Hort. 59:342-348.

Richards L.A. (editor) 1954. Diagnosis and improvement of saline and alkalai soils. Agriculture Handbook No.60. USDA Washington DC, USA.

Richards, S.J., J.E. Warneka, A.W. Marsh, and F.K. Aljibury. 1964. Physical properties of soil mixes used by nurseries. Calif. Agr. 18:12-13.

Robertson, W.C., F.E. Groves, R. Hagen Jr., L. Espinoza, M. Ismanov, and R. Franks. 2007. Evaluation of drip irrigation for cotton in Arkansas. In: Summaries of Arkansas cotton research 2006, AAES research series 552, DM Oosterhuis ed. pp 73-77.

Robinson J.B. 2000. The mineral nutrition of wine grapes in Australia. Acta Hort. 512 ISHS.

Roddy, E. 2006. Fertigation Fertilizer Sources. www.omafra.gov.on.ca/english/crops/hort/news/vegnews/2006/vg0406a2.htm

Rolston, D.E., R.S. Rauschkolb, and D.L. Hoffman. 1975. Infiltration of organic phosphate compounds in soil. Soil Science Society of America 39:1089-1094.

Romero, F., H. Taber, and R. Gladon. 2006. Nitrogen source and concentration affect growth and performance of bedding-plant Impatiens. J. Plant Nutrition, 29:1315-1326.

Römheld, V. 2000. The chlorosis paradox: Fe inactivation as a secondary event in chlorotic leaves of grapevine. J. Plant Nutrition, 23: 1629–1643.

Roy, R.N., A. Finck, G.J. Blair, and H.L.S. Tandon. 2006. Plant Nutrition for Food Security. A guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin 16. Food and Agriculture Organization of the United Nations. Rome.

Russell EJ. 1950. Soil Conditions and Plant Growth, 8th ed. London: Longmans Green & Co.

Ryan, J. and H. Tabbara. 1989. Urea phosphate effects on infiltration and sodium parameters of a calcareous sodic soil. Soil Sci Soc of Am J 53:5 p 1531-1536.

Sagi, M., C. Scazzocchio, and R. Fluhr. 2002. The absence of molybdenum co-factor sulfuration is the primary cause of the flacca phenotype in tomato plants. The Plant J. 31:305-317.

Sagiv, B., J. Ben-Asher, B. Bar-Yosef, U. Kafkafi and D. Goldberg 1974. Combined irrigation and fertilization of tomatoes grown on sand dunes. Symposium Israel-France on ecological research on development of arid zones (Mediterranean deserts) with winter precipitation. Special Publication 39, Dept. of Scientific publications ARO, Volcani Center. Bet Dagan , Israel.

Sammis, T.W. 1980. Comparison of sprinkler, trickle, subsurface and furrow irrigation methods for row crops. Agron. J. 72:701-704.

Santos, F.L. 1996. Quality and maximum profit of industrial tomato as affected by distribution uniformity of drip irrigation system. Irrigation and Drainage Systems 10:281-294.

Scaife, A. and B. Bar-Yosef. 1995. Nutrient and fertilizer management in field grown vegetables. IPI Bulletin No. 13. International Potash Institute, Basel, Switzerland.

Scaife, A. and M. Turner. 1983. Diagnosis of mineral disorders in plants. Vol. 2. Vegetables. J.B.D. Robinson (ed.). Ministry of Agriculture, Fisheries and Food. London.

Shae, J.B., D.D. Steele, and B.L. Gregory. 1999. Irrigation scheduling methods for potatoes in the Northern Great Plains. American Society of Agricultural Engineers 42:351-360.

Shalhevet, J., D. Shimshi, and T. Meir. 1983. Potato irrigation requirements in a hot climate using sprinkler and drip method. Agron. J. 75:13-16.

Shannon, M.C.and C.M. Grieve,1999. Tolerance of vegetable crops to salinity. *Scientia Horticulturae*, v.78, p.5-38.

Sharpley, A. N., T.C. Daniel, and D.R. Edwards. 1993. P movement in the landscape. Journal of Production Agriculture 6:492-500.

Shimshi, D. and M. Susnoschi. 1985. Growth and yield studies of potato development in a semiarid region. 3. Effect of water stress and amounts of nitrogen top dressing on physiological indices and on tuber yield and quality of several cultivars. Potato Res. 28:177-191.

Shock, C.C., E.B. Feibert, L.D. Saunders. S.R. James.2003. Umatilla Russet' and `Russet Legend' Potato Yield and Quality Response to Irrigation. HortScience, 38: 1117 - 1121.

Shorrocks, V.M., 1997. The occurrence and correction of boron deficiency. Plant Soil 193:121–148.

Shock, C.C., Z.A. Holmes, T.D. Stieber, E.P. Eldredge, and P. Zhang. 1993. The effect of timed water stress on quality, total solids and reducing sugar content of potatoes. Am. Potato J. 70:227-241.

Silber,A., B. Bar-Yosef, I. Levkovitch, L. Kautzky, D. Minz. 2008. Kinetics and mechanisms of pH-dependent Mn(II) reactions in plant-growth medium. Soil Biology and Biochemistry. 40:2787-2795.

Silber, A., M. Bruner, E. Kenig, G. Reshef, H. Zohar, I. Polaski, H. Yehezkel, D. Shmuel, S. Cohen, M. Dinar, E. Matan, I. Dinkin, Y. Cohen, L. Karni, B. Aloni, and S. Assouline.

2005. High fertigation frequency and phosphorus level: effects on summer-grown bell pepper growth and blosson-end rot incidence. Plant and Soil: 270: 135-146.

Silber, A., G.Xu, I. Levkovitch, S. Soriano, A. Bilu and R. Wallach. 2003. High fertigation frequency: the effects on uptake of nutrients, water and plant growth. Plant and Soil 253: 467-477.

Silber A., R. Ganmore-Neumann, and J. Ben-Jaacov. 1998. Effects of nutrient addition on growth and rhizosphere pH of Leucadendron 'Safari Sunset'. Plant and Soil 199:205-211.

Silberbush, M., B. Gornat, and D. Goldberg. 1979. Effect of irrigation from a point source (trickling) on oxygen flux and on root extension in the soil. Plant and Soil 53: 507-514.

Simonne, E., N. Ouakrim, and A. Caylor. 2002. Evaluation of an irrigation scheduling model for drip-irrigated potato in southeastern United States. HortScience 37:104-107.

Smajstrla, A.G., S.J. Locascio, D.P. Weingartner, and D.R. Hensel. 2000. Subsurface drip irrigation for water table control and potato production. Appl. Eng. Agric. 16:225-229.

Sne, M. 2006. Micro irrigation in arid and semi-arid regions. Guidelines for planning and design. Ed. by S.A. Kulkarni. ICID-CIID. International Commission on Irrigation and Drainage. New Delhi, India.

Snyder, R.G. and J.G. Thomas. 2007. Publication 2037. Extension Service of Mississippi State University, cooperating with U.S. Department of Agriculture. http://msucares.com/pubs/publications/p2037.htm

Soil Fertility Manual. 2003. Potash and Phosphate Institute. ISBN#0-9629598-5-5.

Sonneveld, C. and W. Voogt. 1997. Effects of pH value and Mn application on yield and nutrient absorption with rockwool grown gerbera. Acta Horticulturae 450: 139-147.

Sosnitsky P. 1996. Salinity, potassium and N nutrition effect on lycopene content of processing tomato. MSc. Thesis, Faculty of Agriculture, Rehovot, Israel. Supervised by U. Kafkafi (in Hebrew).

Standard Methods for the Examination of Water and Wastewater 20th Edition. 1998. Lenore S. Clesceri, WEF, Chair. Arnold E. Greenberg, APHA. Andrew D. Eaton (Eds.), AWWA.American Public Health Association 1015 Fifteenth Street, NW Washington, DC 2005-2605.

Steyn, J.M., H.F. Du Plessis, P. Fourie, and T. Ross. 2000. Irrigation scheduling of drip irrigated potatoes. Micro-irrigation technology for developing agriculture. 6th International Microirrigation Congress. South Africa. October 22-27, 2000.

Susnoschi, M. and D. Shimshi. 1985. Effect of water stress and amounts of nitrogen top dressing on growth of several cultivars. Potato Res. 28:161-176.

Tanaka, A., K. Fujita, and K. Kikuchi. 1974. Nutro-physiological studies of the tomato plant I. Outline of growth and nutrient absorption. Soil Science Plant Nutrition 20:57-68.

Tarchitzky, J. and G. Eitan. 1997. Irrigation with wastewater. Recommendations for sampling and analyzing. Soil & Water Extension Service, Ministry of Agriculture and Rural Development, Israel. (In Hebrew).

Tarchitzky, J., M. Bar-Hay, A. Lowengart-Aycicegi, M. Peres, A. Zilberman, E. Kenig, E., Y. Menashe, Y. Gal, A. Eizenkot, Y. Eisenstadt. 2004. "National survey on treated wastewater". Extension Service. Ministry of Agriculture and Rural Development. Israel (In Hebrew).

Tarchitzky, J., O. Lerner, U. Shani, A. Guilboa, A. Loewengart-Acycii, and A. Brener, and Y. Chen . 2007. Water distribution pattern in treated-wastewater-irrigated soils: hydrophobicity effect. European J. Soil Sci. 58:573-588.

Teixeira, L.A.J., W. Natale, and C. Ruggiero. 2002. Nitrogen and potassium fertilization of 'Nanicao' banana (Musa aaa cavendish subgroup) under irrigated and non-irrigated conditions. Acta Hort. (ISHS) 575: 71-779.

Terman G.L. and Hunt, C.M. 1964. Volatization losses of nitrogen from surface-applied fertilizers, as measured by crop response. Soil Sci. Soc. Am. Proc. 28:667-672.

Tisdale, S.L., W.L. Nelson, and J.D. Beaton. 1985. Soil Fertility and Fertilizers. Macmillan Publishing Company, New York.

van Beusichem M.L., Kirkby, E.A. and Baas R. 1988. Influence of nitrate and ammonium nutrition, and the uptake, assimilation and distribution of nutrients in *Ricinus cummunis*. Plant Physiol. 86: 914-921.

van Delden Arnout 2001. Yield and growth components of potato and wheat under organic nitrogen management. *Agronomy J.* 93:1370-1385.

Van Tuil, H.D.W. 1965. Organic salts in plants in relation to nutrition and growth. Ctr. For Agric. Pub and Docu.Wageningen. Agric. Res. Rep. No. 657.

Vangush A. and Keren R. 1995. Saline water and saline sources In: Israel shore aquifer: Hydrogeochemical aspects. Water and Irrigation 340:4-11. (Hebrew).

Verdonck, O. 1981. The influence of the substrate to plant growth. Acta Horticulturae 126:251-258.

Verdonck, O. 1983. Reviewing and evaluation of new materials used as substrates. Acta Horticulturae 150:467-473.

Volder, A. Smart, D. R. Bloom, A.J., Eissenstat, D.M. 2005. Rapid decline in nitrate uptake and respiration with age in fine lateral roots of grape: implications for root efficiency and competitive effectiveness. New Phytologist 165:493-502.

Volk, G.M. 1959. Volatile loss of ammonia following surface application of urea to turf or bare soils. Agron. J. 51:746–749.

Voss R.D. 1993. Corn. In: Nutrients deficiencies and toxicities in crop plants. W.F. Bennet (ed.). The American Phytopathological Society, St. Paul, Minnesota, USA.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 1999. Irrigation and nitrogen management effect on potato yield, tuber quality, and nitrogen uptake. Agron. J. 91:991-997.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 2000. Irrigation- and nitrogen-management impacts on nitrate leaching under potato. Environ. Qual. 29:251-261.

Walker, R.R., D.H. Blackmore, and P.R. Clingelffer. 1996. Salinity-vine vigor interactions and their effect in fruitfulness and yield of Sultana on Ramsy and own roots. Aust. Dried Fruit News, NS 23:16-18.

Watt, M. and J.R. Evan, 1999. Proteoid roots: Physiology and development. Plant Physiology, American Society of Plant Physiologists.121:317-323.

Westcot, D.W. and R.S. Ayers. 1985. Irrigation water quality criteria. In: Irrigation with reclaimed municipal wastewater: A guidance manual. G.S. Pettygrove and T. Asano (Eds.). Lewis Publishers, Inc. Chelsea, MI.

Wilson, G.C.S. 1984. The physico-chemical properties of horticultural substrates. Acta Horticulturae 150: 19-32.

Winsor, G., P. Adams, P. Fiske, and A. Smith. 1987. Diagnosis of mineral disorders in plants. London (UK). Her Majesty's Stationary Office. V. 3, 168 p.

Xu, G.H., H. Magen, J. Tarchitzky, and U. Kafkafi. 2000. Advances in chloride nutrition of plants. Advances in Agronomy 68: 97-150.

Xu, G.H., S. Wolf, and U. Kafkafi. 2001. Effect of varying nitrogen form and concentration during growing season on sweet pepper flowering and fruit yield. J. Plant Nutr. 24:1099-1116.

Yermiyahu, U. and U. Kafkafi. 2009. Higher yields and reduction incidence of stem brittle in white carnation by increasing potassium concentration and $NO_3^-:NH_4^+$ ratio in the fertigation medium. International Fertilizer Correspondence (IFC), June 2009. International Potash Institute, Horgen, Switzerland. http://www.ipipotash.org/eifc/2009/20/2

Yermiyahu, U., S. Nir, G. Ben Hayyim, U. Kafkafi, and T.B. Kinraide. 1997. Root elongation in saline solution related to calcium binding to root cell plasma membranes. Plant and Soil 191:67-76.

Yogev, H. 1986. Radiation effects on translocation and assimilation partitioning in the cotton canopy. Ph. D. thesis, Faculty of Agriculture, Rehovot.

Zartman, R.E., L. Rosado-Carpio, and R.H. Ramsey. 1992. Influence of trickle irrigation emitter placement on yield and grade distribution of potatoes. HortTechnology 2:387-391.

Zekri, M. and R.C.J. Koo. 1994. Treated municipal wastewater for citrus irrigation. J. Plant Nutr. 17:693-708.

Zhang J., L. Jiu Sheng, R. MinJie. 2004. Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source. Agricultural Water Management, 67:89-104.

Zhang, H., D. Smeal, R.N. Arnold, and E.J. Gregory. 1996. Potato nitrogen management by monitoring Petiole nitrate level. J. Plant. Nutr. 19:1405-1412.

Zhang, M., Alva, A.K. Li, Y. C. and Calvert. D. V. 1996. Root distribution of grapefruit trees under dry granular broadcast vs. fertigation method. Plant and Soil 183:79-84.

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