Chapter 12
Nutrient Solutions for Soilless Cultures

12.1 Introduction

Nutrient solutions intended for plant growth are already used from the middle of the 19th century, when the importance of mineral elements for plant growth was made clear by Justus von Liebig. In advance, the nutrient solutions used to grow plants in so called "water cultures" had a simple composition and consisted of salts like KNO_3, $Ca(NO_3)_2$, $KHPO_4$, $MgSO_4$, and a little Fe-compound (Hoagland and Arnon, 1950), thus, containing all the major elements and some Fe. The relative success with these solutions will be due to the not knowingly supplied micro nutrients from the impurities of the chemicals and fertilizers used to compose the solutions. It can be supposed that the impurities contained sufficient micronutrients, to prevent the crops grown from serious nutrient disorders. Knowledge about the necessity of micro nutrients for plant growth was mainly gathered in the first half of the 20th century (Marschner, 1997), when the purification of fertilizers and chemicals were improved. The first systematic description for the preparation of nutrient solutions was given by Hoagland and Arnon (1950) and since then in many publications reference is given to them, when one or another nutrient solution is used to grow plants in soilless cultivation systems.

Hydroponics systems are used for many years for experimental purposes, to study effects of nutrient supply on agriculture crops. Despite, that many experiments were carried out with hydroponics or hydroponics related systems and these systems in advance got an enthusiast reception, it never came to a big scale professional development and practical application until the seventies of the 20th century. In that time, the development with soilless growing started with the production of tomato, cucumber and some cut flowers in peat bales, mostly called sausages, on the Channel Islands (Dally, 1974; States of Guernsey Horticultural Advisory Service, 1974). These sausages were long and slim sacks of about 80 cm length and 20 cm diameter, filled with 25 l of peat. In the same period growing in rock wool was initiated in the Scandinavian countries and soon developed in The Netherlands as a high technological system (Verwer, 1974; Sonneveld, 1980), while in the UK nutrient film technique (NFT) has been developed (Graves, 1983). In all these systems the development of nutrient solutions played a key role, because the quantity of nutrients available at any moment in hydroponics (NFT) or in related systems, like rock

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wool, peat and perlite, is restricted and cover only few percentages of the total crop requirements on minerals (Sonneveld, 1981; Voogt, 2002). For some substrates, like peat, the quantities of micro nutrients applied in advance are considerable in relation to the total absorption (Sonneveld, 2002), but it cannot be exactly predicted whether these elements will be sufficiently available for the whole growing period. Leaching and inactivation of these elements will be considerable during long growing periods. Thus, even in such cases a regular check on the availability of micro nutrients will be recommended to control the application.

When soilless culture in the greenhouse industry started on a large scale with the growing systems mentioned soon it appears that the development of nutrient solutions specific to crops and growing conditions was necessary. The use of the Hoagland solutions mentioned and the so called universal nutrient solutions (Steiner, 1968 and 1984) are only suitable in small scale experiments and if a regular replacement of the solution is carried out. Therefore, in line with the development of soilless cultivation in the seventies of the 20th century nutrient solutions for specific crops in relation to growing conditions have been developed (Sonneveld and Straver, 1994). Important factors to be considered with the development of nutrient solutions were for example: the specific uptake of the crops, the characteristics of the substrate, the chemical composition of the irrigation water used, the growth stage of the crop, the climatic conditions, and most of all whether or not reuse of the drainage water.

In the present chapter the preparation of nutrient solutions for specific crops will be explained in relation to the different factors mentioned. Fertilizers suitable to the purpose will be discussed and an algorithm for the required calculations presented.

12.2 Characteristics of Nutrient Solutions

Modern nutrient solutions for soilless culture mostly contain more or less all nutrients necessary for plant growth. This despite that substrates used sometimes contain nutrient elements that can become available to plants. The availability of those nutrients is quite often uncertain and depends strongly on the pH, which is not a stable factor in substrate growing. The risk of nutrient disorders is economical not acceptable in the high technical greenhouse industry, because the costs of the damage in such cases has no relationship to possible extra fertilizer costs. Therefore, usually all plant nutrients are added to nutrient solutions. Substantial quantities of nutrients present in the irrigation water or possibly released from the substrate will be taken into account in advance or will be controlled during the cropping period. Such adjustments will be based on the data of chemical analysis of substrates or solutions from the root environment.

The elements added to nutrient solutions are following:

Major nutrients	N, P, S, K, Ca, Mg
Micro nutrients	Fe, Mn, Zn, B, Cu, Mo

Elements being essential, but deliberately not added are Cl and Ni, while Na and Co are essential for some plants and beneficial for others. Si is beneficial for some plants, but not essential. Cl and Na are usually abundantly available in the irrigation water used to cover the essential requirements. An exception is the addition of Cl in nutrient solutions for tomato to promote the uptake of Ca as discussed further on in this section. For Co knowledge is still restricted and it is to be expected that in many cases this element is sufficiently available from impurities.

The necessity of the addition of Ni to nutrient solutions for substrate systems is not yet clear. For soil grown crops there is no clear evidence of Ni deficiency, but for pot experiments with soil effects have been found (Marschner, 1997). Thus, for substrate grown crops effects can be expected also, which mainly will depend on the composition of the substrate. Insufficient research is carried out for the determination of required concentrations. Addition on basis of rough estimations is dangerous, because the optimum and toxic concentrations for sensitive crops are close together. Rahman et al. (2005) found for barley grown in de-ionized water optimal plant weights with a concentration of 1 μmol l^{-1}. Balaguer et al. (1998) working with acid washed volcanic material found a substantial improvement of the growth of tomato at a concentration of 85 μmol l^{-1} in the nutrient solution added, compared with no addition. However, this concentration can be considerably above the optimum, because Marschner (1997) mentioned 5 μmol l^{-1} in the root environment as a maximum acceptable level for sensitive crops. In the experiment of Balaguer (1998) the level of 85 μmol l^{-1} was the lowest application rate, therefore this experiment was merely suitable for conclusions about toxic levels. The addition of Ni affected strongly the uptake and transport of other metal micro nutrients Rahman et al. (2005).

Si is identified as beneficial for a number of plants, but estimated as being not essential. The uptake differs strongly between plant species. It is abundantly available in soils and a number of substrates. For soilless cultures it is valuable to pay attention to the application of Si to nutrient solutions, dependent on the type of substrate used, the Si content of the primary water and the expected reaction of the crops (Voogt and Sonneveld, 2001). Si has an effect on the suppression of powdery mildew mainly with cucurbits and roses (Bélanger et al., 1995) and will increase the yield of some crops, (Miyake and Takahashi, 1983; Voogt and Sonneveld, 2001).

Besides uptake of the elements mentioned, being essential for the development of crops, plants also absorb many other elements present in the root environment. Effects of application of most of these elements to nutrient solutions for soilless culture are not yet studied and therefore, not yet applied to nutrient solutions as long as the application has not been proved to be relevant.

Sometimes, an extra addition or a reduction on the application of an element aggravate or reduces the uptake of a different element, which sometimes shows a beneficial effect on the development of plants. This well known antagonism and synergism effects, respectively do not only exists mutually among anions and cations, but also between anions and cations. In Fig. 12.1 an example is shown with replacement of NO_3 by Cl at high EC values in the root environment for a tomato crop

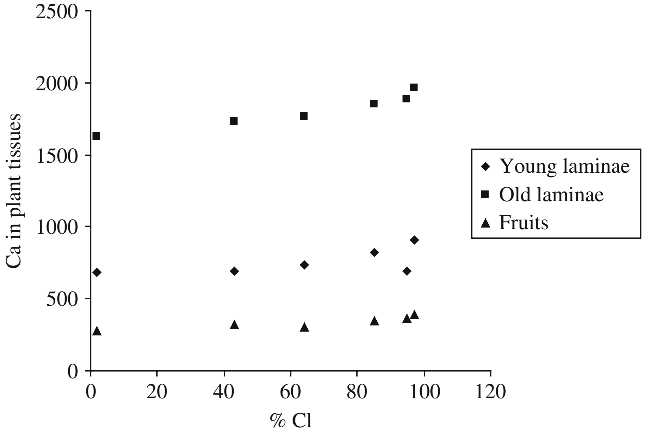

Fig. 12.1 Relationships between the % Cl ions of the sum (NO_3+ Cl) in the root environment and the Ca concentrations of plant tissues of rock wool grown tomatoes (mmol kg^{-1} dry matter, for fruits multiplied by 10). The sum of NO_3 + Cl was 22.5 mmol l^{-1}. Data after Voogt and Sonneveld (2004)

(Voogt and Sonneveld, 2004). This replacement strongly increases the uptake of Ca and thereby reduces the appearance of blossom-end rot, which can be a serious problem for example at high EC values, as has been discussed in Chapter 9.

Beside the addition of the elements mentioned the osmotic potential and the pH are important characteristics of nutrient solutions. The osmotic potential of nutrient solutions is mostly measured by the electrical conductivity (EC) and is build up in nutrient solutions by mineral salts. Therefore, a linear relationship between the osmotic potential and the EC will be supposed (Sonneveld et al., 1966; Sonneveld and Van den Ende 1967; Van den Ende, 1968). The pH in the root environment is important, because very low pH values in the root environment are toxic to plants. However, in practice the pH is mainly important because of its effects on the availability of many plant nutrients, especially micro nutrients, in the root environment (Lucas and Davis, 1961; Peterson, 1982).

The nutrient elements are mostly supplied in the form of fertilizers, mineral salts, acids and bases. N can be given in the form of NH_4 as well NO_3 and even as NH_2. The choice is mainly determined by the pH in the root environment. Addition of NH_4 lowers the pH in the root environment, because of an activation of the cation (NH_4) uptake and a reduction of the anion (NO_3) uptake. Standard quantities of NH_4 added to nutrient solutions for soilless culture are between 5 and 10% of the total N supply and seldom will exceed 15%. The tuning of the NH_4 addition merely occurs during crop growth in relation with the pH development in the root environment and will be discussed in detail in Section 13.4. High concentrations of NH_4 can be toxic to plants (Barker and Mills, 1980), especially at high pH values (Bennet, 1974).

Fe in mineral salts is very unstable and easily precipitates in solutions. Therefore, this element is supplied in the form of organic complexes, best known as chelates.

With the addition of major elements to nutrient solutions by fertilizers or other mineral compounds one always should be aware that besides the nutrient ion in view one or more other ions are added. Such accompanying ions should be taken into account too. For micro nutrients the accompanying ions are mostly Cl, NO_3 or SO_4, being major nutrient ions. The quantities of major ions added by this application are insignificant and can be neglected, because they are very low in comparison with the quantities of major elements required.

12.3 Nutrient Solutions for Different Crops and Development Stage

The nutrient uptake differs strongly between crops, not only with respect to the quantity of nutrients absorbed, but also the ratios between the nutrients are different. This is illustrated by the data listed in Table 12.1 where the yearly uptakes of major elements of high yielding tomato, chrysanthemum and cymbidium crops are compared. The data of tomato and chrysanthemum are derived from regression equations presented by Sonneveld (1997) with which the relationship between yield and nutrient uptake of two specific crops are presented. The data of cymbidium are derived from a study on different nurseries (Voogt et al., 2005). The yearly uptake of N and K of high yielding tomato and chrysanthemum crops are of the same order and ratio, but the uptake and the ratio of the other elements differ strongly. For cymbidium the quantities as well the ratios for most elements differ strongly from those of both other crops.

The variation in the uptake over the year differs strongly and is related with the growth rate of the crop. The driving force behind the growth rate is the radiation and therefore, the daily uptake varies strongly with the radiation input. Thus, the daily uptake is much higher in summer time than in winter time, especially in areas where the global radiation input in the winter is low. It has been found that the water use of crops, mainly due to transpiration, is also strongly related to the radiation input

Table 12.1 Yearly uptakes of major elements (kg ha^{-1}) by high yielding tomato (round and beefsteak types), chrysanthemum and cymbidium (cv Yonina) crops; being 60 kg of fruit fresh weight and 22.5 and 2.3 kg flower fresh weight yr^{-1} m^{-2} respectively

	Tomato		Chrysanthemum		Cymbidium	
Nutrients	kg ha^{-1}	Ratio N = 100	kg ha^{-1}	Ratio N = 100	kg ha^{-1}	Ratio N = 100
N	1185	100	903	100	110	100
P	284	24	129	14	18	16
S	290	24	61	7	37	34
K	2044	172	1567	174	163	148
Ca	863	73	259	29	111	101
Mg	208	18	82	9	10	9

(De Graaf and Esmeijer, 1998). This implies that the ratio between nutrient uptake and water uptake will be more or less constant. This ratio, often called uptake concentration, has no physiological basis, because the uptake of water and nutrients are independent processes (Sonneveld and Voogt, 1990). Nevertheless, the uptake concentration appears to be not altogether stable (Kläring et al., 1997) and increases with low and decreases with high radiation input. This can be explained by the fact that the photosynthesis of crops is curve linearly related with radiation input, while transpiration is merely linearly related with radiation input (Sonneveld, 2002). Experimental data showed that the fluctuations of the uptake concentrations are less than those of the daily uptake (Savvas and Lenz, 1995). Therefore, the uptake concentration is often used as a rough basis for the addition of fertilizers to the irrigation water in substrate systems.

For an accurate nutrient application the development of standard nutrient solutions is important (Sonneveld and Straver, 1994). Such solutions will be defined as nutrient solutions due to addition in soilless cultures to keep the nutrient status in the substrate optimal for the crop under the current growing conditions. These growing conditions will be defined and mainly concern the climatic conditions, the irrigation patterns and the development stages of the crop. With the climatic conditions, the light intensity and the transpiration rate are detected as being important. With the irrigation, the fraction drain to waste, the reuse of drain water and the circulation rate are main factors. With the development stages, the change from the vegetative to the reproductive phase is important. Mainly the K:Ca ratio of the uptake increases in the reproductive phase as has been described for tomato (Voogt, 1993) and other fruit vegetables (Voogt, 2002). It also occurs with head formation of lettuce crops and the shoot up of a flower flush with cut flowers like roses and carnations. The explanation is the relative much higher K:Ca ratio in the reproductive organs, like fruits and flower stems than in the vegetative organs, mainly leaves. (Van Goor et al., 1988; Voogt, 1988; Voogt and Sonneveld, 1997; Ward, 1967). The cation distribution of a tomato and a cucumber crop are shown in Table 12.2. The K:Ca ratios of fruits are much higher than those of leaves, especially with tomato. Therefore, adjustment of the solution added to the growing system is necessary during crop development, like shown in Table 12.3 (Voogt, 1993).

Table 12.2 Distribution of dry matter and K, Ca and Mg over different plant parts in % of the total aboveground uptake for long term tomato and cucumber crops

	Tomato				Cucumber		
	Leaf	Shoots[1]	Stem	Fruit	Leaf	Stem	Fruit
Dry matter	20	4	14	62	28	14	58
K	18	5	11	66	22	10	67
Ca	76	4	15	5	56	23	20
Mg	50	5	15	30	44	19	37

[1] Young shoots removed with pruning

Data derived from Roorda van Eijsinga and Haeff (1964); Voogt (1993) and Voogt (2002).

Table 12.3 Guidelines for the adjustment of the nutrient solution supplied to tomatoes in a closed growing system in relation to the growth stage

	mmol.l^{-1}						
Growth stages	NH_4	K	Ca	Mg	NO_3	SO_4	H_2PO_4
Standard solution	1.0	6.5	2.75	1.0	10.75	1.5	1.25
Saturation root medium	−0.5	−2.5	+1.0	+0.5	[2]		
Start till 1st truss[1]		−1.2	+0.3	+0.3			
1st till 3rd truss							
3rd till 5th truss		+1.0	−0.25	−0.25			
5th till 10th truss		+3.5	−1.25	−0.50			
10th till 12th truss		+1.0	−0.25	−0.25			
After the 12th truss							

[1] Adjustments are related to the truss number at anthesis

[2] Where no value is given, standard concentration is recommended

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Effects of climatic conditions are shown by the results of Bakker and Sonneveld (1988) with cucumber. With a high humidity the uptake of Ca is strongly reduced and thus, a high Ca supply is necessary to prevent Ca deficiency, as shown in Fig. 9.4. Effects of the irrigation practises are shown with the nutrient solutions used in a free drainage system and in a closed system to realise equal concentrations in the substrate solution in the root environment with a tomato crop, as listed in Table 12.4. In the free drainage system a leaching fraction of about 30% is taken into account. The mutual ratios of the nutrient concentrations in the solution supplied in a free drainage system and those supplied in a closed system differ substantially. The bivalent ions are relatively lower in the solution for closed systems. This is linked up with the usually desired strong accumulation of the bivalent nutrients in the root environment, because of the relatively low uptake of these ions like discussed in Section 3.5.

Table 12.4 Composition of the nutrient solution in the root environment recommended for tomato and the composition of the supplied solution recommended for a closed system and for a free drainage system

Parameters	Root environment	Supplied closed system	Supplied free drainage	Ratio free/closed
EC dS m^{-1}	4.0	1.6	2.6	1.6
NH_4mmol l^{-1}	< 0.5	1.0	1.2	–
K	8.0	6.5	9.5	1.5
Ca	10.0	2.75	5.4	2.0
Mg	4.5	1.0	2.4	2.4
NO_3	23.0	10.75	16.0	1.5
SO_4	6.75	1.5	4.4	2.9
H_2PO_4	1.0	1.25	1.5	1.2

After Sonneveld (2002). *Reprinted after permission of Embryo Publications.*

12.4 Water Quality

The quality of the primary water affects the requirements for the composition of nutrient solutions in different ways. Preferably, water is used with low concentrations of mineral elements, that means concentrations equal or lower than the uptake concentrations. When such is the case for all elements, the drainage water can be completely reused. This situation mainly exists with the use of rain water or desalinated water. Natural ground waters or surface waters commonly contain substantial concentrations of mineral elements often beyond those of the uptake concentrations. When such is the case, the water is less suitable for closed growing systems. Different effects of the presence of mineral elements in the irrigation water on the preparation of nutrient solutions will be discussed successively.

In the first place the situation that the water contains minerals acting as plant nutrients and residual salts, the concentrations of which are equal or below the uptake concentration. The adjustment exists in a reduction on the addition of the required nutrient(s).

Secondly, the concentration of a nutrient element or a residual salt in the primary water is higher than the uptake concentration of the crop grown. The addition of the nutrient element in question is eliminated from the addition. Nevertheless, the residual concentration of the nutrient or the residual salt will accumulate in the root environment. The maximum acceptable accumulation levels, vary for crops and growing conditions. Under certain conditions the accumulation fits in the composition of the nutrient solution in the root environment, before leaching is necessary (Sonneveld, 2000). Guidelines for adjustments in relation to the acceptable accumulations of residual salts are discussed in Section 7.7.

Thirdly, when concentrations of minerals in the primary water are much higher than the uptake concentrations and the accumulation of such minerals easily exceeds the maximum acceptable level, a systematic drainage to waste is necessary. With this drainage water, beside the mineral(s) in question, also other minerals (nutrients) are removed from the root environment and by this the addition should be adjusted to a systematic leaching requirement, as discussed in Section 12.3.

Fourthly, adjustments are necessary when the primary water contains (bi)carbonate. When substantial concentrations of these ions are present, the pH of the nutrient solution easily becomes too high, because of the alkaline buffering capacity of the carbonate. This problem can be solved by addition of equivalent concentrations of free acids in the nutrient addition. HNO_3 and possible H_3PO_4 or H_2SO_4 are most suitable to the purpose. Following reaction occurs with the acid addition.

$$HCO_3 + H_3OA \rightarrow 2H_2O + A + CO_2 \uparrow \tag{12.1}$$

In this equation A is placed for the anion of the acid used and can be in the current situation a NO_3, H_2PO_4, or SO_4 ion.

Finally, Fe available in natural waters cannot be taken into account, because it easily precipitates, like discussed in Section 6.4. Cu in such waters sometimes can be affected by complex formation in combination with soluble organic compounds present in the water. Hereby, the metal can be bound that strongly in the complex that it is scarcely available to plants. See also the discussion about this effect in Section 13.4. Therefore, it is experienced that Cu as determined by chemical analysis cannot always completely taken into account in natural waters.

12.5 Adjustments

The intention of the application of nutrients during crop cultivation is the maintenance of a nutrient level in the root environment for an optimal crop development, which holds a maximum production of the required quality. To this purpose as much as possible information about nutrient use during crop cultivation should be outlined in a systematic scheme, as discussed in Section 12.3. Important processes that determine the equilibrium between the addition to and the extraction from the nutrient solution in the root environment are the uptake by the crop and the immobilisation processes. In case of free drainage systems also the leaching of nutrients is an important factor. Often insufficient information is available about these processes, which results in disturbance of the equilibrium and an unsettlement of the chemical composition of the nutrient solution in the root environment. Therefore, a regular check on the chemical composition is necessary. The sampling frequency varies between once a month and once a week dependent on risks and chances to be expected. The analysis is mostly carried out by professional laboratories. Besides the determination of chemical composition on the laboratory, frequent measurements of EC and pH are recommended with the aid of portable instruments on the greenhouse holdings itself.

The results of the measurements will be compared with the guide values developed for crop and prevailing growing conditions. These values are different from those of the nutrient solution added as given by Sonneveld and Straver (1994); see also the examples in Table 12.4. On basis of the comparison conclusions will be drawn about the necessity of adjustments on the nutrient solution added. The extent of the adjustments depend on the deviation of the current values from the standardized guide values. For major nutrients with a high absorption rate like N, P, and K deviations – reduction or increase – of 30% on the addition are applied, while for Ca, Mg, S and micro nutrients deviations up to 50% are thinkable. Seldom results lead to exclusion of the application of a nutrient element. Judgement of the analytical data of P and Mn need extra attention, since the results of these elements will be judged in relation to the pH and the duration of the cropping period. The availability of both elements is strongly affected by the pH. At pH values >6.5 the concentration can be low independent of the concentration added with the irrigation water. P is less soluble at high pH values. Mn at such pH values can become very low after some months by the development of Mn oxidising micro organisms in the root environment, as will be discussed in detail in Section 13.4. Sometimes the ratio between elements is more important than the actual concentration. This for example is the case for the K:Ca ratio for fruit vegetables, as will be explained in Section 13.4.

Adjustments with regard to pH and EC mostly occur on basis of the frequent measurements by the portable instruments. The pH will be regulated mainly by adjustments of the NH_4 application since the pH in the root environment can be hardly affected by acid or base applications. Only in systems with a high circulation rate, addition of acids also offers possibilities for pH control (Voogt, 2009). At the moment research is going to the development of *in situ* measurements of different nutrients in solutions (Gieling, 2001) under growing conditions, but these systems are not yet operative. In future they offer possibilities for a full automation of nutrient supply.

For interpretation of the analytical data the sampling method, the sampling place and the extraction method on the laboratory are important factors too to be taken into account with the interpretation. See therefore the Chapters 4 and 8.

12.6 Fertilizers

Not all fertilizers used in horticultural practise are suitable for the preparation of nutrient solutions for soilless culture. The fertilizers, but also the other chemicals used to that purpose, should be rapidly and completely soluble in water and should not contain insoluble residues, contaminants of heavy metals or other components leading to concentrations in nutrient solutions toxic to plants or, after absorption by plants, to human beings. Insoluble residues, although not directly harmful to plants, are undesirable because such residues easily block the narrow canals of the irrigation systems commonly used. In Table 12.5 common fertilizers used for the preparation of nutrient solutions in greenhouse cultivation are listed.

Table 12.5 Fertilizers and acids used in the greenhouse industry to compose nutrient solutions, chemical compositions and molecular weights

Fertilizer	Chemical composition	mol weight
Calcium nitrate	$5[Ca(NO_3)_2.2H_2O]NH_4NO_3$	1080.5
Ammonium nitrate	NH_4NO_3	80
Potassium nitrate	KNO_3	101.1
Magnesium nitrate	$Mg(NO_3)_2.6H_2O$	256.3
Nitric acid 100%	HNO_3	63
Mono potassium phosphate	KH_2PO_4	136.1
Phosphoric acid 100%	H_3PO_4	98
Potassium sulphate	K_2SO_4	174.3
Magnesium sulphate	$MgSO_4.7H_2O$	246.3
Manganese sulphate	$MnSO_4.H_2O$	169
Zinc sulphate	$ZnSO_4.7H_2O$	287.5
Copper sulphate	$CuSO_4.5H_2O$	249.7
Borax	$Na_2B_4O_7.10H_2O$	381.2
Sodium molybdate	$Na_2MoO_4.2H_2O$	241.9
Iron chelate EDTA 13% Fe	Fe-EDTA	430
Iron chelate DTPA 6% Fe	Fe-DTPA	932
Iron chelate EDDHA 5% Fe	Fe-EDDHA	1118

Picture 12.1 Installation for the preparation of nutrient solutions. At the back the reservoirs for concentrated fertilizer solutions are placed

The formula given for calcium nitrate is a little complicated, but necessary to use in the calculations, to get the right NH_4 concentration in the solution. With the fertilizer of this source, often 50% or more of the required NH_4 is brought in. For the acids molecular weights of 100% pure chemicals are given. However, such acid solutions do not exist. The strength of the solutions in trade is different. The molecular weights of such solutions will be calculated following formula (12.2).

$$mol\ weight\ current\ solution = \frac{mol\ weight\ 100\%\ solution}{0.01 \times current\ \%} \tag{12.2}$$

For micro nutrients most common types are given, but also other types are suitable, like the chloride or nitrate salts of Mn, Zn and Cu. Furthermore, the water bound in the salt crystals can differ, which affects also the molecular weight. For Fe DTPA and EDTA chelates can be used and are suitable up to a pH of 6.5 (Lindsay et al., 1967). When the pH will arise above this value Fe-EDDHA is often used, because the compound is stable at all pH values and thus suitable under all pH conditions. However, the applicability is not unequivocal due to side effects, see Section 13.4.4. Moreover, the price of the latter compound is mostly much higher than those of the other compounds and therefore less frequently used. All Fe-chelates are available in different qualities (% of chelated Fe) and with the deviation from the percentages mentioned the dosing will be adjusted accordingly.

Besides the group of common fertilizers and chemicals mentioned in Table 12.5, the Dutch fertilizer industry has manufactured special groups of chemical compounds or mixtures of such compounds tuned to substrate growing (Sonneveld and

Voogt, 1994). Such special groups merely consist of highly concentrated solutions of mineral salts, fertilizers, acids and alkalines. The acids and alkalines are due to chemical reactions when put together in the stock solution at the greenhouse holdings, with mineral salts as a result. Following reaction occur when a base is used in combination with an acid

$$H_3OA + MOH \rightarrow 2H_2O + A + M \tag{12.3}$$

And when a carbonate is used

$$H_3OA + MHCO_3 \rightarrow 2H_2O + CO_2^{\uparrow} + A + M \tag{12.4}$$

In which is

A = an anion
M = a cation

Nowadays several methods are available for the preparation of nutrient solutions. Traditionally fertilizers and chemicals were brought together in two concentrated stock solutions in separate reservoirs mostly called A and B. Compounds containing Ca and Fe should be added to the A reservoir and compounds containing SO_4 and H_2PO_4 and the bulk of the acids to the B reservoir. In this way precipitation of Ca-phosphates ($CaHPO_4$ and $Ca_3(PO_4)_2$ or $CaSO_4$ will be prevented as well as decomposition of Fe-chelates, which easily occurs in a strong acid solutions.

The A and B stock solutions are usually 100 times higher concentrated than the nutrient solution to be supplied. This is possible until an EC value in the supplied solution of about 2.0, for the commonly used compositions. When higher concentrated solutions are required, the stock solutions become over saturated with precipitation of some salts and an unsettlement of the composition as a result.

Addition of the stock solutions to the water is carried out by devices, automatic or semi- automatic types. The semi- automatic types inject the stock solution in the water flow or in a mixing tank on a preset proportional basis without a feedback of an EC measurement. The automatic types inject the stock solution in the water flow or into the mixing tank, whereby the final concentration of the nutrient solution supplied is regulated by means of continuous EC measurements. In last case, also a continuous measurement of the pH is carried out and possible adjustments are performed by addition of small quantities from separate either acid or alkaline stock solutions. For the preparation of the acid stock solution HNO_3 is preferred to H_3PO_4, because the small applications make relatively more sense to the P than to the N application. Besides, long duration of P overdoses especially with reuse of drainage water will easily induce high P levels in the root environment, which can become toxic to some plants (Howell and Bernhard, 1961). Alternatively, the use of H_2SO_4 to the purpose is possible. The alkaline stock solution best can be prepared with KOH or $KHCO_3$.

More advanced fertilizer supply is carried out by individual and direct injection of the fertilizers in the water flow or onto a mixing tank. In this case all the fertilizers have to be in liquid form or have to be dissolved in separate concentrated stock solutions. These systems are furnished with the same number of injectors as the number of fertilizer stock solutions that will be added. Such systems are fully computerized and have the advantage that the recipe of the nutrient solution can directly be brought in the managing computer and that the recipe thus can instantly be adjusted.

The application of Si to nutrient solutions is complicated because the Si compounds applicable for plant nutrition purposes are not stable in diluted, ready to use, nutrient solutions at pH <9 and in particular not in concentrated stock solutions. Precipitation of Si can become a serious problem in irrigation systems, especially with respect to blockings in trickle irrigation systems. For the addition of Si to nutrient solutions highly alkaline concentrated Si compounds, containing Si, K and OH in the mol ratios of 1:2:2, respectively are recommended. These compounds are stable in concentrated form, but not in concentrated nutrient stock solutions. Therefore, it should be separately added from the other fertilizers in the ready (diluted) nutrient solutions. Beforehand, the fertilizer recipe will be adjusted for the K and alkaline input of the Si compound, being an equivalent reduction of K and addition of H_3O. After the Si addition the alkalinity is instantly neutralized by the H_3O in the adjusted fertilizer recipe. In the diluted form at "neutral" pH values a maximum concentration of about 1.5 mmol l^{-1} Si will be soluble in the monomer ($Si(OH)_4$ form, likely the only form absorbed by plants (Iler, 1979). Optimal effects of Si are derived by a relatively low concentration, as is clear from the data shown in Fig. 12.2. Higher applications increase the uptake of Si like shown in Fig. 12.3, but did not increase yield. It only increases the risk on blocking of the irrigation system. Thus, if there is no Si available from the substrate or from the irrigation water a concentration of about 0.75 mmol. l^{-1} in the nutrient solution is sufficient for an optimal response for most crops that react on Si application (Voogt and Litjens, 1991; Voogt 1992).

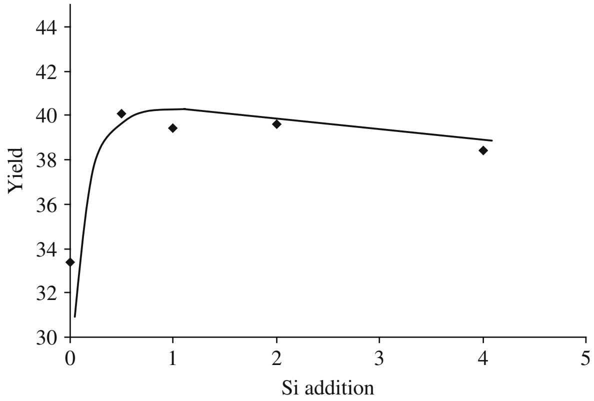

Fig. 12.2 Relationship between the addition of Si to the nutrient solution (mmol l^{-1}) and the yield of cucumbers (kg m^{-2}). Data derived from Voogt and Sonneveld (2001)

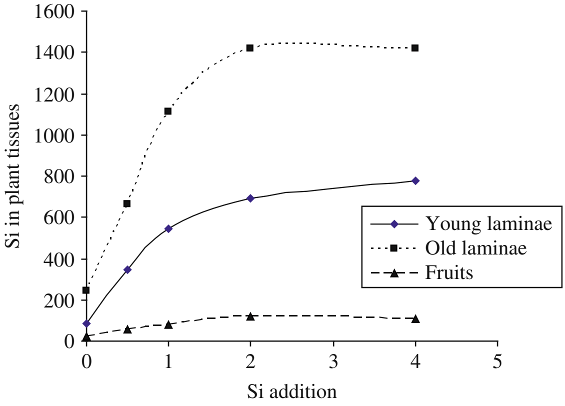

Fig. 12.3 Relationships between the addition of Si (mmol l^{-1}) to the nutrient solution and the Si uptake (mmol kg^{-1} dry matter) in different organs of cucumbers grown in rock wool. Data derived from Voogt and Sonneveld (2001)

12.7 Algorithm

For the calculation of nutrient solutions a universally suitable algorithm is developed (Sonneveld et al., 1999). With this algorithm the fertilizer composition of nutrient solutions can be calculated based on standard recipes (Sonneveld and Straver, 1994) with adjustments on water quality, pH, EC and recommendations by chemical analysis of the nutrient solution in the root environment. Last adjustments can be formulated as single anions and/or cations, because the algorithm equalizes the possible difference between the sum of anions and of cations relatively over the anions and/or cations. In this way the mutual ratios of anions and the mutual ratios of cations are kept constant.

Following steps in the calculations of the algorithm should be carried out in the order given.

1. Selection of the standard nutrient solution depending on crop, growing system and possible growth stage and growing conditions.
2. Possible adjustments of nutrient elements, for example recommendations based on the chemical composition of the nutrient solution in the root environment.
3. Equalizing of differences between anion and cation sums, keeping the EC equal to those of the standard solution. NH_4, P, and micronutrient are excluded from this equalization.
4. Adjustment on the EC required in the supplied solution, from which components are excluded as in step 3.
5. Adjustment on the quality of the primary water
6. Calculation of fertilizer composition.

In step 3 and 4 NH_4 is excluded from the equalization, because the application of the ion is primarily connected with the pH regulation. P is excluded from it because an over supply of this element easily disturb the uptake of some other nutrients and P can be toxic, when the concentration in the root environment become too

Picture 12.2 Rooting system of chrysanthemum grown in a hydroponics system

high, as already mentioned in Section 12.6. Micro nutrients are excluded from these corrections, because the EC is not notably affected by these elements.

The standard nutrient solution for step 1 can be selected from the available sources, or drawn up by the grower or by an advisor. The adjustments under step 2 are mostly based on chemical analysis of a sample of the nutrient solution from the root environment. For the calculations necessary in the other steps following formulae are developed (Sonneveld et al., 1999; Sonneveld, 2002).

For step 3 calculations of cations:

$$c_{s(x)}\text{'} = \frac{\{c_{st(x)} + c_{adj(x)}\} \times \{C_{st}^{+} - c_{st(NH_4)} - c_{adj(NH_4)}\}}{\{C_{st}^{+} - c_{st(NH_4)} + \sum [V_{(x)} \times c_{adj(x)}]\}} \tag{12.5}$$

For step 3 calculations of anions:

$$c_{s(x)}\text{'} = \frac{\{c_{st(x)} + c_{adj(x)}\} \times \{A_{st}^{-} - c_{st(H_2PO_4)} - c_{adj(H_2PO_4)}\}}{\{A_{st}^{-} - c_{st(H_2PO_4)} + \sum [V_x \times c_{adj(x)}]\}} \tag{12.6}$$

In which

$c_{s(x)'}$= calculated concentration in the water supplied after adjustment of the mutual ratios of the macro nutrients in mmol l^{-1}
$c_{st(x)}$= concentration of any ion x in the standard nutrient solution in mmol l^{-1}
$c_{adj(x)}$= concentration adjustment of any ion x except P and NH_4 in mmol l^{-1}
A_{st}^{-}= sum of electrons of the standard solution in mmol l^{-1}
C_{st}^{+}= sum of protons of the standard solution in mmol l^{-1}
$V_{(x)}$= valence of ion x

It should be noticed that for the concentrations NH_4 and P the following is operative: $c_{s(NH4)'} = c_{st(NH4)} + c_{adj(NH4)}$ and $c_{s(H2PO4)}' = c_{st(H2PO4)} + c_{adj(H2PO4)}$, respectively

If the desired EC of the nutrient solution supplied differs from the EC of the standard nutrient solution, Step 4 will be carried out.

Step 4 calculation of cations:

$$c_{s(x)} = \frac{10EC_s - c_{s(NH_4)'}}{10EC_{st} - c_{s(NH_4)'}} \qquad (12.7)$$

Step 4 calculation of anions:

$$c_{s(x)} = \frac{10EC_s - c_{s(H_2PO_4)'}}{10EC_{st} - c_{s(H_2PO_4)'}} \qquad (12.8)$$

In which

$c_{s(x)}$ = concentration after adjustment on the EC in the nutrient solution supplied

The ultimate concentrations that will be supplied by addition of fertilizers are derived after correction on the nutrients available in the primary water. These calculations are carried out by steps 5 and 6, the adjustments of anions and cations on the composition of the primary water. The composition of which will be given by chemical analysis.

$$c_{f(x)} = c_{s(x)} - c_{w(x)} \qquad (12.9)$$

In which

$c_{f(x)}$ = the concentration of ion x added by fertilizer application in mmol l^{-1}
$c_{w(x)}$ = the concentration of any ion x in the primary water in mmol l^{-1}

The HCO_3 will be neutralized by addition of equivalent quantities of acid, as given in Section 12.4. An example of the calculations is given in Table 12.6.

An example of the calculation of the fertilizer composition is listed in Table 12.7. In this calculations it should be noted that 1 mol of a salt in a fertilizer after dissociation often contain more than one mole of the element concerned. This is for example quite clear with K_2SO_4, but more complicated with the fertilizer calcium nitrate. After dissociation 1 mol contains following nutrient compounds.

$$5[Ca(NO_3)_2.2H_2O]NH_4NO_3 \rightarrow 5Ca + 11NO_3 + NH_4$$

Beside the calcium nitrate fertilizer, there are high concentrated calcium nitrate solutions on the market. These solutions are often free from NH_4. There are much

Table 12.6 An example of the calculation of a nutrient solution worked out for a cucumber crop with reuse of drainage water

	Steps of the calculations					
Elements	1 (c_{st})	2 (c_{adj})	3 (c_s')[1]	4 (c_s)[2]	5 (c_w)	6 (c_f)[3]
EC dS m^{-1}	1.5		1.5	1.9		
NH_4 mmol l^{-1}	1.0	+0.25	1.25	1.25		1.25
K	6.5		6.88	8.88		8.88
Ca	2.75	−0.5	2.38	3.07	0.6	2.47
Mg	1.0		1.06	1.37	0.3	1.07
NO_3	11.75		11.54	14.96		14.96
SO_4	1.0		0.98	1.27	0.4	0.87
H_2PO_4	1.25	+0.25	1.50	1.50		1.50
HCO_3					1.0	
H_3O						1.0
Fe µmol l^{-1}	15		15	15		15
Mn	10		10	10		10
Zn	5		5	5		5
B	25		25	25	10	15
Cu	0.75		0.75	0.75		0.75
Mo	0.5		0.5	0.5		0.5

[1] Using formulae (12.5) and (12.6);
[2] using formulae (12.7) and (12.8);
[3] using formula (12.9)
The standard solution is derived from Sonneveld and Straver (1994).

Table 12.7 Calculations of the quantities of fertilizer necessary for the composition of the nutrient solution given in the last column of Table 12.6

			Elements added in mmol l^{-1}							
Fertilizers	mmol l^{-1}	mg l^{-1}	NH_4	K	Ca	Mg	H_3O	NO_3	SO_4	H_2PO_4
Calcium nitrate[1]	2.47/5	534	0.49		2.47			5.43		
Ammonium Nitrate	0.76	61	0.76					0.76		
Mono pot. phosphate	1.50	204		1.50						1.50
Magnesium nitrate	1.07	274				1.07		2.14		
Potassium sulfate	0.87	152		1.74					0.87	
Nitric acid 38%	1.00	166					1.00	1.00		
Potassium nitrate	5.64	570		5.64				5.64		
Sums			1.25	8.88	2.47	1.07	1.00	14.97	0.87	1.50

[1] fertilizer

more concentrated fertiliser solutions on the market containing more than two nutrient elements varying in concentrations and ratios between the nutrients. It is obvious that the calculations become more complicated with such compound fertilizers than with fertilizers containing a single salt. Furthermore it should be noticed that 1 mol Borax ($Na_2B_4O_7.10H_2O$) $\equiv$ 4 mol B, but when for example boron acid (H_3BO_3) is used that 1 mol $H_3BO_3 \equiv 1$ mol B.

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