Fertigation and Substrate Management in Closed Soilless Culture

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Abstract

Greenhouse crops cover a small fraction of total cultivated land in the world, but they may play an important role for regional or national economy. Greenhouse operations crops are often concentrated in relatively small areas (sometimes nearby cities) with potential consequences on the environment due to the discharge of waste materials (e.g. plastics and artificial growing media) and the large use of water and agrochemicals. Awareness of the pollution associated with greenhouse cropping systems forces growers to adopt more environment-friendly cultivation methods, such as closed soilless culture and biological control of pests and diseases. Closed systems, in which drainage water is captured and recirculated, reduce water consumption and nutrient leaching. However, commercial application of these systems is scarce, as their management is more difficult compared with open (free-drainage) cultivation systems. Alongside the possible diffusion of root-borne diseases, the salinity of irrigation water is the main difficulty for the management of closed systems.

In this document, guidelines are provided for best management of growing medium and fertigation (i.e. the application the nutrients with irrigation water) in closed soilless cultivation with the aim to reduce the consumption of water and fertilisers (and then production costs) and the environmental impact associated to the disposal of spent substrates and the emission of nutrients and other agrochemicals with drainage water. The document is based on the state of the art of hydroponic technology as well as on the results of specific studies conducted between 2008 and 2010 within the framework of Euphoros project. Two Excel spreadsheets are annexed to this document: i) nutrient solution calculator, which provides the composition of stock nutrient solutions based on the characteristics of raw water and desired ion concentration of the nutrient solution fed to the crop; ii) a simulation tool for water and mineral relations of open or closed substrate cultures.

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PREFACE

Although greenhouse horticulture occupies a small portion of agricultural land in the world, in the last decades it expanded considerably in many areas, particularly in the Mediterranean Basin and in China. Greenhouses are generally concentrated in small areas (e.g. ”Campo de Dalias”, Almeria, Spain; Vittoria, Ragusa, Italy) and may contribute to environmental degradation due to the discharge of waste materials (e.g. plastics and artificial growing media) and the large use of water and agrochemicals. Awareness of the pollution associated with greenhouse cropping systems forces growers to adopt more environment-friendly cultivation methods, such as closed soilless culture and biological control of pests and diseases.

Closed systems, in which drainage water is captured and recirculated, reduce water consumption and nutrient leaching. However, commercial application of these systems is scarce, as their management is more difficult compared with open (free-drainage) cultivation systems. Alongside the possible diffusion of root-borne diseases, the salinity of irrigation water is the main difficulty for the management of closed systems.

In this document, guidelines are provided for best management of growing medium and fertigation (i.e. the application the nutrients with irrigation water) in closed soilless cultivation with the aim to reduce the consumption of water and fertilisers (and then production costs) and the environmental impact associated to the disposal of spent substrates and the emission of nutrients and other agrochemicals with drainage water. The document is based on the state of the art of hydroponic technology as well as on the results of specific studies conducted between 2008 and 2010 within the framework of Euphoros project.

Two Excel spreadsheets were also prepared: i) nutrient solution calculato, which provides the composition of stock nutrient solutions based on the characteristics of raw water and desired ion concentration of the nutrient solution fed to the crop; ii) a simulation tool for water and mineral relations of open or closed substrate cultures. These programs and the project reports cited herein are freely available and can be downloaded from Euphoros WEB site (www.euphoros.wur.nl) or requested by email (alberto.pardossi@agr.unipi.it).

1 HYDROPONIC TECHNOLOGY

1.1 Growing systems

Hydroponics (or soilless culture) is a broad term that includes all techniques for growing plants in solid media other than soil (substrate culture) or in aerated nutrient solution (water culture).

The classification of soilless culture considers the type of substrate and container, how the nutrient solution is delivered to the plant (drip irrigation; subirrigation; flowing, stagnant or mist nutrient solution culture) and the fate of the drainage nutrient solution: open (free-drain) or closed (recirculating water) systems.

The most widely used soilless techniques are container cultivation, while water culture systems such Nutrient Film Technique (NFT), floating culture and aeroponics are widely used for research work, but much less on commercial scale with some exception. For instance, floating culture is increasingly used for producing fresh-cut leafy vegetables and herbs or to force bulbs like tulips. **Table 1** summarizes the main characteristics of different hydroponic techniques, including the risk associated to the technical failure of the equipments and to the occurrence of root diseases.

Table 1. Main characteristics of various soilless growing systems.

	Substrate and drip irrigation	**Substrate and subirrigation**	**NFT**	**Floating system**	**Aeroponics**
Commercial application	Large	Large	Scarce	Increasing	Rare
Crop type	Fruit veg. Strawberry Cut flowers	Pot plants	Leafy vegetables	Leafy vegetables Bulb flowers	Vegetables
Substrate	Yes	Yes	No	No	No
Recirc. NS*	Yes/no	Yes	Yes	Stagnant or fairly static	Yes
Investment costs	Moderate/high	High	High	Low	Very high
Running costs	Moderate/high	Moderate/high	Moderate	Low	Fair/high
System's buffer	High	High	Low	High	Very low
Growing risks	Moderate	Moderate	High	Moderate	Very high

*NS: nutrient solution.

A few examples of soilless culture: top, row crops on substrate (tomato, left; gerbera, right); middle, pot plants in ebb-and-flow benches (right) or floor (left); bottom, basil seedlings (left) or tulips (right) in stagnant water culture.

Water culture could be used only for crops with short growing cycles, such as leafy vegetables.

Container (substrate) culture is generally used for row crops, such as fruit vegetables (solanancea, cucurbits), strawberry and cut flowers (rose, gerbera, anthurium, etc.). Different containers (banquette, pots, bags, slabs) are used filled with inorganic or organic substrate, or a combination of two or three different materials, such as the peat-perlite or peat-pumice mixture. An excess of nutrient solution (with respect to crop water requirement) is typically supplied to the crop by drip irrigation up.

In the cultivation of pot ornamentals, subirrigation is increasingly adopted; the pots are cultivated in gullies with an intermittent flow of nutrient solution or in ebb-and-flow benches or floors.

1.2 Substrates

In container cultivation, many types of growing media are used. They are generally selected by the growers on the basis of their availability and cost (including shipping), as well as local experience.

In substrate culture, the volume of growing media ranges from approximately 10 (e.g. rockwool or polyurethane slabs) to 40 (e.g. perlite bag) L m^{-2} (100 to 400 m^3 ha^{-1}).

In the European Union, annual use of growing media (including home gardening) is around 40 millions m^3 (15 millions tons); the consumption of mineral wool, perlite and peat in professional horticulture is about 0.90, 0.14 and 11.9 millions m^3, respectively (SV&A, 2005). In Spain, 30.000 to 40.000 m^3 of this substrate are substituted in soilless cultivations every year (Giulini, 2011).

The disposal of artificial growing media (or substrate) at the end of cultivation is a potential threat to the environment due to a number of reasons. In fact, they may contain pesticides and affect the landscape visual amenity, in particular when they are discarded illegally. Several types of substrates, such as mineral wools, are disposed to landfill at the end of one or more growing cycles; however, landfill costs are increasingly expensive and unavailable in many countries.

Montero et al. (2009) used Life Cycle Assessment (LCA) tool to evaluate several greenhouse production systems in Europe and concluded that substrate

manufacturing has an important environmental burden. Thus, the reutilization of substrate must be strongly encouraged along with the reduction of substrate volume.

In general, volume substrate reduction leads to a slight but significant decrease in crop yield and quality. However, in an experiment conducted at University of Pisa with tomato grown in perlite bags no difference in crop growth and fruit yield was found between standard (30 L m^{-2}) and reduced (24 L m^{-2}) bag volume.

Illegal disposal of spent perlite bags.

1.3 Open versus closed system

Both open and closed system may be set-up for drip-irrigated substrate culture. In closed systems, the drainage water is captured and reused following the adjustment of pH and nutrient concentration (namely, the electrical conductivity, EC) and, eventually, disinfection to minimize the risks of root-borne diseases.

In substrate culture, an excess of fresh (newly prepared) nutrient solution is generally supplied to overcome the difficulties associated the unequal transpiration of individual plants and to prevent the salt accumulation and the imbalance in the nutrient solution. Typically, a drain fraction of at least 20-25% is used in substrate cultivation to prevent root zone salinization. Therefore, in open soilless systems there is a massive waste of water and nutrients, which is responsible for an increase in running costs and in contamination of ground and surface water. For instance, Malorgio et al. (2001) reported that the annual drainage loss of water and nitrogen from open substrate culture of rose was, respectively, 2123 m^3/ha and 1477 kg ha^{-1}.

The European Nitrate Directive (1991) has designed many areas affected by nitrate pollution as Nitrate Vulnerable Zones (NVZs). In NVZs, an action program is laid down with a number of measures for tackling nitrate loss from agriculture and

husbandry. The discharge of drainage water from soilless culture, which generally contains high nitrate concentration, is not compatible at all with the rules established in NVZs.

Therefore, the application of closed soilless systems is essential for sustainable protected horticulture. Unfortunately, the application of these systems is scarce on a commercial scale and, with the exception of The Netherlands where they are compulsory, open soilless cultures are commonly used for vegetable and ornamental crops, as their management is much simpler.

Along with the risks consequent to the possible diffusion of root pathogens, the salinity of irrigation water represents the main difficulty for the management of closed growing systems. When the use of saline water is imposed, there is a more or less rapid accumulation of ballast ions, like sodium and chloride. Under these conditions, the nutrient solution is normally recirculated till electrical conductivity (*EC)* and/or the concentration of some potential toxic ion reach a maximum acceptable value, afterwards it is replaced, at least partially ('semi-closed' systems).

Summary:

- Soilless culture is an effective tool to increase crop yield and, if closed irrigation systems are adopted, to reduce the environmental impact of greenhouses and nurseries.
- Substrate culture is the main soilless technique used on a commercial scale; its main disadvantage is the disposal of artificial growing medium at the end of cultivation. In order to minimize this drawback some action could be adopted:
    - the substrate volume could be reduce until 25%, without yield reduction, if irrigation scheduling is adapted to the lower water buffer;
    - -prolong as much possible the use of substrate, using new quick test for assessing the real physical, chemical and the phitopatological characteristics before to start with a new cultivation.

In the following chapters, main guidelines to the management of substrate and fertigation in (semi-)closed systems are illustrated. The aim is to advice growers on how to prolong the use of substrate and to recirculate nutrient solution as long as possible, thus reducing production costs and environmental impact. A list of more comprehensive textbooks on hydroponic technology is reported in the Literature section.

Research note: Open vs closed soilless system

The application of closed substrate culture to greenhouse tomato cultivation was tested in a commercial greenhouse in Tuscany, Italy. Two separate experiments were conducted in spring and summer-fall of 2010 using grafted tomato plants.

In open system, the crop was fertigated according to the grower's protocol. In closed system, the plants were fed with a slightly different nutrient solution (in general, it had lower nutrient concentration) with respect to that used in the open culture, in order to maintain a constant nutrient concentration in the root zone. In closed system, recirculating nutrient solution was periodically analyzed with reflectometer in order to adjust the composition of the refill nutrient solution.

Due to low NaCl concentration (<2.5 mol m^{-3}) in irrigation water, in closed system the nutrient solution was never discharged. Fruit yield and quality were not significantly different in the two cultures. The application of closed system reduced the use of water (-21%) and nutrients (-17 to -35%) and made it possible to carry out the cultivation without any nutrient leaching, which instead was massive in open culture.

Parameter	Unit	Open system	Closed system	Saving
Fruit yield				
Commercial yield	kg m^{-2}	19.9	19.6	
Total soluble solids	°Brix	4.4	4.5	
Water				
Use	m^3 ha^{-1}	8632	6831	21%
Drainage	m^3 ha^{-1}	1682	0	100%
Crop uptake	m^3 ha^{-1}	6950	6831	2%
Nitrogen				
Use	kg ha^{-1}	1591	1032	35%
Leaching	kg ha^{-1}	266	0	100%
Crop uptake	kg ha^{-1}	1325	1032	22%
Phosphorus				
Use	kg ha^{-1}	306	244	20%
Leaching	kg ha^{-1}	25	0	100%
Crop uptake	kg ha^{-1}	281	244	13%
Potassium				
Use	kg ha^{-1}	2422	2000	17%
Leaching	kg ha^{-1}	343	0	100%
Crop uptake	kg ha^{-1}	2079	2000	4%

Further reading: Incrocci L, Incrocci G. Diara C., Pardossi A., 2001. Report on Italy test site. EUPHOROS Project Report, www. euphoros.wur.nl.

2. SUBSTRATE MANAGEMENT

2.1 Substrate characteristics

In container cultivation, many types of growing media are used. They are generally selected by the growers on the basis of their availability and cost as well as local experience. Whatever the nature and the origin, an ideal media should have the following features (Yeager et al., 2007):

- adequate mechanical properties to guarantee plant stability;
- low bulk density to facilitate the installation of growing systems; bulk density is lower than 900 kg/m^3 and may be as low as 80-120 kg/m^3 in light peat, rockwool and perlite (Table 2.1);
- high porosity (50-85%);
- consistent distribution of air (oxygen) and water in order to sustain root activity;
- a pH between 5.0 and 6.5, or easily adjustable for instance, many types of peat are acid and therefore have to be neutralized with calcium carbonate;
- low soluble salts content;
- chemical inertia, that is the substrate should not interfere with the nutrient solution by releasing inorganic ions and toxic root exudates, or by immobilizing nutrients (e.g., phosphorus and nitrogen in some substrates);
- the ability to maintain the original characteristics during the cultivation, which may be quite long;
- the absence of pathogens and pests; however, the substrate must not be necessarily sterile.
- Availability in standardized and uniform batch in order to permit the use of consistent fertilization and irrigation programs for each successive crop.

Regarding hydrological properties, a substrate is formed by three phases:

1. a solid phase ensuring plant anchorage;
2. a liquid phase ensuring the water and nutrients supplying;
3. a gaseous phase ensuring the oxygen and carbon dioxide transport between roots and external air.

Water storage in substrates is identified by terms as total porosity, water container capacity, air-filled porosity and available water. Bulk density is another important property.

Table 2.1. Bulk density and porosity of some growing media widely used in greenhouse and nursery crops.

Substrate	Bulk density (kg/m^3)	Total porosity (%v/v)
Light peat	60-100	90-95
Dark peat	100-150	85-90
Vermiculite	90-150	90-95
Perlite	80-120	85-90
Rockwool	80-90	94-97
Expanded clay	600-900	85-90
Pumice	650-900	65-75
Ideal	*190-700*	*50-85*

In soilless growing media (in soil too), the relationship between volumetric water content (θ) and matric potential (ψ_m; also called tension or suction) is described by the water release (or retention) curve (WRC). WRC depends on the nature of the growing media and is determined in the laboratory following standard methods, for instance the method described by De Boodt and Verdonck, (1972) or the EN 13041 method. An example of water retention curve for a soilless substrate is reported in **Figure 2.1.**

Several noteworthy quantities are derived from water retention curve:

1. θ at -1 kPa suction;
2. air content at -1 kPa (air capacity, AC);
3. the difference in θ between –1 and –10 kPa suction, which represents the water available to the crop (AW).

Depending on the nature of substrate, AW from 7 to 35% and tends to increase with the porosity and the bulk density of the material.

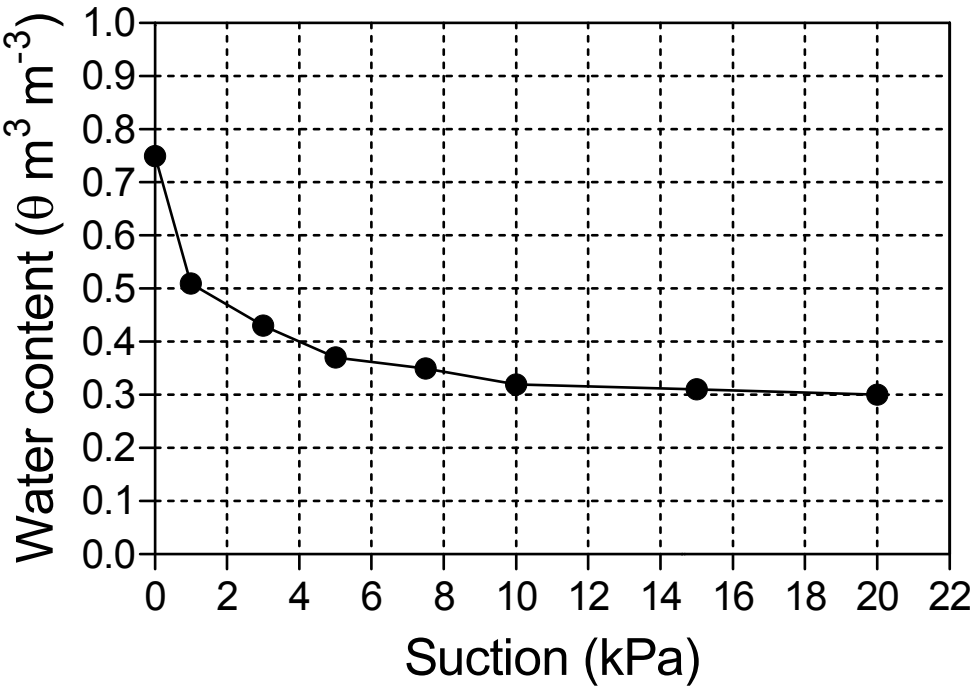


Figure 2.1. *Water retention curve of a peat-pumice mixture. The determination was conducted in the laboratory following De Boodt's method. According to this method, five to seven different suctions are applied to the sample: 1.0, 3.0, 5.0, 7.5, 10.0, 15.0 and 20.0 kPa. The value of water content at saturation (suction equal to 0) was estimated from the measurement of porosity (75,2%).*

Data on AC and W for the most used substrates are reported in table 2.1. In containerized substrate, AW (AW_{Cont}) depends also on container geometry, in particular on its height, which influences drainage: the taller the container, the more drainage and the less capacity media will have to hold water.

Water container capacity is defined as the amount of water retained in a containerized substrate system after drainage from saturation, but before evaporation.

Table 2.3 reports AW_{cont} values for the combinations between different substrates and containers, along with the main state variabled derived from WRC including the water (θ_{CC}) and air content (A_{CC}) at container capacity. A good estimation of AW_{cont} can be obtained applying the following equation (R^2= 0.97:

$$AW_{cont} = 0.832 \cdot AW - 52.95 \cdot h_{cont} + 21.67 \qquad \text{(Eq. 2.1)}$$

where substrate AW is expressed in % and container height (h_{cont}) in m.

Table 2.2. Volumetric water content at different matric potentials of various growing media as determined in the laboratory. These values are used to draw water retention curve, which is a physical properties of growing media. Air capacity (at -1 kPa) and available water (the difference in water content between –1 and –10 kPa suction) are also reported.

	Matric potential (suction; kPa)							
Substrate	0	-1.0	-3.0	-5.0	-7.5	-10.0	AC (%)	AW (%)
Coconut	93	70	44	40	37	35	23	35
Peat	90	72	46.0	41	37	35	18	37
Perlite	95	35	31	28	25	22	60	13
Pumice	69	41	37	36	35.5	35	28	6
Rockwool	97	82	7	6	5	4	15	78
Peat-perlite	75	54	40	36	33	30	21	24
Peat-pumice	77	51	43	37	35	32	26	19

Table 2.3. Water (θ_{CC}) and air (A_{CC}) content at container capacity, and available water (AW) in different container filled up with various growing media. Water retention curve of these media are reported in Table 2.2**.**

			Container type								
Substrate	Container size	Unit	Slab	Bag (1)	Bag (2)	Bench 1	Bench 2	Bench 3	Pot 16	Pot 24	Pot 32
	Height	m	0.075	0.15	0.20	0.20	0.30	0.40	0.14	0.21	0.29
	Length	m	1	0.20	0.20	0.40	0.30	0.40	-	-	-
	Width	m	0.15	1	1	1	1	1	0.16	0.24	0.32
	Volume	L	11.25	30.00	40.00	80.00	90.00	160.0	2.81	9.50	23.31
Peat	θ_{CC}	% v.		77	75	75	70	66	78	74	70
	A_{CC}	% v.		17	20	20	25	29	17	21	24
	AW	% v.		43	40	40	35	31	43	39	36
Perlite	θ_{CC}	% v.		55	50	50	44	41	56	49	44
	A_{CC}	% v.		45	50	50	56	59	44	51	56
	AW	% v.		33	28	28	22	19	35	27	23
Pumice	θ_{CC}	% v.		49	46	46	44	42	50	46	44
	A_{CC}	% v.		24	26	26	29	31	23	27	29
	AW	% v.		14	12	12	9	7	15	11	9
Coconut	θ_{CC}	% v.	84	77	74	74	69	64	78	73	69
	A_{CC}	% v.	14	21	24	24	29	33	20	25	29
	AW	% v.	50	42	39	39	34	30	43	39	35
Rockwool	θ_{CC}	% v.	91	85	81	81	72	63	86	80	73
	A_{CC}	% v.	11	17	21	21	30	40	16	22	29
	AW	% v.	88	82	77	77	68	59	83	76	69
Peat-perlite	θ_{CC}	% v.	67	61	58	58	55	52	61	58	55
	A_{CC}	% v.	12	18	21	21	24	27	18	21	24
	AW	% v.	37	31	28	28	25	22	31	28	25
Peat-pumice	θ_{CC}	% v.	67	59	57	57	53	50	60	56	53
	A_{CC}	% v.	14	22	24	24	28	31	21	25	28
	AW	% v.	35	28	25	25	21	19	28	24	22

2.2. Substrate re-use

Re-use represents an important option for environmental management of growing media and of soilless culture as such. Moreover, it may increase crop profitability, although substrate costs generally constitutes a small fraction of the total production costs of greenhouse and nursery crops (Montero et al., 2009).

During cultivation a number of modifications may occur in the substrate and must be taken into account before re-use:

- alterations of porosity and water holding capacity due to: decomposition of organic matter, root activity, compactation (aggregation and segregation of fine particles), swelling and shrinkage due to wetting/drying cycle;
- changes in pH and salinity (EC); higher salinity and pH are often detected at the end of cultivation as a result of fertigation with alkaline and/or saline water, as it occurs frequently in the Mediterranean area.
- proliferation of pathogens and parasites (in particular, nematodes);
- accumulation of toxic compounds released from the roots and/or from the decomposition of organic matter.

Physical modification of inorganic material hardly occur after one or two growing cycles, as it was found at University of Pisa with peat-pumice mix or perlite.

The number of growing cycles a substrate can be reused depends on its nature and the type of crop. Generally, inorganic substrates tend to last longer: polyurethane up to 10 years (Benoit and Cuestermans, 1994; Hardgrave,1995), perlite up to 2-3 years (Wilson, 1988); rockwool up to 3 years (Kang and Jung, 1995). Organic substrates have a shorter life, up to 2-3 years, due to minor biostability (Beavre, 1980; Celikell and Caglar, 1999; Kampf and Jung, 1991).

Several authors investigated crop response to the cultivation in re-used substrates compared to the new ones. Some of them found a reduction of crop yield and/or produce quality in reused media (e.g., Abd-Elmoniem and El-Behairy, 2004), while others reported no or minimal differences between virgin and reused substrate (Rea et al., 2008; Celikel and Caglar, 1999; Giuffrida et al., 2007; Acuna et al., 2005; Fernandes et al., 2006; Urrestarazu et al., 2008).

In general, solving the problems associated to excessive salinity and pH is easy while preventing the diffusion of pests and diseases is more tricky.

In order to extend as much as possible the use of substrate, a number of measures must be adopted, as reported below.

Guidelines to substrate re-use

- Adopt **prophylactic measures** to prevent the entry of pests and pathogens in the greenhouse environment;
- Disinfect the recirculating nutrient solution, in order to minimize the risk of spreading diseases in the cultivation;
- Monitor the presence of pathogens in the growing system (substrate, nutrient solution and plants);
- Disinfect the substrate before a new cultivation in case of low or moderate incidence of root diseases and/or pests.
- In contrast, when a crop is severely affected by root diseases or nematodes, re-using growing media is quite risky, notwithstanding disinfection.

Prophylactic measures

1. Clean and disinfect greenhouse floor and structures (e.g. benches, irrigation lines, etc.).
2. Prevent entry of pests and pathogens from outside with clothes and shoes as well as with irrigation water (surface and collected rain water may be contaminated before and/or during storage).
3. Keep crop healthy by:
   - adequate integration of physical, chemical and biological control tools;
   - appropriate management of climate and fertigation;
   - regular scouting and removal of all infected materials;
   - grow grafted plant, especially if substrate is re-used.

Substrate disinfection

The use of physical (steam and solarisation) or chemical control (application of fungicide by drip irrigation or fumigation) methods for substrate recycling can represent a viable and straightforward solution (Hallmann et al., 2005).

Solarization is an alternative method for substrate disinfection. Moncada et al. (2008) cultivated two different tomato cultivars on new and solarised coconut coir dust that was previously used for two consecutive cultivations. No differences were found between used perlite and virgin perlite in terms of crop yield and produce quality.

Research note: Substrate suppresiveness.

Several studies demonstrated that suppressiveness to root-borne diseases in soilless growing media can be induced by introducing microbial antagonists preliminarily isolated from suppressive soils and/or used soilless media (Grosch et al., 2001; Fravel and Larkin 2002; Hanafi et al., 2007; Horinouchi et al., 2007; Howell, 2003; Borrero et al., 2008). Biological control agents should be added as early as possible in order to achieve a stable microbial community with a maximum of beneficial organisms before the development of pathogen populations. The artificial introduction of selected microorganisms may also be combined with other disease control tools including the application of fungicides (Song et al., 2004), nutrients (e.g. calcium; von Broembsen and Deacon, 1997) or specific irrigation methods (e.g. subirrigation coupled with the addition of surfactant to the recirculating nutrient solution; Stanghellini et al., 2000).

The microflora present in used rockwool plays a key role in suppressing several root rot diseases (including *Pythium* and *Fusarium*) in cucumber (Postma et al., 2004) and tomato (Clematis et al., 2009; Srinivasan et al., 2009). Clematis et al. (2009) demonstrated the natural occurrence of suppression of *Fusarium* crown and root rot of tomato in reused perlite maintained after autoclaving, thus suggesting that it was mediated not only by the resident microflora.

Research note: elimination of growth inhibition in closed substrate culture of greenhouse rose.

In closed substrate cultivation of greenhouse rose, in particular in the Netherlands, the recirculating nutrient solution is discharged frequently in order to avoid excessive concentration of both NaCl and the plant growth inhibition caused by unknown (putative) organic substances, which is indicated by an increase in flower production and quality in the weeks following the discharge (Van Os et al., 2011).

Recently, these authors investigated the effect of advanced oxidation of recirculating nutrient solution in two rose nurseries in the Netherlands. Advanced oxidation is based on the addition of hydrogen peroxide to the nutrient solution followed by an exposure to UV-C light. It was found that advanced oxidation reduced the growth inhibition, degraded plant protection products added to the recirculating nutrient solutions, eliminated plant pathogens with no important effect of the composition of the nutrient solution (with the exception of iron, due to UV-C degradation of iron chelate).

Unit for UV disinfection of recirculating nutrient solution
(Photo: Spagnol Greenhouse Technologies, Vidor, Italy).

Nutrient solution disinfection

Over the years, various methods and technologies have been developed for disinfecting recirculating nutrient solution (Ehret et al., 2001; Wade, 2011). **Table 2.4** illustrates the main features of different disinfection methods.

Table 2.4. The advantage and disadvantage of most popular nutrient solution disinfection methods (from van Os et al., 2003; Runia, 1996, van Os 2011; Stewart-Wade, 2011).

Disinfection method	Doses	Advantages	Disadvantages
Heat treatment	95°C for 30 s 85°C for 3 min	High efficacy	High investment and running costs (only for farm > 1 Ha).
UV-C radiation	100-250 mJ/cm^2 UV-C	Moderate efficacy and investment cost	Sometimes unreliable results; needs pre-filtration; iron chelate breakdown.
Membrane filtration	Pores size: 0.05 μm for *Fusarium*; 0.1 μm for *Verticillum*	High efficacy	Very expensive; low lifetime of filter membrane.
Ozone	10 g m^{-3} h^{-1}	High efficacy	Expensive; needs preventive filtration and acidification; iron chelate breakdown.
Chlorine	2 ppm di Cl per 1' for P. Cinnamomi	High efficacy; used for sanitation of greenhouse structure and devices	Difficulties to establish the efficacy doses; acidity and organic compound influence the efficiency.
Hydrogen peroxide	100 ppm for *Fusarium* spp.	Low investment costs	No kill completely the nematodes; iron chelate breakdown.
Slow filtration	Flow rate of 100–300 L m^2 h^{-1} Sand grain size: 0-2 mm	Low investment costs; suitable for low technology, small-size greenhouse operations	Eliminates completely zoosporic fungi and only partially *Fusarium*, viruses and nematodes.

Substrate monitoring

Analyzing the growing media, regularly during the growing cycle or before its re-use in a successive crop, is crucial to make fertigation adjustments and limits substrate modifications. Generally, the knowledge of substrate pH and EC is sufficient to check occurrence of anomalies. On the other hand, the aqueous solution sampled from the substrate can be analysed by external laboratories or on farm by means of quick test in order to have more information about the content of individual nutritive or ballast ions, such as Na and/or Cl.

The NS retained by pre-shaped substrate (i.e. rockwool or polyurethane slabs) is typically sampled with a syringe after an irrigation event in order to standardize the moisture level at sampling. It is assumed that, after irrigation (with enough drainage), substrate θ corresponds to container capacity. In contrast, loose substrates (i.e. perlite, pumice, peat) are monitored by preparing an aqueous extract.

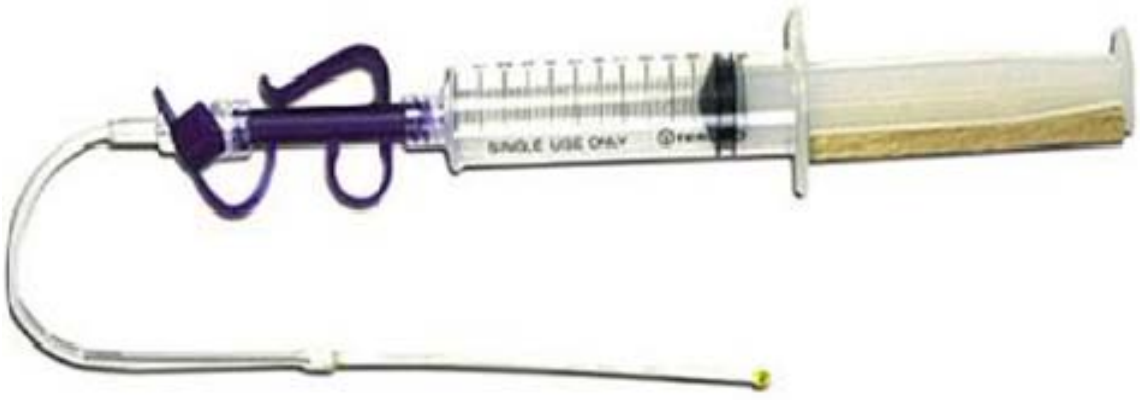
Aqueous extract is obtained by adding appropriate volume of substrate (previously moistened at container capacity) to distilled or deionized water at a ratio of 1:1.5, 1:2 or 1:5. The 1:1.5 dilution is used for organic material (e.g. peat, compost, coconut fiber) while other ratios are used for inorganic substrates. A detailed description of substrate extraction and analysis is reported in the following Textbox, while interpretative scales for each extraction procedure are presented in **Table 2.5.**

Another method is the pour-through technique, which is non-destructive, is generally used for pot plants and the main drawback is the difficult of result interpretation. In this method, after irrigation a specified volume of water is applied to the pot surface in order to push the substrate solution out of the bottom of the container into a collection saucer.

A method similar to the one used for slabs is based on Rhizon Soil Moisture Sampler (RSMS). RSMS consists of a porous plastic extraction tube, which is connected to the sample vial through a hypodermic needle and is inserted into the substrate. A second tube is also connected to the vial through a hypodermic needle and, on its other hand, to a hand-activated vacuum pump. The vacuum draws substrate solution into the extraction tube and then into the vial.

Table 2.5. Guide values for pH, electrical conductance and ion concentration in aqueous extracts (prepared with various proportion between substrate and water) of greenhouse growing media.

Parameter	Extraction method (substrate: water in v:v)		
	1:1.5	1:2	1:5
pH	5.5 - 6.0	5.5 - 6.0	5.5 - 6.0
EC (dS m^{-1})	0.6 – 1.5	< 1.5	0.2 – 0.5
NO_3- (mg L^{-1})	40 - 80	50 - 70	10 - 20
NH_4+ (mg L^{-1})	25 - 35	3-6	8 - 10
K (mg L^{-1})	12 - 45	50 - 100	11 - 16
P (mg L^{-1})	20 - 30	3 - 5	6 - 8
Ca (mg L^{-1})	40 - 80	50 - 80	10 - 20
Mg (mg L^{-1})	25 -45	20 - 30	6 - 10
Na (mg L^{-1})	40 - 60	< 90	10 - 16
SO_4- (mg L^{-1})	115 - 150	40 - 90	35 - 45
Cl (mg L^{-1})	60 - 100	< 90	18 - 30
Fe (mg L^{-1})	01 – 0.4	0.5 - 1	0.1 – 0.5
Mn (mg L^{-1})	0.01 – 0.3	0.2 - 0.4	0.01 – 0.1
Cu (mg L^{-1})	0.01 – 0.06	0.05 - 0.1	0.01 – 0.03
Zn (mg L^{-1})	0.01 – 0.3	0.1 - 0.2	0.01 – 0.1
B (mg L^{-1})	0.01 – 0.3	0.2 - 0.4	0.01 – 0.1



Rhizon Soil Moisture Sampler for extracting nutrient solution from growing medium.

Substrate testing

Step 1: substrate moistening.

A sample of about 300 ml of substrate is placed in a plastic vessel of appropriate size and then is moistened to container capacity by adding slowly distilled water and by stirring gently with a spoon or spatula till there is little water on the bottom.

Step 2: Extraction (1:2 dilution).

Place 400 ml of distilled water into a graduate plastic bottle and then add the substrate till a volume of 600 ml is reached.

Shake the bottle for about 2 minutes, leave the suspension to equilibrate for 15 minutes and then filter the sample by pouring the slurry through a small filter funnel lined with coarse filter paper.

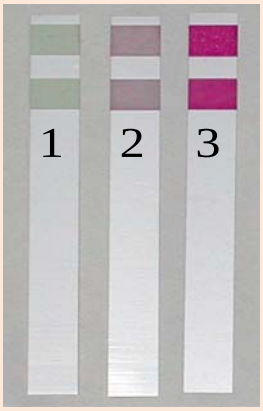
Step 3: measuring EC and pH.

Electrical conductivity and pH represent basic parameters for substrate testing. They can easily measured with portable EC and/or pH-meter.

REMEMBER**:** *check regularly (i.e. weekly) EC/pH meter calibration.*

Step 4: measuring ion content.

The concentration of specific ion can be on-farm determined directly in aqueous extracts by quick tests. A reflectometer for nitrate determination (Reflectoquant ™, Merk, Darmstadt, Germany) is shown below. A reactive strip is dipped in the solution and a purple colour develops with an intensity proportional to nitrate content. The strip is read after a test-specific time (f.i. 60 sec., for nitrate determination).



Step 5: interpreting test results.

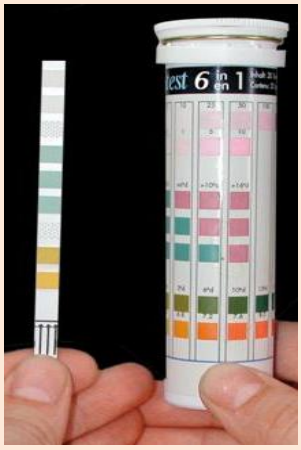
Check the results using the guide values developed for each extraction method and, more importantly, against your own reference guidelines.

REMEMBER*: recording data for each crop is crucial for correct interpretation of the results of both quick or laboratory analysis and for early detection of substrate anomalies.*

Quick analysis

Quick test kits (QTK) are valid alternative to time-consuming and expensive laboratory analysis of substrate extracts and nutrient solution. A large variety of QTK is commercially available. Many manufacturers offer QTK for a great number of analytes (e.g: Sigma-Aldrich, Milano, Italy; Merck, Darmstadt, Germany).

QTK generally consist of ready-to-use reagents, vessels and a portable measuring device. Their average prices range from a few euros (colorimetric assays with reactive strips) to a few hundred euros for ion selective electrodes (ISE). The commercially available QTK are basically of the following types:



Titrimetric QTK: they are based on the reaction between the analyte and a reagent of known concentration; the reaction occurs generally in the presence of a substance undergoing a colour change when the reaction is complete.

Colorimetric QTK: they entail a colour-forming reactions. The simplest colorimetric tests are the reactive strips. The colour intensity of the final compound, which is proportional to analyte concentration, is measured quantitatively by means of a photometer or a reflectometer, or semi-quantitatively by comparing sample colour with standard scale.

A study conducted at the University of Pisa found that titrimetric and reflectometric determinations were suitable for analysing the following ions in irrigation water, substrate extract and recirculating nutrient solution:

- **Ammonium** (reflectometry; 0.2 – 0.7 mg L^{-1})
- **Boron** (titrimetric assay; >0.2 mg L^{-1})
- **Chloride** (reflectometry; 2 – 50 or 50 – 1000 mg L^{-1})
- **Nitrate** (reflectometry; 2 - 90 or 5 - 225 mg L^{-1})
- **Phosphate** (reflectometry; 0.1 – 5 or 5 - 120 mg L^{-1})

A portable **multi ion-meter** is now available on the market (Clean Grow, Cork, Ireland; www.cleangrow,com) at a price of some thousands euros. It has a single probe combining six ISEs. The following ions can be analyzed: **ammonium**, **calcium**, **chloride**, **copper**, **nitrate**, **potassium** in addition to **pH** and other analytes. No independent evaluation of this device for horticultural application has been performed.

For further reading: Maggini, R., Cini F., Carmassi, G., Incrocci, L., Pardossi, A. 2011. Evaluation of quick test kits for the determination of nitrate, ammonium, phosphate, potassium, boron and chloride in soil and in hydroponic nutrient solutions EUPHOROS Project Report, www. euphoros.wur.nl.

Detecting pathogens and phytotoxic compounds

An early diagnosis prevents the occurrence of root diseases.

Using DNA methodology may allow the detection and identification of pathogens in many types of crop samples including irrigation water, nutrient solution, plant tissues and growing media. DNA tests are quick (the results may be available in a couple of days since sampling), specific (only the target pathogen is detected), sensitive and indicates the level of infection. Regular (once a month to once every six weeks) test are needed for determining whether a disinfection of the recirculating nutrient solution is necessary or not.

Contacts:

- **MICROBIOTEST inc**, Kleimoer 15 9030 Mariakerke (Gent), Belgium http://www.microbiotests.be/;
- **Groen Agro Control**, 2600 AM Delft, The Netherlands, http://www.agrocontrol.nl/en/
- **Relab Den Haan b.v.,** Lookwatering 62635 EA DEN HOORN, The Netherlands, www.denhaan.nl

Another problem that could reduce the crop production is an accumulation of plant and microbial metabolites that could occurred in the recirculating nutrient solution and/or in the growing media substrate.

Some of these compounds may have beneficial consequences on plant growth, but others have an allelopathic nature and may have a phytotoxic effect.

To investigate the presence of harmful metabolites in the drain water the Phytotoxkit® has been recently used by Van Os et al. (2010). The Phytotoxkit® (http://www.microbiotests.be/toxkits/phytotoxkit.pdf)is a rapid and easy-to-use test, which is based on germination and early growth of a few plants such as *Sorghum saccharatum* (monocotyl), *Lepidium sativum* and *Sinapis alba* (dicotyls), as reference plants.

Tips for substrate re-use

Drawbacks	Remedies
▪ Lower air capacity ▪ Higher water capacity	▪ Substrate re-mixing ▪ Adjustment of fertigation regime
▪ Higher pH ▪ Higher salinity (EC) ▪ Accumulation of toxic ions ▪ Nutrient imbalance	▪ Leaching irrigation ▪ Adjustment of fertigation regime
▪ Pest and pathogen contamination ▪ Allelopathy	▪ Disinfection ▪ Use of resistant genotypes ▪ Grafting ▪ Biological control ▪ Suppressiveness

Remember: *analyze spent substrate before re-use.*

Summary:

- The knowledge of the physical and chemical characteristics of growing medium is crucial for adequate management of soilless culture.
- Container geometry, in particular height, influences the amount of available water to the crop.
- Before re-using an exhausted substrate, detect the presence of phytopathogens and check the physical and chemical characteristics by laboratory analysis and/or quick tests.
- The application of a number of prophylactic measures can prolong the use of growing medium

3 IRRIGATION SCHEDULING

3.1 Generalities

Protected crops are often over-irrigated and this results in water loss and pollution due to fertilisers leaching. Thompson et al. (2007) reported that inappropriate IS was responsible for nitrate leaching from greenhouse tomato crops in Almeria.

Annual use of irrigation water in protected cropping system ranges from 150-200 mm (L m^{-2}) in short-cycle, soil-grown crops, such as leafy vegetables, to 1,000-1,500 mm in soilless-grown row crops such as solanaceas and cucurbits.

☞ *Unit for irrigation volume: 1 L m^{-2} =1 kg m^{-2} =10 m^3 ha^{-1} = 1 mm*

Over-irrigation often is the result of inappropriate irrigation scheduling, which consists in the determination of optimal **irrigation dose** and **frequency**.

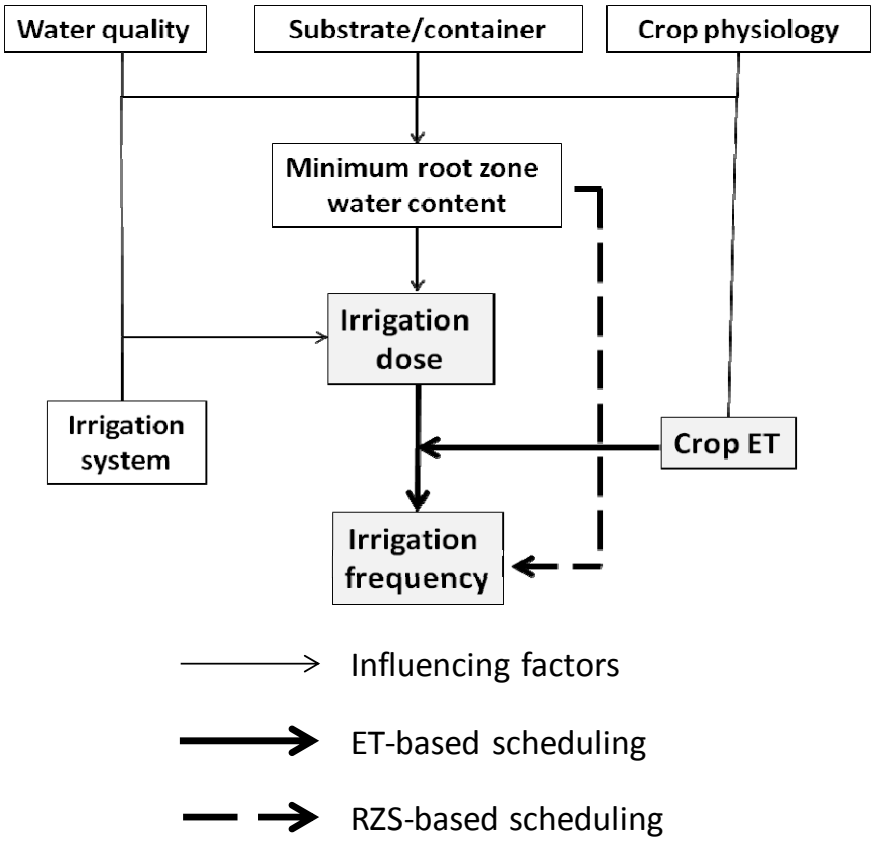


Figure 3.1. *Conceptual framework of irrigation scheduling in soilless culture.*

Figure 3.1 illustrates the conceptual framework of irrigation scheduling. Crop physiology (i.e. response to water status of the growing medium), water quality (i.e. salinity and concentration of specific ions) and layout of irrigation system (i.e. discharge rate of emitters, minimum irrigation length, irrigation efficiency and uniformity, etc.) must be known to determine irrigation dose while the frequency is determined by crop water uptake (W_U), which is dominated by ET ($\geq$90%) by ET.

Accurate irrigation scheduling is crucial in open substrate as it determines the seasonal use of water (W) and the pollution resulting from agrochemicals leaching.

On the other hand, over-irrigation or deficit irrigation may affect crop growth and yield also in closed system, for instance by increasing the incidence of physiological disorders (such as blossom-end rot in tomato and pepper; Savvas et al. 2009) or the susceptibility to root diseases (Saha et al., 2008).

3.2 Irrigation dose

The determination of optimal watering irrigation dose requires the computation of two quantities: net (I_{net}) and gross or actual (I_{gross}) irrigation volume (expressed as L m^{-2}).

The first quantity corresponds to the maximum oscillation in substrate θ that is tolerated by the crop and is calculated as:

$$I_{net} = \frac{AW_{cont}}{100} \cdot V_{cont} \cdot \mathrm{f} \qquad \text{(Eq. 3.1)}$$

where AW_{cont} (%) is the available water in the container-substrate system under consideration (Table 2.3), V_{cont} is substrate volume (L m^{-2}) and *f* (dimensionless) is a crop-specific irrigation coefficient ranging from 0.05 to 1.0: the lower *f*, the smaller the variation in substrate moisture and the shorter the irrigation.

Therefore, *f* must be selected according to: the hydraulic properties of the substrate; the layout of irrigation system, which affects water distribution uniformity and determines the minimum duration of each irrigation event; crop physiology.

Actual irrigation dose is generally higher than I_{net} as generally an excess of water is necessary due to: i) the unequal transpiration of individual plants; ii) the differences in water discharge of individual trickle nozzles and the consequent uneven water distribution; iii) the need to prevent salt accumulation in the root environment.

Hence, I_{net} is calculated as

$$I_{gros} = I_{net} \cdot K_S \quad \text{(Eq. 3.2)}$$

where K_S (dimensionless) is a safety coefficient.

For each irrigation event, drain fraction (DF; it is the percent ratio between water supply and drainage) approximates to:

$$LF = 100\ \frac{\left(I_{gross} - I_{net}\right)}{I_{gross}} \quad \text{(Eq. 3.3)}$$

K_S depends on crop and irrigation uniformity and the risk of substrate salinization. Safety coefficient ranges from 1.15 (uniform crop and water distribution; use of irrigation water with relatively low salinity; high crop tolerance to salinity) to 2.0 (large inter-plant variability in ET; poor irrigation uniformity; use of saline water; salt-sensitive crop), which results in a DF of 0.13 and 0.50, respectively.

A K_S of 1.30 (LF = 23%) is suitable in most conditions.

Evidently, the determination of K_S is less relevant in closed system, although too large K_S and then DF increases the costs for water pumping and NS disinfection.

The duration (D_I) of each irrigation in drip-irrigated substrate culture is generally very short (in the order of tens of seconds to a few minutes) and depends on the density (d, number of drippers per unit ground area) and discharge rate (r, L h^{-1}) of emitters and it is calculated as follows:

$$D_I = \frac{d \cdot 3600}{r} \quad \text{(Eq. 3.4)}$$

where D_I is expressed in seconds.

3.3. Irrigation frequency

In principle, irrigation frequency is computed as crop ET divided by I_{net} (not I_{gross}). For instance, if ET is expressed on a daily basis, the result is the number of irrigation events in a day.

In substrate culture, generally the crop is irrigated many times during the daytime

with the first irrigation occurring early in the morning. More than 90% of daily crop *ET* occurs during the light period, which is around 10 hours or less in autumn-winter and 12-14 hours in spring-summer (Fig.3.2). In heated greenhouse or dry seasons and/or regions, irrigation may be also necessary in the middle of the night.

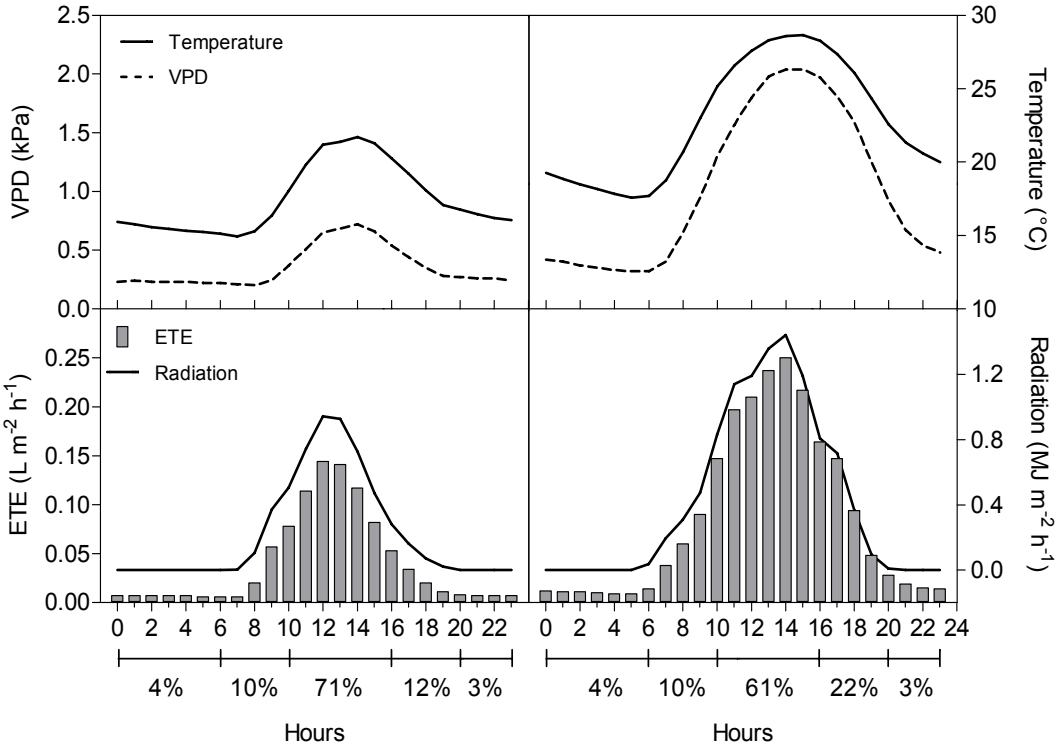


Figure 3.2. *Hourly rate of transpiration (ET) in greenhouse gerbera grown in rockwool in unheated greenhouse under the typical Mediterranean conditions of autumn (left) or spring (right). Night-time ET accounted for 7% of daily ET in both seasons.*

As results of frequent watering, irrigation of soilless culture is generally under the automatic control provided by:

1) **timer**, on the basis of grower's estimate of **crop ET**;

2) **weather station** or simple **light sensor**, on the basis of crop ET predicted with more or less complicated equations (modelling approach);

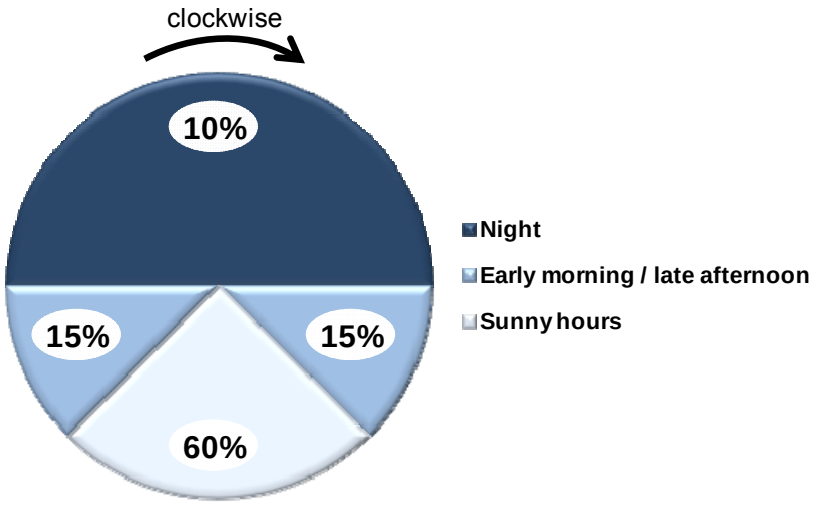
2) **weighing gutter** (or similar devices), which measures gravimetrically ET (and possibly growth) of a few test-plants over a short time (minutes to hours).

3) **root zone sensor(s);** which measures directly θ or ψ_m.

Weighing gutter for automated monitoring of crop evapotranspiration and irrigation control in tomato substrate culture (Photo: A. De Koning, Hortimax, Pijnacker, NL).

Timer

When irrigation is controlled by timer, a rule of thumb is to distribute irrigation events during the whole 24 h period as indicated in the diagram below, which shown how daily ET is partitioned in different time period (early morning, sunny hours, late afternoon and night).



ET modelling

Models of different complexity have been developed for predicting *ET* in greenhouse crops. Among the different approaches used to calculate *ET*, the FAO Penman-Monteith (PM) equation is currently considered a standard reference (Stanghellini, 1987; Allen et al., 1998; Walter et al., 2002. However, its application is not straightforward as it requires the knowledge of several variables and parameters. Therefore, several authors proposed simplified equations for predicting *ET* as a function of *LAI*, intercepted radiation (R_{int}, MJ m^{-2} h^{-1}) and *VPD* (kPa):

$$\mathrm{ET} = \mathrm{A} \cdot \frac{\mathrm{R_{int}}}{\lambda} + \mathrm{B} \cdot \mathrm{LAI} \cdot \mathrm{VPD} \qquad \text{(Eq. 3.5)}$$

where *A* (dimensionless) and *B* (kg m^{-2} h^{-1} kPa^{-1}) are empirical coefficients:

R_{int},, is estimated from *LAI* and a crop-specific light interception coefficient (*k*):

$$\mathrm{R_{int}} = 1 - \exp^{-\mathrm{k} \cdot \mathrm{LAI}} \qquad \text{(Eq. 3.6)}$$

After appropriate calibration, the equation reported previously predicted accurately *ET* in a variety of greenhouse crops.

Table 3.1 reports the values of coefficients A and B for some greenhouse crops.

A simple model for estimating daily *ET* of row crops in heated greenhouse was proposed by De Graaf (1988):

$$\mathrm{ET} = \frac{\mathrm{h}}{\mathrm{m}} \cdot \left[\mathrm{a} \cdot \mathrm{R} + \mathrm{b} \cdot \Sigma_{1440}^{1} \min_{\mathrm{i}} \left(\mathrm{T_t} - \mathrm{T_a}\right)\right] \qquad \text{(Eq. 3.7)}$$

where *h* and *m* are actual and maximum height of the crop, respectively; *R* is the inside global radiation; *a* and *b* are crop-specific coefficients, the latter being attributable to heating; $\min_i$ is the successive minutes during the day that the temperature of heating pipeline (T_t) is different from air temperature (T_a). The value of *b* is 0.22 10^{-4} for tomato and cucumber grown in Dutch growing conditions.

Table 3.1. Values for the coefficient A and B of Eq. 3.5 reported in the literature for some greenhouse crops.

Crop	Growing conditions	LAI	A	B	Reference
Begonia	Pot plants	2.7	0.20	0.026	Baille et al., 1994.
Cyclamen		2.9	0.32	0.019	
Hibiscus		2.4	0.37	0.037	
Impatients		5.1	0.67	0.013	
Pelargonium		5.7	0.61	0.017	
Poinsettia		2.0	0.12	0.017	
Schefflera		4.4	0.60	0.014	
Gardenia		4.5	0.46	0.019	
Gardenia		6.6	0.53	0.013	
Cucumber	Mediterranean regions (Almeria); autumn and spring; perlite pot substrate	0.5 - 2.6	0.26 0.42 0.24 0.24	0.034 0.042 0.032 0.055	Medrano et al., 2005.
Geranium	Mediterranean regions (Spain)	2.5	0.56	0.018	Montero et al., 2001.
Zucchini	Mediterranean regions (Italy); autumn and spring; pumice culture	0.5-5.5	0.63	0.009	Rouphael and Colla, 2004.
Gerbera	Mediterranean regions (Almeria, Spain); autumn and spring; semi-closed rockwool culture.	1.0 – 2.2	0.55	0.019	Carmassi et al. 2011
Rose	Mediterranean regions (Greece); perlite pot culture	2.5-3.5	0.236	0.026	Kittas et al. 1999
Tomato	Mediterranean regions (Spain); autumn and spring; perlite culture	2.5	0.580	0.025	Medrano, personal communication

As solar radiation is the main climate variable influencing *ET* in protected crops, especially under unheated greenhouse conditions (Baille et al., 1994; van Kooten et al., 2008), simple linear regression of *ET* against outside or inside solar radiation has been also proposed for practical management of irrigation in greenhouse crops (Morris et al., 1957; de Villèle, 1974). In the first case, the light transmission coefficient of the covering material must be known; this coefficient typically ranges from 0.60 to 0.70.

Table 3.2 reports the ratio of *ET* on *R (i.e. K_C)* of a few soilless-grown greenhouse crops as determined in a series of experiments conducted under unheated greenhouse in Central Italy. The ratio ranged from 0.65 to 0.80 and, as expected, was higher for crops with larger *LAI*.

Table 3.2. Measured values of *LAI* and the ratio between evapotranspiration (*ET*) and incident radiation *R* (converted in kg m^{-2} day^{-1}) in different greenhouse crops grown in soilless culture. * NFT: nutrient film technique.

Crop	Growing system	Season	*LAI*	*ET/R*
Tomato	Pumice; NFT*	Autumn - spring	3.0 - 3.5	0.75 - 0.80
Melon	NFT*	Autumn - spring	3.0 - 3.5	0.70 - 0.75
Strawberry	substrate	Spring	2.0 - 2.5	0.65 - 0.70
Gerbera	substrate	Year-round	2.4 – 2.8	0.65 - 0.70
Rose	substrate	Year-round	2.4 – 2.8	0.70 - 0.75

Root zone sensors

Soil moisture sensors could be used to regulate the frequency of irrigation and, possibly, the water dose by continuously monitoring θ or ψ_m of the growing media (Pardossi et al., 2009).

Expensive and complicated SMSs, such as neutron probe and TDR (time-domain reflectometry) instrument, are available for soil and plant scientists, while low-cost and practical devices are needed for irrigation control of commercial crops. Interesting possibilities have been opened up by new types of SMS that measure soil dielectric properties (Pardossi et al., 2009). New dielectric SMSs are cheaper and

need much less maintenance and user's expertise compared to traditional water-filled tensiometers.

The utilization of SMS technology for irrigation management in both soil and soilless culture has been documented by many papers (e.g., Muňoz-Carpena et al., 2008; Zotarelli et al., 2009) and currently a variety of simple irrigation controllers are available on the market that are interfaced to one or more SMSs.

Threshold values for θ or ψ_m depend on crop species and growing media. Typical range for ψ_m is from -4 kPa to -10 kPa in substrate growing systems (Pardossi et al., 2009). This value can be converted to θ with WRC (Table 1). For instance, a ψ_m of -5 kPa corresponds to a θ of 34% in perlite.

Sensors, such as 5TE (Decagon Devices) or WET (Delta-T Device), have been also developed for simultaneous measurements of temperature, θ and pore water EC in soil or soilless media (Pardossi et al., 2009). These sensors provide the possibility of controlled fertigation.

Recently, an automated fertigation device was designed and tested successfully to modulate both irrigation frequency and EC of fertigation water based on the simultaneous measurement of θ and pore water EC (EC_{PW}) of the growing medium by means of the WET sensor (Incrocci et al., 2010). Specific algorithms were implemented in the control software in order to activate irrigation when a pre-set θ threshold was reached and to modulate irrigation dose and/or nutrient solution EC (also by mixing different sources of water such as recirculated water, groundwater, rainwater, etc.), with the aim of avoiding salt accumulation in the substrate and minimizing water drainage.

Summary:

- Inaccurate irrigation scheduling results in water loss and pollution due to fertilizer leaching.
- Irrigation scheduling consists in the determination of both irrigation dose and frequency.
- Irrigation dose is function of water quality, the content of available water in the substrate-container system and crop species.
- The determination of irrigation frequency requires the assessment of crop evapotranspiration (ET) and/or the direct measure of moisture level in the growing medium.

Calculating irrigation dose

1) Define your growing system

- Crop: gerbera
- Season: spring-summer
- Crop density: 6 plants per slab; 1 slab m^{-2}; 1 dripper per plant (d = 6 dripper m^{-2})
- Dripper discharge rate (r): 4.0 L h^{-1}
- Substrate: perlite bag
- Substrate volume (V_{cont}): bag dimensions = 1.0 x 0.15 x 0.15 m; vol. = 22.50 L m^{-2}.
- Available water (AW_{cont}) (see Tab. 2.3) = 34% (0.34).
- *Crop irrigation coefficient (f)*: 0.05.
- Safety coefficient (K_S): 1.30.

2) Calculate net irrigation volume (I_{net})

It represents the maximum oscillation of substrate moisture and, together with crop ET, determines irrigation frequency.

$$I_{net} = AW_{cont} \cdot V_{cont} \cdot f = 0.34 \cdot 22.5 \cdot 0.05 = 0.38 \, L \, m^{-2}$$

3) Calculate gross irrigation volume (I_{gross}) and duration (I_{time})

It is the quantity of water delivered to the crop in occasion of each irrigation event; it includes surplus water and then determines leaching fraction.

$$I_{gross} = I_{net} K_S = 0.38 \cdot 1.3 = 0.50 \, L \, m^{-2}$$

$$I_{time} = \frac{I_{gross} \cdot 3600}{d \cdot r} = \frac{0.50 \cdot 3600}{6 \cdot 4} = 75 \, sec$$

Setting irrigation controller

Timer

1) Estimate crop ET

(f.i.) ET: 3.0 L m^{-2}.

2) Calculate number of irrigations (N_I)

$$N_I = \frac{ET}{I_{net}} = \frac{3.0}{0.38} \cdot = 7.89 \cong 8$$

3) Schedule irrigation events during the 24 h period

Time	Interval (h)	Irrigation events	Period between two irrigations (min)
Dawn	-	1	-
8.00 to 10.00	2	1 (9.00)	-
10.00 – 16.00	6	4	90
16.00 to 20.00	4	1 (18.00)	-
Midnight	-	1	-
	total	8	

Solarimeter

1) Estimate crop K_C

(f.i.) K_C = 0.65.

2) Set radiation threshold (R_{th})

$$R_T = \frac{I_{net} \cdot \lambda}{k_C} = \frac{0.38 \cdot 2.45}{0.65} = 1.43\, MJ\, m^{-2}$$

Crop is irrigated whenever cumulated radiation is equal to 1.43 MJ m^{-2}.

Meteo station

1) Set threshold value for ET: 0.38 L m^{-2}.

Crop is irrigated whenever cumulated ET is equal to 0.38 L m^{-2}.

☞ Check regularly **leaching fraction** and adjust irrigation volume and/or frequency in order to maintain the desired value.

4. FERTIGATION MANAGEMENT

4.1. Plant mineral nutrition in soilless culture

The positive effect of hydroponics on crop growth and yield is the result of the optimal conditions provided by artificial substrate, if any, and the supply of a well-balanced and highly-concentrated NS. The use of high concentration aims to:

1. to guarantee adequate nutrient supply without the difficulties of maintaining a fairly constant ion concentration in the root zone;
2. to prepare automatically the nutrient solution by means of fertigation mixer systems that normally dilute 100- to 200-fold concentrated stock solutions with raw water on the basis of the measurement of electrical conductivity (EC). Due to the salt dissolved in raw water as well as the accuracy of current mixers, it would be not possible to use low-concentration culture solutions in commercial greenhouses.
3. at least in some crops such as fruit vegetables, to improve fruit quality (osmotic effects). In these cultivations, EC higher than 2.5 to 3.0 mS cm^{-1} is normally necessary for high quality standards.

4.2 Nutrient solution

NS contains all macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulfur) and micronutrients (iron, boron, copper, manganese, zinc and molybdenum) at concentration of the order of milli- and micro-moles per liter, respectively. Optimal values of pH are between 5.5 and 6.5.

Depending on many factors, such as crop characteristics (e.g. tolerance to salinity) and stage, climate and hydroponic system, total molar concentration range between 20 and 40 mM or between 1 and 2 g l^{-1}. **Table 4.1** reports the concentrations of both macronutrients and micronutrients in the NS (nutrient recipes) used for different greenhouse crops. On a molar basis, the dominant ion in the NS is nitrate. Generally, horticultural crops do not tolerate ammonium form of nitrogen, which then is not used or used at very low concentration in hydroponic culture.

Table 4.1. Concentration of macro- and micro-nutrients in the nutrient solutions used for commercial vegetable and ornamental crops

Macronutrients (mol m^{-3})							
Crop	$N\text{-}NO_3$	$N\text{-}NH_4$	P	S	K^3	Ca	Mg
Tomato	11-15	1-1.5	1.5-2	3.5-4.5	5-9	3.5-5	2-2.5
Pepper	14-17	1-1.25	1.5-2.5	1.75-2	4-7	4-5	1.5-2
Eggplant	13-17	1.5-2	1.5-2	1.25-2	4-6	3-3.5	2-2.5
Cucumber	16-18	1-1.25	1.25-2	1.25-2	5-8	3.5-4	1.5-2
Zucchini	15-18	1-1.5	1.5-2	1.75-2	5-8	3.5-4.5	2-2.5
Strawberry	11-13	1-1.25	1-1.75	1-15	4-6	3-3.5	1-1.5
Melon	16-19	0.5-1	1-1.75	1.25-2	5-8	4-5	1.5-2
Carnation	13-16	1.5-2.5	2-2.5	3-3.5	7-9	3.5-4	2-2.5
Gerbera	11-13	0.5-1.5	1.75-2	3-3.5	4.5-6	3.5-4	1.5-2
Rose	12-15	1-1.5	1.5-2	2.75-3	4.5-6	3.5-4.5	2-2.5
Solidago	12-14	1.5-2	2-2.5	1-1.5	5-8	3.5-4	1.75-2
Limonium	10-13	1-1.5	1.75-2	1-1.5	5-7	3.5-4	1-1.5
Lisianthus	13-15	1-1.5	1.75-2	1-1.5	4-7	3.5-4	1.5-2
Anthurium	7.5-9	0.5-1	1-1.25	1-1.5	4.5-5.5	1-1.75	1-1.25
Micronutrients (mmol m^{-3})							
	Fe^3	B^3	Cu	Zn	Mn^3	Mo	
Tomato	20-25	30	1	5	10	0.5	
Pepper	20-25	30	1	7	10	0.5	
Eggplant	15-20	30	1	5	10	0.5	
Cucumber	15-20	25	1	5	10	0.5	
Zucchini	10-15	30	1	5	10	0.5	
Strawberry	20-25	15	1	7	10	0.5	
Melon	10-15	25	1	5	10	0.5	
Carnation	30-35	30	1	5	5	0.5	
Gerbera	35-45	35	2	5	5	0.5	
Rose	35-45	30	1	5	10	0.5	
Solidago	25-35	30	1	5	10	0.5	
Limonium	10-20	25	1	5	10	0.5	
Lisianthus	25-35	30	1	5	10	0.5	
Anthurium	15-20	20	0.5	3	5	0.5	

Normally, the concentration is expressed as EC (dS m^{-1}). For most balanced NSs in the range of 1.0 to 4.0 dS m^{-1}, a simple linear relationship may be used to convert equivalent concentration of cations (C^+, meq L^{-1}) in EC, assuming that the concentration of cations is equal to the one of anions (Sonneveld et al., 1999):

$$EC = 0.19 + 0.095\ C^+ \qquad \text{(Eq. 4.1)}$$

Chemical characteristics of the NS can be relieved through portable instruments, rapid test kits and/or laboratory analysis. Commonly, pH and EC are checked very frequently, also automatically, especially in closed system.

NS is prepared by mixing stock nutrient solutions, acids and raw water.

It is recommended the use of fertilizers with a high purity grade and solubility. This operation is accomplished by fertigation system that generally works using volumetric or electronic injectors.

Stock NSs are generally 50 to 200 times more concentrated than the NS fed to the crop. In order to avoid precipitations of salts, such as calcium phosphate, at least two stock NSs are prepared in order to separate calcium salts from phosphates and sulphates.

Water contains often excessive concentration of one or more ions that are non essential for plant growth (ballast ions).

The quality of raw water is a key factor and must be known in order to:

i) check whether water can be utilized as such or needs specific treatments;

ii) to calculate the amount of fertilizers required to prepare nutrient stocks.

Table 4.2 reports guideline values for irrigation water.

Some spreadsheets and computer programs are available, also in the Internet, to calculate the exact amount of salts required to prepare stock NSs. An example is an Excel spreadsheet (NS Calculator), which is annexed to this document.

Table 4.2. Evaluation of the main water parameters as required for fertigation use.

Parameter	Units	Degree of restriction on use		
		None	Slight to Moderate	Severe
EC	dS m^{-1}	0-0.75	0.75-2.25	>2.25
Bicarbonates	mol m^{-3} (ppm)	0-2 (0-120)	2-6 (120-360)	>6 (>360)
Nitrates	mol m^{-3}	<0.5	0.5-2	>2
Ammonium	mol m^{-3}	≈0	0.1-1	>1
Phosphorus	mol m^{-3}	<0.3	0.3-1	>1
Potassium	mol m^{-3}	<0.5	0.5-2.5	>2.5
Calcium	mol m^{-3}	<1.5	1.5-5	>5
Magnesium	mol m^{-3}	<0.7	0.75-2	>2
Sodium	mol m^{-3}	<3	3-10	>10
Chloride	mol m^{-3}	<3	3- 10	>10
Sulphates	mol m^{-3}	<2	2-4	>4
Iron	mmol m^{-3}			>90
Boron	mmol m^{-3}	30	30-100	>100
Cupper	mmol m^{-3}			>15
Zinc	mmol m^{-3}			>30
Manganese	mmol m^{-3}			>10

Nutrient Solution Calculator

Nutrient solution calculator (NSC) is a EXCEL™ spreadsheet developed Dr. Luca Incrocci (University of Pisa; incrocci@agr.unipi.it) to assist growers and consultants in the calculation of salt concentration of stock nutrient solutions.

NSC has a user-friendly interface and a database with: i) nutrient recipes for many greenhouse crops; ii) composition and prices of different fertilizers and acids. The database can be edited and extended by the user.

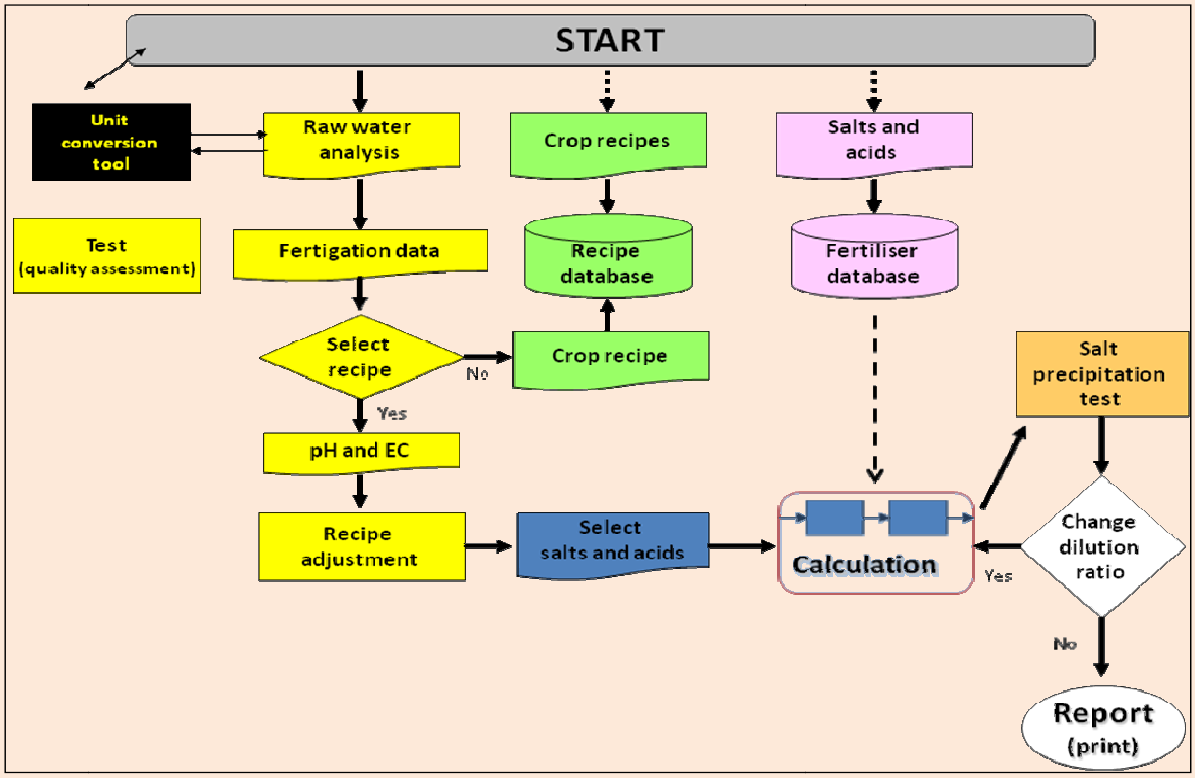
The spreadsheet calculates the composition and the cost of nutrient stocks (fertigation system A+B) based on:

i) ion composition of irrigation water;

ii) crop recipe (i.e., pH, EC and nutrient concentrations of the nutrient solution to be delivered to the crop);

iii) technical characteristics of the fertigation device (i.e., volume of stock tanks and dilution ratio).

NSC also assesses the possible occurrence of salt precipitations in the nutrient stocks due to excessive concentration.



Flow-chart of NS Calculator.

4.3 Fertigation system

A fertigation system may be composed by:

1. pressured and filtered raw water from single or multiple sources such as surface water, groundwater, rainwater, reclaimed wastewater and, in closed system, recirculating NS (disinfected or not);
2. dosing machine (many devices are available on the market; Seligman, 2011), which injects two to more stock solutions into raw water and adjust pH of the supply NS by means of acids or bases;
3. probes for monitoring EC and pH of supply, recirculating and drainage NS;
4. water meters to control the injection of nutrient stocks and water flows in the system;
5. climate sensors, which are used to estimate crop ET;
6. control system (computer program), which schedules irrigation and adjusts the chemical characteristics of the NS according to grower's instructions;
7. hydraulic components such as pipelines, drippers, electrovalves and tanks.

A few of these components (e.g, 5 and 6) are not essential and are installed only in sophisticated fertigation system.

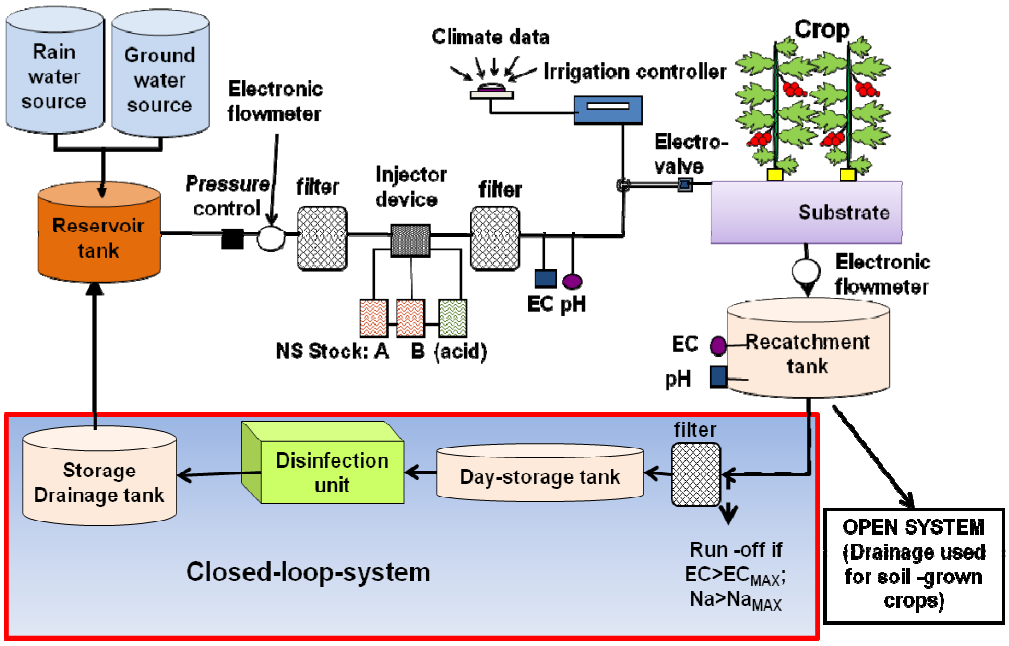
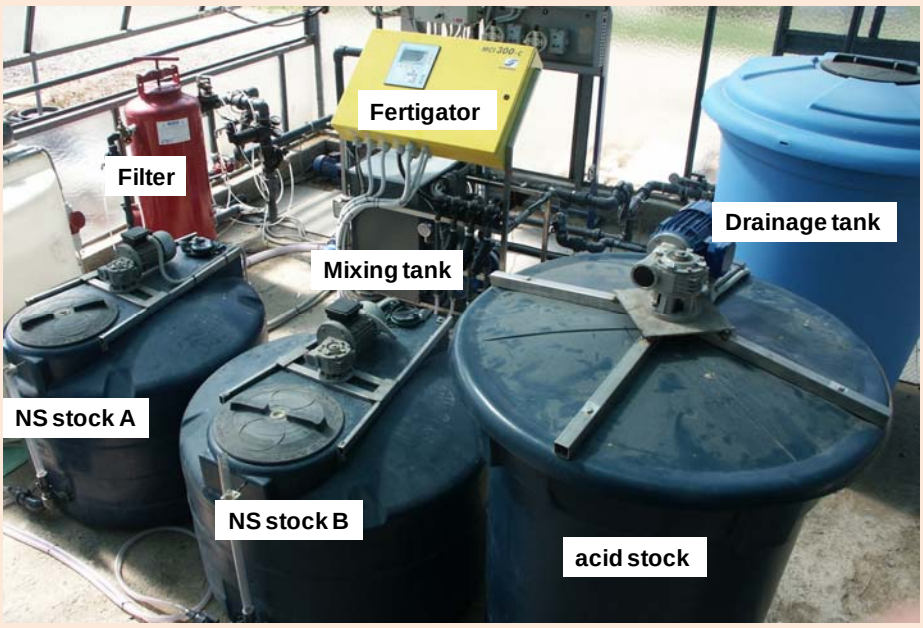


Fig. 4.1. Tipical layout of substrate soilless growing system.



An example of fertigation device. Two stock nutrient solutions and diluted acid are mixed to raw water with Venturi injectors under the control provided by EC and pH probes. The software also schedules irrigation based on weather-based estimation of crop transpiration.

☞ Professional systems ensure best water and nutrient use efficiency. Contact irrigation designer and company for cost-effective irrigation systems.

4.4. Fertigation strategy

The fate of drainage water is the criteria to distinguish open system from closed system. In open system, the surplus of NS applied to the substrate could be collected or not, but in both cases drainage water is not re-used on the same culture (Fig. 4.1): it could be used for soil-grown crops in the field, however.

In closed systems, the drainage is collected, filtered, and adjusted for pH and nutrient concentration (namely, **EC**) and re-used for irrigating the same crop (see fig.4.1). Due to the risk of pathogen contamination, the disinfection of recirculating NS is advisable (see previous section). In closed systems, water requirements correspond to genuine crop water uptake ($\mathbf{W_U}$, that is **ET**) as generally evaporation from the substrate and uncontrolled seepage are negligible.

If saline water is used, there is a more or less rapid accumulation of ballast ions,

which are dissolved in the water at concentration higher than crop uptake concentration (C_U, the ratio between the ions and the water taken up by the plants). Under these conditions, NS is recirculated till its EC (EC_{NS}) and/or the concentration of some ions (e.g., Na, Cl or trace elements such as B) reach maximum acceptable thresholds value (EC_{MAX} or C_{MAX}) for the crop under consideration; afterwards, NS is replaced, at least partially (flushing).

Three different procedures differing for the criterion used for nutrient replenishment could be adopted in commercial closed systems.

A) Reservoir tank is replenished by refill NS that is prepared by mixing raw water and drainage NS at a ratio generally equal to drain fraction (DF), in order to use all drainage water, and adding nutrient stocks to reach a target EC (Fig. 4.2). This procedure maintains the EC of recirculating NS constant but it results in progressive nutrient depletion, if some or more ballast ions are dissolved in raw water. In this system, evidently EC does not provide information on the concentrations of individual ions, as shown by the example reported in Figure 4.3.

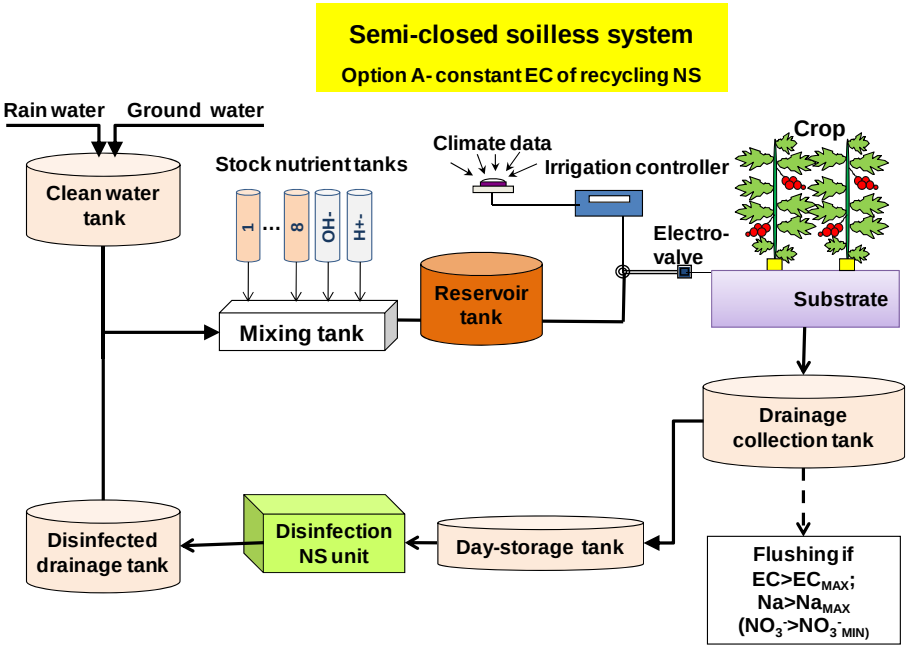


Fig 4.2. *Fertigation scheme following Strategy A (see text).*

Water loss from soilless culture: definitions.

In soilless culture, water use (**W**) includes both crop water uptake ($\mathbf{W_U}$), which is determined by evapotranspiration (**ET**) and growth (generally, less than 10% of $\mathbf{W_U}$) and, in open (free-drain) and semi-closed systems, by drainage (**D**).

In semi-closed systems, **D** is systematically recirculated but, more or less frequently the nutrient solution is discharged (leaching, **L**).

Excess water supplied to the crop can be expressed in different manners:

- Drain fraction (**DF**): $DF = \frac{D}{I}$

  where **I** the water applied at each irrigation event

- Leaching fraction (**LF**): $LF = \frac{L}{W}$

  In open system, **DF** corresponds to **LF**

- Leaching requirement (**LR**): $LR = \frac{L}{W_U} \approx \frac{L}{ET}$

  Then, in semi-closed systems**:**

  $LR = \frac{LF}{1 - LF}$,

  $W = ET \cdot (1 + LR)$

  and

  $LR = \frac{W}{ET} - 1$

In open systems, **DF** ranges normally between 0.20 and 0.50.

W corresponds to $\mathbf{W_U}$ (then, to ET) only in fully closed growing systems, where **D** is completely recirculated and **L** is negligible.

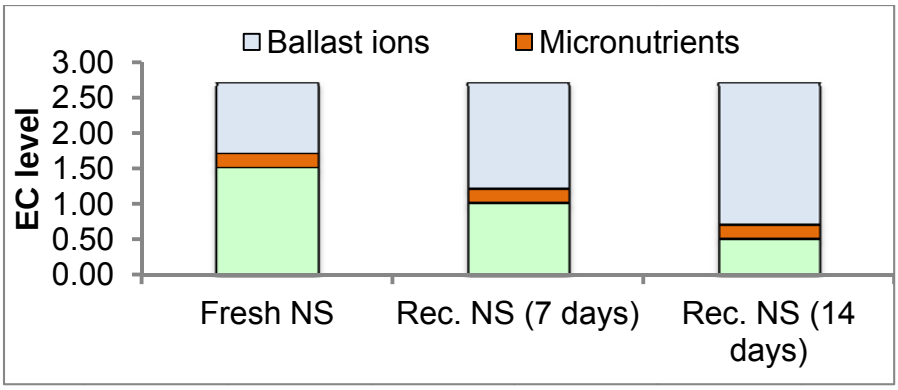


***Fig. 4.3**. Contribution of different types of ions to the EC of nutrient solution (NS) in closed substrate culture of greenhouse tomato (Massa D., unpublished). The values refer to newly-prepared NS or NS that was recirculated for one or two weeks.*

Therefore, recirculating NS should be regularly (every 1-2 weeks) analyzed by quick tests (on farm) or by external laboratory in order to adjust the composition of refill NS and make a decision about the need for flushing. NS is discharged when the concentration of a given ion reaches C_{MAX}. For instance, in The Netherlands, growers have the permission to leach their systems whenever a crop-specific ceiling of Na^+ concentration is reached (Vermeulen et al., 2005): for example, 8 mol m^{-3} for tomato. Alternatively, NS is discharged when the concentration of some polluting agents (e.g. nitrate) is lower than a maximum limit imposed by legislation to wastewater.

B) $\mathbf{W_U}$ was compensated by refilling the mixing tank with nutrient solution at full strength (with the concentrations of macronutrients equal or close to the corresponding mean uptake concentrations as determined in previous studies) and the recirculating NS was flushed out whenever its EC and/or concentration of a given ion surpasses EC_{MAX} or C_{MAX}. This procedure results in a relatively constant concentration of nutritive ions but leads to a progressive EC increase due to accumulation of ballast ions. The main disadvantage of this fertigation strategy is that EC oscillated in the NS and this is not suitable for salt-sensitive crops (Fig. 4.4).

C) This procedure is similar to Strategy A, but when EC_{MAX} or C_{MAX} is reached, crop W_U is compensated only with pH-controlled raw water for a few days, in order to minimize the concentration of polluting ions in the NS before flushing.

Figure 4.5 illustrates time-course of EC of drainage (open system) or recirculating (semi-closed systems) and how nutritive and ballast ions contribute to EC.

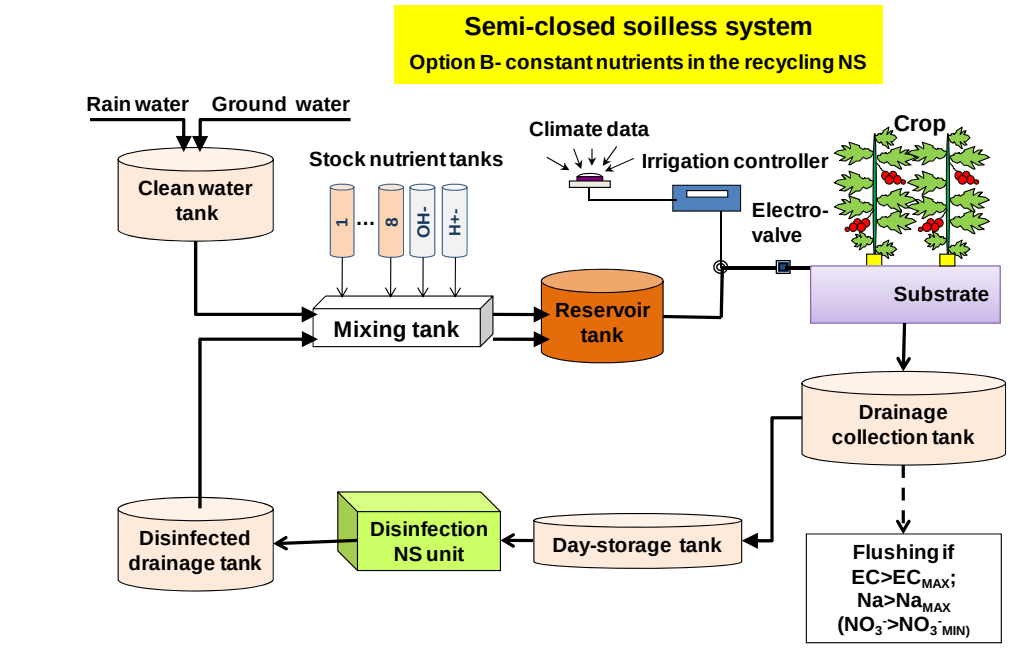


Fig 4.4. *Fertigation scheme following Strategy B or C (see text).*

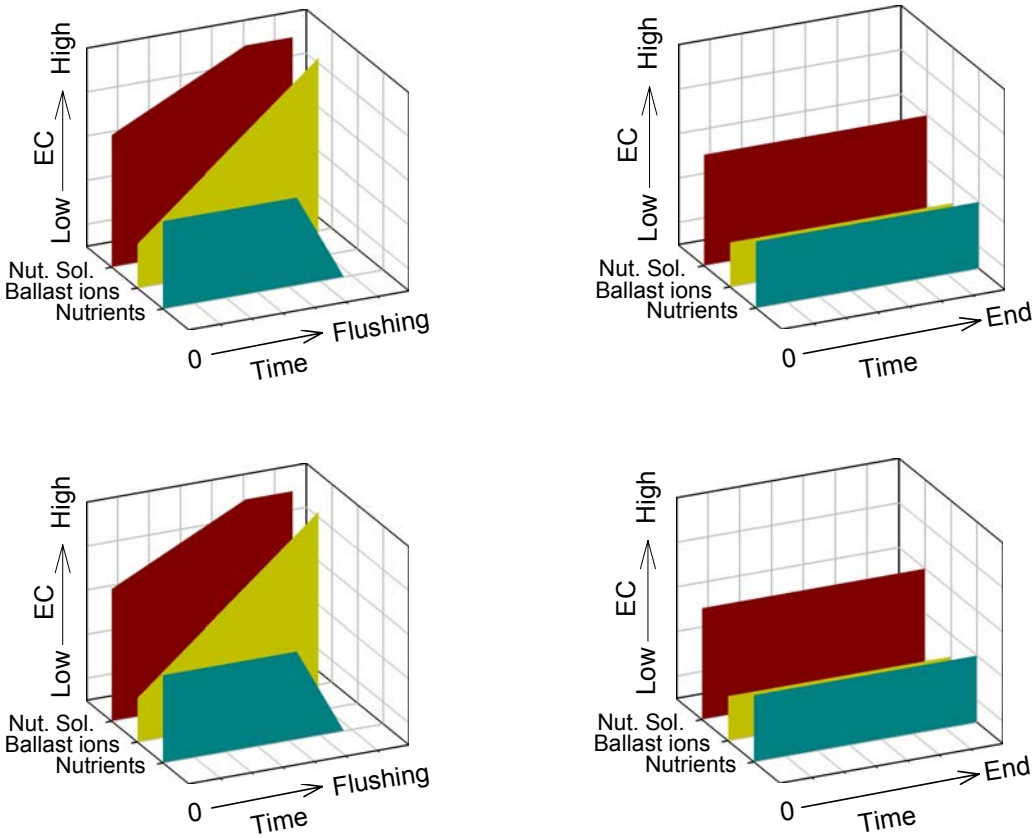


Fig. 4.5*. Schematic illustration of different fertigation strategies. The graphs show the contribution of nutritive and saline (e.g. NaCl) ions to EC of the recirculating nutrient solution in semi-closed systems (Strategies A-C), described in the manuscript, or drainage nutrient solution in open (free-drain) system (Strategy D).*

Research note: Simulating water and mineral relation in open and closed soilless culture.

A composite model was developed by Massa et al. (2011) for water and mineral relations of greenhouse tomato cultivated in semi-closed or open soilless (rockwool) culture. The model simulated on a daily basis:

i) the evolution of crop leaf area index and water uptake using empirical equations;

ii) the variations of ion concentrations and electrical conductivity (EC) in the recirculating or drainage nutrient solution using a mass balance equation based on the concept of ion uptake concentration.

The model was calibrated using measured data collected in previous works and validated in two independent experiments carried out in 2005 and 2007. In these experiments, fertigation strategies were tested using nutrient solutions prepared with saline (9.5 mol m^{-3} NaCl) water.

In most cases, simulations of seasonal crop water uptake were within the confidence interval of the measurements with a maximum deviation of -6%. The model predicted acceptably the time course of EC and ion concentration in recirculating (semi closed systems) or drainage (open system) nutrient solution. In general, there was a good agreement between simulated and measured values of total water and nutrient use.

Main advantages of this model are that it is easy to use, requires few variables and parameters, and can be easily recalibrated based on measurement and chemical analysis of the nutrient solution.

The composite model could be implemented in a decision support system (DSS) for fertigation management in soilless culture management. In addition, the model could enable local assessment of water withdrawal and fertiliser leaching in greenhouse crops or scenario analysis of different cropping practices. In The Netherlands, the current legislation imposes limits to the amount of irrigation water that may be applied to greenhouse crops (for instance, 1140 L m^{-2} in tomato culture; Stanghellini et al., 2007). Simulation models of seasonal water use may be useful tools for both growers (for efficient water management at the farm gate) and policy makers (for instance, for establishing limits to water and fertiliser application).

The model could be also used to estimate emission of plant protection products applied to the crop through recirculating nutrient solution. These emissions depend on dissipation kinetics and root uptake of the substance under consideration, and on the frequency of discharging recirculation water (Vermeulen et al., 2010).

The model is currently implemented in an Excel spreadsheet (SIMULHYDRO), which is freely available to interested readers, who can download both reference manual and software from EUPHOROS website.

Research notes: water salinity and fertigation strategy

According to **Stanghellini et al. (2005)**, when saline (or poor quality) irrigation water is available to the grower, closed systems are not financially viable under strict environmental rules and the most valuable strategy is likely the improvement of water quality, by means of desalinization or rainwater collection.

Nevertheless, in species with moderate salt tolerance (e.g., tomato and melon) the application of fertigation control procedures may give positive results in terms of both crop sustainability and productivity by prolonging the recirculation of the same nutrient solution (NS) and minimizing the content of polluting agents, like nitrate, in the effluents, when the water is ultimately discharged.

In two consecutive years, **Massa et al. (2010)** explored the influence of three fertigation strategies (A-C, as described in the text and in Figure 4.5) on water and nitrogen use efficiency of semi-closed rockwool culture of greenhouse tomato conducted using saline water (NaCl concentration of 9.5 mol m^{-3}). The strategies under comparison were the following:

A) crop water uptake was compensated by refilling the mixing tank with nutrient solution at full strength (with the concentrations of macronutrients equal or close to the corresponding mean uptake concentrations as determined in previous studies) and the recirculating nutrient solution was flushed out whenever its EC surpassed 4.5 dS m^{-1} due to the accumulation of NaCl;

B) the refill nutrient solution had a variable EC in order to maintain a target value of 3.0 dS m^{-1}; due to the progressive accumulation of NaCl , the EC and macronutrient concentration of the refill nutrient solution tended to decrease with time, thus resulting in a progressive nutrient depletion in the recycling water till nitrate content dropped below 1.0 mol m^{-3}, when the nutrient solution was replaced;

C) likewise strategy A, but when EC reached 4.5 dS m^{-1}, crop water uptake was compensated with fresh water only in order to reduce $N\text{-}NO^{3-}$ concentration below 1.0 mol m^{-3} before discharge.

In the semi-closed system conducted following strategy A, B or C, NS was replaced, respectively, 10, 14 and 7 times in 2005, and 19, 24 and 14 times in 2006, when the cultivation lasted 167 days instead of 84 days in 2005. In both years, there were no important differences in fruit yield and quality among the strategies under investigation. Strategy C produced the best results in terms of water use and drainage, while strategy B was the most efficient procedure with regard to nitrogen use. In contrast to strategies A and D, the application of strategies B and C minimized nitrogen emissions and also resulted in nitrate concentrations in the effluents that were invariably lower than the limit (1.42 mol m^{-3}) imposed to the nitrate concentration of wastewater discharged into surface water by the current Italian legislation associate to European Nitrate Directive.

4.5. Leaching requirement in semi-closed system

Simulation models can contribute to improved fertigation control in semi-closed system by considering variations in the ionic composition of recirculating NS and supporting grower's decision on nutrient replenishment and leaching requirements.

Models of **W**, which is determined by crop ET and LR, may be useful tools for both growers (for efficient water management at the farm gate) and policy makers (for instance, for establishing limits to water and fertiliser application). In The Netherlands, limits are imposed to the amount of irrigation water that may be applied to greenhouse crops (e.g., 1140 L m^{-2} in tomato; Stanghellini et al., 2007). Several models were designed for automated fertigation in closed systems (e.g. Heinen, 2001; Silberbush and Ben-Asher, 2001; Silberbush et al., 2005; Mathieu et al., 2006). However, commercial applications of these models are difficult, as they require many variables and parameters. Instead, Carmassi et al. (2007) proposed a simple mass balance equation to predict W of semi-closed soilless culture based on few variables and parameters, including $\mathbf{C_U}$ of nutritive and ballast ions.

From the equation proposed by Carmassi et al. (2007), a simple equation can be derived with the following assumptions:

i) C_U is negligible compared to the concentration of considered ion in the refill NS (that is, in raw water; C_I);

ii) at flushing, the entire volume of recirculating NS (including the one in the substrate) is discharged.

The equation is the following:

$$LR = \frac{C_I}{C_{NS}^{MAX} - C_I} \qquad \text{(Eq. 4.2)}$$

After rearrangement, this equation can be used to estimate the maximum C_I that will make it possible to grown crop with known **ET** and tolerance to the ion under consideration (expressed by $\mathbf{C_{NS}^{MAX}}$) and with the constraints of limited water availability ($\mathbf{W^{MAX}}$), which in turn determines LR:

$$C_I^{MAX} = C_{NS}^{MAX} \cdot \left(\frac{LR}{1 + LR} \right) \qquad \text{(Eq. 4.3)}$$

where

$$LR = \frac{W^{MAX}}{ET} - 1 \qquad \text{(Eq. 4.4)}$$

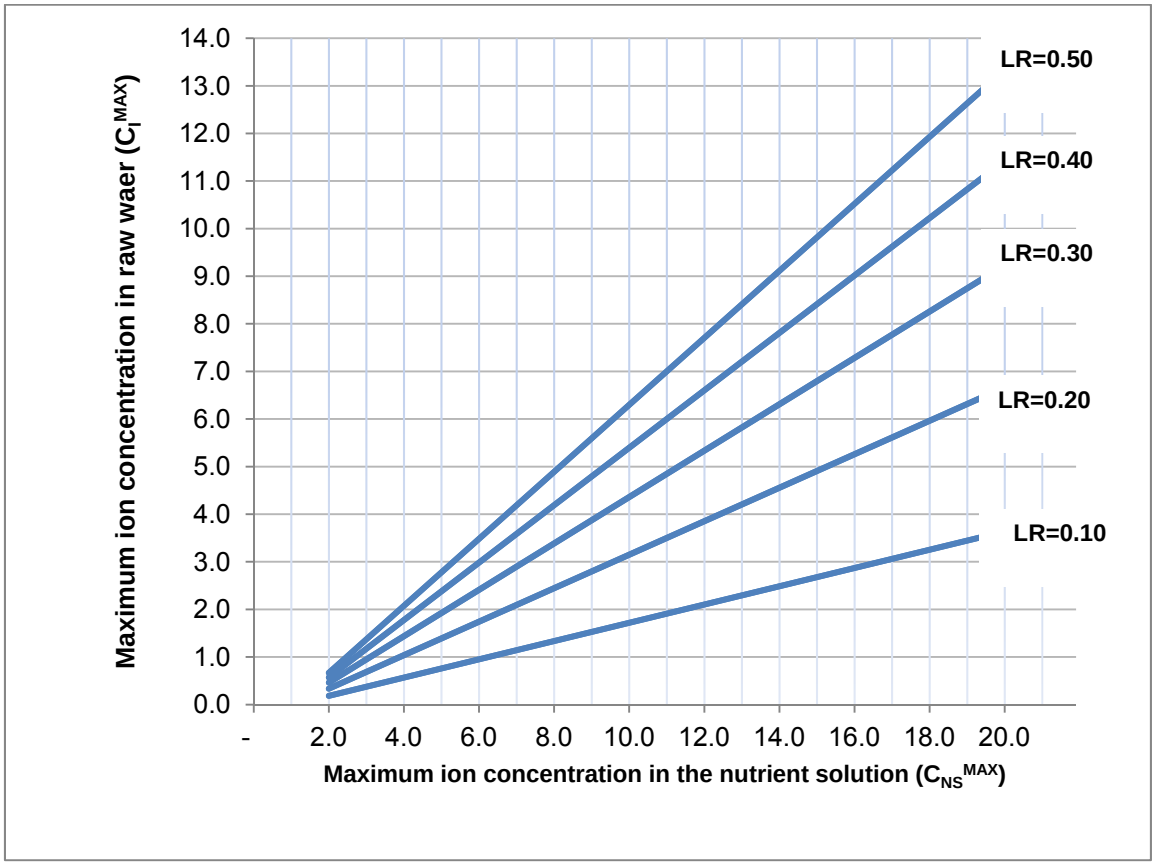


***Figure 4.6**. Maximum concentration of a given ballast ion in the raw water as determined by crop tolerance to this ion (as expressed by ceiling concentration in the recirculating nutrient solution) and target leaching requirement.*

Summary:

- The composition of the nutrient solution must be selected according to crop species and environmental condizione
- A nutrient solution calculator is available to compute the salt concentration of stock solutions based on the composition of irrigation water and crop recipe and the characteristics of available acids and salts.
- One of the main drawbacks of closed soilless systems is the accumulation of ballast ions in the recirculating nutrients solution, which may results in an increase in electrical conductivity (EC).
- Nutrient solution must be checked frequently (also by means quick tests).
- A simulation tool is available to predict the EC and the ion composition of recirculating nutrient solution.

NOMENCLATURE

Symbol or abbreviation	Description	Unit
A	Regression coefficient of the global radiation in the Baillè equation for the crop ET calculation.	adimensionless
a	Regression coefficient of the global radiation in the de Graaf equation for the crop ET calculation.	adimensionless
AW	Available water; it is the percentage of available water in a substrate as determined by the difference between the percentage water content at -1 and -10 kPa in the retention curve	%
AW_{cont}	Container available water	%
B	Regression coefficient of the product Lai*VPD in the Baillè equation for the crop ET calculation.	kg $m^{-2}h^{-1}kPa$
b	Regression coefficient of the global radiation in the de Graaf equation for the crop ET calculation.	Kg m^{-2} $°C^{-1}$
C^+	Sum of valences of cations	mol m^{-3}
C_I	Ion concentration	mol m^{-3}
C_I^{max}	Maximum ion concentration in the irrigation water tolerate by the crop with a pre-set LR.	mol m^{-3}
C_{NS}^{max}	Maximum ion concentration tolerated by the crop in the root zone (or recirculating NS)	mol m^{-3}
C_U	Plant uptake concentration; it is the quantity of ions absorbed by plants per litre of water taken up	mol m^{-3}
D	Drainage water volume; it is the volume of water drained out from the substrate during irrigation	L m^{-2}
d	Number of drippers	n m^{-2}
DF	Drain fraction; it is the fraction of I drained out from the substrate during irrigation	dimensionless
D_I	Duration of a single irrigation event	sec
EC	Electrical conductivity	dS m^{-1}
EC^{max}	Maximum value of EC tolerated by the crop	dS m^{-1}
ET	Effective crop evapotranspiration	L m^{-2}
f	Crop specific coefficient used for the determination of I_{net}	dimensionless
GDD	Growing degree days	°C
h	Actual height of the crop	m
h_{cont}	Container height	m
I	Irrigation volume; it is the volume of water applied at each irrigation	L m-2
I_{gross}	Gross irrigation volume; it is the actual volume of water delivered to the crop at each irrigation	L m^{-2}
I_{net}	Net irrigation volume; it is the volume of water evapotranspirated by plants between two consecutive irrigation events	L m^{-2}

Symbol or abbreviation	Description	Unit
k_C	Crop coefficient	dimensionless
K_s	Safety coefficient used for the determination of I_{gross}	dimensionless
L	Leaching water volume; it is the cumulative volume of water leached out from the system during a cultivation cycle	L m^{-2}
LAI	Leaf area index	dimensionless
LF	Leaching fraction; it is the fraction of W leached out from the substrate	dimensionless
LR	Leaching requirement; it determines the quantity of water leached out from the system per litre of W_U	dimensionless
m	maximum height of the crop	m
N_I	Number of irrigations	n $time^{-1}$
NS	Nutrient solution	L m^{-2}
r	Discharge rate of drippers	L $time^{-1}$
R	Radiation measured inside the greenhouse	MJ m^{-2} $time^{-1}$; W m^{-2}
R_{int}	Intercepted radiation	MJ m^{-2} $time^{-1}$; W m^{-2}
R_T	Radiation threshold for determination of irrigation events	MJ m^{-2} $time^{-1}$; W m^{-2}
T_a	Air temperature	°C
T_t	Heating pipeline temperature	°C
V_{cont}	Container volume	L m^{-2}
VPD	Vapour pressure deficit	kPa
W	Water use; it is the cumulative volume of water used during a cultivation cycle	L m^{-2}
W^{max}	Maximum volume of water available at farm level for a determined crop cycle	L m^{-2}
W_U	Plant water uptake	L m^{-2}
λ	Latent heat of water vaporization	2.45 MJ m^{-2}
θ	Volumetric water content	%
ψ_m	Matricial potential	kPa

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